RTU RĒZEKNE

RTU RĒZEKNES AKADĒMIJA
Inženierzinātņu centrs

REZEKNE ACADEMY OF RIGA TECHNICAL UNIVERSITY
Engineering Centre

VIDE.TEHNOLOĢIJA. RESURSI

XVI starptautiskās zinātniski praktiskās konferences rakstu krājums
2025. gada 19.–20. jūnijs

2. SĒJUMS

ENVIRONMENT. TECHNOLOGY. RESOURCES

Proceedings of the 16th International Scientific and Practical Conference
June 19th – 20th, 2025

VOLUME II



Rēzekne 2025

RTU RĒZEKNES AKADĒMIJA
Inženierzinātņu centrs

REZEKNE ACADEMY
OF RIGA TECHNICAL UNIVERSITY
Engineering Centre

VIDE. TEHNOLOĢIJA. RESURSI

XVI starptautiskās zinātniski praktiskās konferences materiāli
2025.gada 19.-20.jūnijs

2. SĒJUMS

ENVIRONMENT. TECHNOLOGY. RESOURCES

Proceedings of the 16th International Scientific and Practical Conference
June 19th – 20th, 2025

Volume II

Rezekne
2025

VIDE. TEHNOLOĢIJA. RESURSI. 16. starptautiskās zinātniski praktiskās konferences materiāli. 2025.gada 19.-20. jūnijs. *2.sējums*: RTU Rēzeknes akadēmija, Rēzekne, Latvija, 2025. 399 lpp.

ENVIRONMENT. TECHNOLOGY. RESOURCES. Proceedings of the 16th International Scientific and Practical Conference on June 19-20, 2025. *Volume II*: Rezekne Academy of Riga Technical University, Rezekne, Latvia, 2025. pp. 399.

16.starptautiskās zinātniski praktiskās konferences "Vide. Tehnoloģija. Resursi" materiālos četros sējumos ir pārstāvēti jaunākie pētījumi vides inženierzinātnē, vides un dabas aizsardzībā, ilgtspējīgā lauksaimniecībā, enerģētikā, materiālzinātnē, mehānikā, metālapstrādē, lāzeru tehnoloģijās, matemātiskajā modelēšanā, elektrotehnikā, vides ekonomikā un vadībā, informācijas tehnoloģijās un sociotehnisko sistēmu modelēšanā, vides izglītībā un ilgtspējīgas attīstības procesos, izglītība inženierzinātnēs, aizsardzības un drošības tehnoloģijās. Krājumā pārstāvēto pētījumu joma ir daudzpusīga un starpdisciplināra, balstīta uz starptautisko zinātnieku kolektīvu sasniegumu rezultātiem. Konferences materiālos iekļauti 317 zinātniskie raksti. Konferences dalībnieki pārstāv 28 valstis.

16.starptautiskās zinātniski praktiskās konferences "Vide. Tehnoloģija. Resursi" norises vieta ir RTU Rēzeknes akadēmija, Rēzekne, Latvija.

Proceedings of the 16th International Scientific and Practical Conference "Environment. Technology. Resources" include recent research in fields of engineering, environmental and nature protection, sustainable agriculture, energy, material science, mechanics, metalworking, laser technologies, mathematical modelling, electrical engineering, environmental economics and management, information technologies and sociotechnical systems modelling, environmental education and sustainable development, education in engineering sciences, defense and security technologies. The research area presented in the proceedings is comprehensive and cross-disciplinary, on the advances of international researchers. The proceedings comprise 317 scientific papers. Conference participants represent 28 countries.

16th International Scientific and Practical Conference "Environment. Technology. Resources." hosted by Rezekne Academy of Riga Technical University, Rezekne, Latvia

https://conferences.rta.lv/index.php/ETR/ETR2025
Link to conference proceedings: http://journals.rta.lv/index.php/ETR

This journal is licensed under
Creative Commons Attribution 4.0 International (CC BY 4.0) License
The author(s) of the paper take responsibility for the content of the paper

Online **ISSN 2256-070X**

Published by **RTU PRESS, 2025**

Scientific Committee Chairman

Dr.sc.ing. Edmunds Teirumnieks, Rezekne Academy of Riga Technical University, Latvia

Scientific Committee Co-Chairmen

Dr. Walter Leal, Hamburg University of Applied Sciences, Germany, Manchester Metropolitan University, United Kingdom
Dr.sc.ing. Andris Martinovs, Rezekne Academy of Riga Technical University, Latvia
Dr.sc.ing. Artis Teilāns, Rezekne Academy of Riga Technical University, Latvia

Scientific Committee

Dr.agr. Aleksandrs Adamovičs, Latvia University of Life Sciences and Technologies, Latvia
PhD Nikolaj Angelov, Technical University of Gabrovo, Bulgaria
PhD Kiril Anguelov, Technical University of Sofia, Bulgaria
PhD Andres Annuk, Estonian University of Life Sciences, Estonia
Dr. agr. Lidiia Antypova, Mykolaiv National Agrarian University, Ukraine
PhD Iluta Arbidane, Rezekne Academy of Riga Technical University, Latvia
PhD Plamen Atanasov, New Bulgarian University, Bulgaria
PhD Todor Balabanov, University of Transport "Todor Kableshkov", Bulgaria
PhD Stefan Bankov, The Ministry of Interior of Bulgaria, Bulgaria
PhD Jānis Bičevskis, University of Latvia, Latvia
PhD Aija Brakovska, Daugavpils University, Latvia
PhD Ģirts Būmanis, Riga Technical University, Latvia
PhD Ivan Byanov, University of Veliko Tarnovo "St. Cyril and St. Methodius", Bulgaria
PhD Hamid Can, Trakya University, Turkey
Dr. hab. Ing. Tadeusz Chrzan, Poltegor Institute, Poland
PhD Dimitar Dimitrov, Todor Kableshkov University of Transport, Bulgaria
PhD Sevdalina Dimitrova, “Vasil Levski” National Military University, Bulgaria
PhD Nadezhda Dimova, New Bulgarian University Department "Economics", Bulgaria
PhD Nikolay Dolchinkov, "Vasil Levski" National Military University, Bulgaria
Dr.hist. Edvins Evarts, Turiba University, Latvia
PhD Vanko Ganev, "Vasil Levski" National Military University, Bulgaria
Dr.sc.ing. Imants Gorbāns, Riga Technical University, Latvia
Dr.sc.ing. Aleksandrs Gorbunovs, Riga Technical University, Latvia
Dr.sc.ing. Pēteris Grabusts, Rezekne Academy of Riga Technical University, Latvia
PhD Grigor Grigorov, “Vasil Levski” National Military University, Bulgaria
PhD Inga Grinfelde, Latvia University of Life Sciences and Technologies, Latvia
PhD Tzvetelin Gueorguiev, Technical University of Gabrovo, Bulgaria
PhD Mart Hovi, Estonian University of Life Sciences, Estonia
PhD Maria Ilcheva, Saint Cyril and Methodius University of Veliko Tarnovo, Bulgaria
Dr. agr. Sofija Jankauskiene, Lithuanian Research Centre for Agriculture and Forestry, Lithuania
PhD Aivars Jermuss, Latvia University of Life Sciences and Technologies, Latvia
Dr.sc.ing. Aivars Kaķītis, Latvia University of Life Sciences and Technologies, Latvia
PhD Sabrina Kalinkova, University of National and World Economy, Bulgaria
Dr.paed. Ilmārs Kangro, Rezekne Academy of Riga Technical University, Latvia
PhD Atis Kapenieks, Riga Technical University, Latvia
Dr. paed. Janis Kapenieks, Riga Technical University, Latvia
PhD Tsanko Karadzhov, Technical University of Gabrovo, Bulgaria
PhD Aivars Kaupuzs, Rezekne Academy of Riga Technical University, Latvia
PhD Stancho Kajkov, “Vasil Levski” National Military University, Bulgaria
PhD Anna Khilya, Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University, Spain
PhD Georgi Komitov, Agricultural University Plovdiv, Bulgaria
PhD Inga Ļašenko, Riga Technical University, Latvia
Dr.sc.ing. Lyubomir Lazov, Rezekne Academy of Riga Technical University, Latvia
PhD Iveta Linina, Turiba University, Latvia

PhD Lyuboslav Lyubenov, University of Ruse "Angel Kanchev", Bulgaria
Dr.sc.math. Maksims Marinaki, University of Latvia, Latvia
PhD Rumen Marinov, “Vasil Levski” National Military University, Bulgaria
PhD Dilyan Markov, Georgi Rakovski Military Academy, Bulgaria
Dr.sc.ing. Linda Mežule, Riga Technical University, Latvia
PhD Ziedonis Miklašēvičs, Rezekne Academy of Riga Technical University, Latvia
PhD Nikolai Minkovski, University of Forestry, Bulgaria
PhD Penko Mitev, Technical University of Sofia, Bulgaria
Dr.sc.ing. Ivan Mitev, Technical University of Gabrovo, Bulgaria
PhD Marufjon Musaev, Tashkent State Technical University, Uzbekistan
PhD Nikolay Padarev, "Vasil Levski" National Military University, Bulgaria
Dr.sc.ing. Desislava Petrova, Technical University of Gabrovo, Bulgaria
Dr.agr. Liena Poiša, Rezekne Academy of Riga Technical University, Latvia
Dr. agr. Valentīna Pole, IK Tava zeme, Latvia
PhD Dimcho Pulov, Technical University of Gabrovo, Bulgaria
PhD Aurelija Pūraitė, Mykolas Romeris University, Lithuania
Dr. agr. Gundega Putniece, Latvia University of Life Sciences and Technologies, Latvia
PhD Todor Rachovski, Plovdiv University “Paisii Hilendarski”, Bulgaria
Dr.sc.ing. Ādolfs Ruciņš, Latvia University of Life Sciences and Technologies, Latvia
PhD Rashmi Jaymin-Sanchaniya, Riga Technical University, Latvia
PhD Iryna Sarancha, Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University, Ukraine
PhD Dafinka Sidova, New Bulgaria University, Bulgaria
PhD Inese Skapste, Latvia University of Life Sciences and Technologies, Latvia
Dr.sc.ing. Andris Skromulis, Rezekne Academy of Riga Technical University, Latvia
PhD Krasimir Slavyanov, "Vasil Levski" National Military University, Bulgaria
PhD Nikolay Stefanov, “Vasil Levski” National Military University, Bulgaria
PhD Julija Steinhart, BA School of Banking and Finance, Switzerland
PhD Agrita Švarta, Latvia University of Life Sciences and Technologies, Latvia
PhD Adiljan Suleymanov, Tashkent State Technical University, Uzbekistan
Dr.sc.ing. Artis Teilāns, Rezekne Academy of Riga Technical University, Latvia
Dr.-Ing. Josef Timmerberg, Jade University of Applied Sciences, Germany
Dr.sc.ing. Edmunds Teirumnieks, Rezekne Academy of Riga Technical University, Latvia
PhD Ērika Teirumnieka, Rezekne Academy of Riga Technical University, Latvia
Dr.biol. Rasma Tretjakova, Rezekne Academy of Riga Technical University, Latvia
PhD Dragomir Vassilev, Technical University of Gabrovo, Bulgaria
PhD Valentin Vassilev, South-West University "Neofit Rilski", Bulgaria
PhD Tsanka Zlateva-Petkova, Technical University of Gabrovo, Bulgaria
PhD Anda Zvaigzne, Rezekne Academy of Riga Technical University, Latvia
PhD Rosita Zvirgzdina, Turiba University, Latvia

Organising Committee Chairman

PhD Nikolay Dolchinkov, "Vasil Levski" National Military University, Bulgaria

Organising Committee

Dr.agr. Aleksandrs Adamovičs, Latvia University of Life Sciences and Technologies, Latvia
Dr. agr. Lidiia Antypova, Mykolaiv National Agrarian University, Ukraine
MA Yanitsa Boyanova, “Vasil Levski” National Military University, Bulgaria
Dr.sc.ing. Aleksandrs Gorbunovs, Riga Technical University, Latvia
Dr.sc.ing. Pēteris Grabusts, Rezekne Academy of Riga Technical University, Latvia
Dr.sc.ing. Ēriks Kronbergs, Latvia University of Life Sciences and Technologies, Latvia
Dr.sc.ing. Sergejs Kodors, Rezekne Academy of Riga Technical University, Latvia
Dr. paed. Janis Kapenieks, Riga Technical University, Latvia
PhD Tsanko Karadzhov, Technical University of Gabrovo, Bulgaria
Dr.sc.ing. Lyubomir Lazov, Rezekne Academy of Riga Technical University, Latvia
Dr.sc.ing. Andris Martinovs, Rezekne Academy of Riga Technical University, Latvia

PhD Rumen Marinov, “Vasil Levski” National Military University, Bulgaria
Dr.agr. Liena Poiša, Rezekne Academy of Riga Technical University, Latvia
Dr.sc.ing. Andris Skromulis, Rezekne Academy of Riga Technical University, Latvia
Dr.-Ing. Josef Timmerberg, Jade University of Applied Sciences, Germany
Dr.sc.ing. Artis Teilāns, Rezekne Academy of Riga Technical University, Latvia
Mg.sc.comp. Gundega Teilāne, Rezekne Academy of Riga Technical University, Latvia
PhD Ērika Teirumnieka, Rezekne Academy of Riga Technical University, Latvia

Reviewers

PhD Nikolaj Angelov, Technical University of Gabrovo, Bulgaria
PhD Andres Annuk, Estonian University of Life Sciences, Estonia
PhD Neli Arabadzhieva - Kalcheva, Technical University of Varna, Bulgaria
PhD Iluta Arbidane, Rezekne Academy of Riga Technical University, Latvia
PhD Svetlana Asmuss, University of Latvia, Latvia
PhD Plamen Atanasov, New Bulgarian University, Bulgaria
Dr.sc.ing. Anita Avišāne, Riga Technical University, Latvia
PhD Todor Balabanov, University of Transport "Todor Kableshkov", Bulgaria
PhD Yanka Baneva, Medical University Varna, Bulgaria
Dr.agr. Biruta Bankina, Latvia University of Life Sciences and Technologies, Latvia
PhD Stefan Bankov, The Ministry of Interior of Bulgaria, Bulgaria
PhD Sholpan Bekmukhanbetova, Kazakh Automobile and Road Institute, Kazakhstan
PhD Daniel Berchev, “Vasil Levski” National Military University, Bulgaria
PhD Ansis Ataols Bērziņš, Riga Technical University, Latvia
PhD Jānis Bičevskis, University of Latvia, Latvia
PhD Aija Brakovska, Daugavpils University, Latvia
Dr. Rene Brunsch, Apromace data systems GmbH, Germany
PhD Ģirts Būmanis, Riga Technical University, Latvia
PhD Ivan Byanov, University of Veliko Tarnovo "St. Cyril and St. Methodius", Bulgaria
PhD Basar Caglar, Izmir Institute of Technology, Turkey
Dr.hab.Ing. Tadeusz Chrzan, Poltegor Institute, Poland
PhD Maria Chunchukova, Agricultural University Plovdiv, Bulgaria
PhD Dimitar Dimitrov, "Georgi Benkovski", Bulgarian Air Force Academy, Bulgaria
PhD Dimitar Dimitrov, Todor Kableshkov University of Transport, Bulgaria
PhD Sevdalina Dimitrova, “Vasil Levski” National Military University, Bulgaria
PhD Nadezhda Dimova, New Bulgarian University Department "Economics", Bulgaria
PhD Nikolay Dolchinkov, "Vasil Levski" National Military University, Bulgaria
Dr.hist. Edvins Evarts, Turiba University, Latvia
Dr. agr. Daina Feldmane, Institute of Horticulture, Latvia
PhD Vanko Ganev, "Vasil Levski" National Military University, Bulgaria
PhD Dmitri Goljandin, Tallinn University of Technology, Estonia
Dr.sc.ing. Imants Gorbāns, Riga Technical University, Latvia
PhD Jānis Grabis, Riga Technical University, Latvia
PhD Grigor Grigorov, “Vasil Levski” National Military University, Bulgaria
PhD Inga Grinfelde, Latvia University of Life Sciences and Technologies, Latvia
Dr. agr. Elvyra Gruzdevienė, Flax museum, the branch of Eriskiai Cultural Center of the Panevezys District, Lithuania
PhD Ilze Gudro, Riga Technical University, Latvia
PhD Tzvetelin Gueorguiev, Technical University of Gabrovo, Bulgaria
PhD Mart Hovi, Estonian University of Life Sciences, Estonia
PhD Maria Ilcheva, Saint Cyril and Methodius University of Veliko Tarnovo, Bulgaria
PhD Valery Ivanov, Defense Institute "Professor Tsvetan Lazarov", Bulgaria
Dr. agr. Sofija Jankauskiene, Lithuanian Research Centre for Agriculture and Forestry, Lithuania
PhD Aivars Jermuss, Latvia University of Life Sciences and Technologies, Latvia
PhD Amit Joshi, BA School of Banking and Finance, Latvia
Dr.sc.ing. Aivars Kaķītis, Latvia University of Life Sciences and Technologies, Latvia
PhD Sabrina Kalinkova, University of National and World Economy, Bulgaria

Dr.paed. Ilmārs Kangro, Rezekne Academy of Riga Technical University, Latvia
PhD Veiko Karu, Estonian Business School, Estonia
PhD Aivars Kaupuzs, Rezekne Academy of Riga Technical University, Latvia
PhD Anna Khilya, Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University, Spain
PhD Andrejs Koliškins, Riga Technical University, Latvia
PhD Georgi Komitov, Agricultural University Plovdiv, Bulgaria
PhD Karīne Laganovska, Latvian University of Biosciences and Technologies, Malnava College, Latvia
PhD Vjaceslavs Lapkovskis, Riga Technical University, Latvia
PhD Inga Ļašenko, Riga Technical University, Latvia
PhD Lazar Lazarov, "Vasil Levski" National Military University, Bulgaria
Dr. Walter Leal, Hamburg University of Applied Sciences, Germany, Manchester Metropolitan University, United Kingdom
Dr.sc.ing. Angel Lengerov, Technical University of Plovdiv, Bulgaria
PhD Iveta Linina, Turiba University, Latvia
Dr.oec. Jelena Lonska, Rezekne Academy of Riga Technical University, Latvia
PhD Slobodan Lubura, University of East Sarajevo, Bosnia and Herzegovina
PhD Lyuboslav Lyubenov, University of Ruse "Angel Kanchev", Bulgaria
PhD Velichko Machev, Todor Kableshkov University of Transport, Bulgaria
Dr.sc.math. Maksims Marinaki, University of Latvia, Latvia
PhD Georgi Marinov, Rakovski National Defence College, Bulgaria
PhD Dilyan Markov, Rakovski National Defence College, Bulgaria
PhD Arturs Medveckis, Liepaja Academy of Riga Technical University, Latvia
Dr.sc.ing. Linda Mežule, Riga Technical University, Latvia
PhD Ziedonis Miklašēvičs, Rezekne Academy of Riga Technical University, Latvia
PhD Roussi Minev, Ruse University, Bulgaria
PhD Nikolai Minkovski, University of Forestry, Bulgaria
PhD Penko Mitev, Technical University of Sofia, Bulgaria
Dr.sc.ing. Ivan Mitev, Technical University of Gabrovo, Bulgaria
PhD Ilie Nuca, Technical University of Moldova, Republic of Moldova
Dr.chem. Sergejs Osipovs, Daugavpils University, Latvia
PhD Nikolay Padarev, "Vasil Levski" National Military University, Bulgaria
PhD Jana Paidere, Daugavpils University, Latvia
Dr.sc.ing. Jeļena Pečerska, Riga Technical University, Latvia
Dr.sc.ing. Desislava Petrova, Technical University of Gabrovo, Bulgaria
PhD Valentina Petrova, Nikola Vaptsarov Naval Academy, Bulgaria
Dr. agr. Valentīna Pole, IK Tava zeme, Latvia
PhD Dimcho Pulov, Technical University of Gabrovo, Bulgaria
PhD Aurelija Pūraitė, Mykolas Romeris University, Lithuania
Dr. agr. Gundega Putniece, Latvia University of Life Sciences and Technologies, Latvia
PhD Todor Rachovski, Plovdiv University "Paisii Hilendarski", Bulgaria
PhD Anton Rassolkin, Tallinn University of Technology, Estonia
Dr.phys. Gita Rēvalde, Riga Technical University, Latvia
Dr.sc.ing. Ādolfs Ruciņš, Latvia University of Life Sciences and Technologies, Latvia
PhD Jolanta Šadauskiene, Kaunas University of Technology, Lithuania
Dr.sc.math. Felikss Sadirbajevs, Daugavpils University, Latvia
PhD Rashmi Jaymin-Sanchaniya, Riga Technical University, Latvia
PhD Iryna Sarancha, Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University, Ukraine
PhD Zhaneta Savova, National Military University, Bulgaria
Dr.geol. Valdis Segliņš, University of Latvia, Latvia
PhD Dafinka Sidova, New Bulgaria University, Bulgaria
PhD Andrejs Šiškins, Riga Technical University, Latvia
PhD Inese Skapste, Latvia University of Life Sciences and Technologies, Latvia
PhD Krasimir Slavyanov, "Vasil Levski" National Military University, Bulgaria
Dr.-Ing. Bambang Soemardiono, Institut Teknologi Sepuluh Nopember, Indonesia
Dr.geol. Juris Soms, Daugavpils University, Latvia
PhD Nikolay Stefanov, "Vasil Levski" National Military University, Bulgaria

PhD Julija Steinhart, BA School of Banking and Finance, Switzerland
PhD Aina Strode, Rezekne Academy of Riga Technical University, Latvia
PhD Agrita Švarta, Latvia University of Life Sciences and Technologies, Latvia
Dr.sc.ing. Edmunds Teirumnieks, Rezekne Academy of Riga Technical University, Latvia
PhD Plamen Teodosiev, University of Library Studies and Information Technologies, Bulgaria
Dr.biol. Rasma Tretjakova, Rezekne Academy of Riga Technical University, Latvia
PhD Dragomir Vassilev, Technical University of Gabrovo, Bulgaria
PhD Valentin Vassilev, South-West University "Neofit Rilski", Bulgaria
Dr.habil.sc.ing. Janis Viba, Riga Technical University, Latvia
PhD Emil Yankov, Rezekne Academy of Riga Technical University, Latvia
Dr.sc.ing. Imants Zarembo, Rezekne Academy of Riga Technical University, Latvia
PhD Tsanka Zlateva-Petkova, Technical University of Gabrovo, Bulgaria
PhD Anda Zvaigzne, Rezekne Academy of Riga Technical University Academy, Latvia
PhD Rosita Zvirgzdina, Turiba University, Latvia

Secretariat Chairman

PhD Ērika Teirumnieka, Rezekne Academy of Riga Technical University, Latvia

Secretariat Members

Dr.agr. Liena Poiša, Rezekne Academy of Riga Technical University, Latvia
Mg.sc.comp. Gundega Teilāne, Rezekne Academy of Riga Technical University, Latvia

II SĒJUMS
SATURS
CONTENTS

Information Technologies

Muhammad Ramzan Ali, Liga Peiseniece, Elina Mikelsone **15**
THE MEDIATING ROLE OF GREEN WORK COMMITMENT IN THE RELATIONSHIP BETWEEN GREEN HR PRACTICES, AI ELEMENTS, AND ENVIRONMENTAL SUSTAINABILITY: A QUANTITATIVE ANALYSIS

Laylo Bakhronkulova, Muhammad Ramzan Ali, Zulfiya Khabirova, Akimjonov Azimjon, Alimova Zebo, Abdumajidova Muslima **23**
ARTIFICIAL INTELLIGENCE IN CYBERSECURITY: THREATS, DEFENSES, AND FUTURE DIRECTIONS

Todor Balabanov, Dimitar Dimitrov **31**
REVIEW OF THE CYBERSECURITY IMPACT AND LIMITATIONS OF THE USE OF ARTIFICIAL INTELLIGENCE IN TRANSPORT

Fayzi Bekkamov, Mumin Babajanov, Mansur Berdimurodov **37**
USING BAYESIAN METHODS TO PREDICT USERS' INFORMATION NEEDS IN A DIGITAL LIBRARY

Hristina Boycheva **43**
DIGITAL TOURISM MARKETING CHANNELS: A POST-COVID COMPARATIVE ANALYSIS OF CONSUMERS' PREFERENCES

Sarvinoz Berdibekova, Sherbek Normatov, Dildora Juraeva, Mehriniso Qudratova, Laylo Sayfieva **49**
ANALYSIS OF USER SATISFACTION OF ACADEMIC DIGITAL LIBRARIES: A CASE OF UZBEKISTAN

Linda Luīze Barbare, Aleksejs Jurenoks, Magone Una Rauba, Zane Viskere **57**
METHODOLOGY FOR ANALYSING LMS DATA TO PREDICT STUDENT DROPOUT RISK IN HIGHER EDUCATION

Linmu Cui, Aldis Bulis **65**
DRIVERS AND BARRIERS TO AI ADOPTION IN RETAIL ENTERPRISES: A SYSTEMATIC LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

Bora Dogan, Yanka Baneva, Yordanka Eneva, Elena Ivanova **77**
EVALUATION OF THE DIAGNOSTIC ACCURACY OF TWO AI MODELS FOR ANALYZING MAMMOGRAPHIC IMAGES

Bora Dogan, Yordanka Eneva, Yanka Baneva, Elena Ivanova **83**
COMPARATIVE ANALYSIS OF THE CAPABILITIES OF TWO ARTIFICIAL INTELLIGENCE MODELS FOR CHEST X-RAY IMAGE INTERPRETATION

Dimitar Dimitrov, Todor Balabanov **93**
METHODOLOGICAL ASPECTS AND LIMITATIONS FOR ENSURING SAFETY IN TRANSPORT MANAGEMENT USING ARTIFICIAL INTELLIGENCE

Dimitar S. Dimitrov, Iliyan Y. Iliev **99**
THE RISK OF PERSONAL SMART DEVICES IN THE OPERATIONAL SECURITY FOR MILITARY BASES, PERSONNEL AND MISSIONS

Dimitar Dimitrov, Dimitar Nikolov **107**
LEVERAGING YARA AND SIGMA RULES TO DETECT CHINESE STATE-SPONSORED HACKING GROUPS OF THE "TYPHOON" TYPE

Dimitar Dimitrov, Evgeni Andreev **115**
CHINA'S STRATEGIC COMPETITION IN CYBERSPACE. VOLT TYPHOON AND SALT TYPHOON AS A PROJECTION OF POWER, A MORE AGGRESSIVE POSTURE AND A FUTURE BEYOND ESPIONAGE

Dimitar Dimitrov, Georgi Penchev, Konstantin Poudin, Georgi Pavlov, Atanas Dimitrov, Vasil Pavlov, Tzvetomira Penkova, Nikola Petrov **123**
ILLEGAL TRADE IN TOBACCO PRODUCTS INDICATOR

Eugene Eteris, Ingrida Veikša **129**
ARTIFICIAL INTELLIGENCE (AI) IN THE LEGAL PROFESSION: EUROPEAN APPROACH

Vasyl Frytsiuk, Iurii Kshyvak, Iryna Baranovska, Olena Teplova, Anna Novosadova, Anna Khilya **137**
DIGITAL ECOSYSTEMS FOR MUSIC TEACHER TRAINING: ICT, SOCIAL MEDIA, AND ONLINE LEARNING ENVIRONMENTS

Peter Grabusts, Jurijs Musatovs, Ērika Teirumnieka **145**
MODELING THE DISTRIBUTION OF LAKE REEDS USING GIS

Stanka Hadzhikoleva, Todor Rachovski, Emil Hadzhikolev, Ivan Ivanov **151**
THE ROLE OF GENERATIVE ARTIFICIAL INTELLIGENCE IN PROGRAMMER TRAINING: OPPORTUNITIES AND CHALLENGES

Rosen Iliev, Denislav Ushovski **157**
MODELING THE PROCESS OF EXTRACTING SENSOR DATA FROM THE TERRAIN USING GENERALIZED NETS

Ivan Ivanov, Kalin Petrov, Todor Rachovski, Desislava Petrova **165**
METHODOLOGICAL AND APPLIED ASPECTS OF ARTIFICIAL INTELLIGENCE IN ENERGY CONSUMPTION PREDICTION

Refat Ibraimov, Maxbuba Sultonova **171**
THE INFLUENCE OF CLIMATE CHANGE ON THE INTEGRAL FUNCTION OF DISTRIBUTION OF HORIZONTAL MINIMUM VISIBILITY DISTANCE

Iryna Kyrychenko, Yehor Nesterenko, Anastasiya Chupryna, Loreta Savulioniene, Paulius Sakalys **177**
APPLICATION OF CLUSTERING METHODS IN RECOMMENDER SYSTEMS FOR USER BEHAVIOR ANALYSIS

Ilmārs Kangro, Harijs Kalis **181**
SPECIAL HYPERBOLIC TYPE APPROXIMATION AND FOURIER METHOD FOR SOLVING 3-D STATIONARY DIFFUSION PROBLEM

Saranya Kanna Baskar, Velga Vēvere **189**
NATIONAL STRATEGIES FOR DIGITIZATION OF HIGHER EDUCATION: A COMPARISON BETWEEN LATVIA AND LITHUANIA

Svitlana Kizim, Oksana Voloshyna, Liudmyla Bondarchuk, Mykyta Sapohov, Tetiana Melnychuk **197**
INNOVATIVE APPROACHES TO THE ORGANIZATION OF DISTANCE LEARNING WITH THE USE OF DIGITAL TECHNOLOGIES IN DOMESTIC AND INTERNATIONAL EDUCATIONAL PRACTICES

Svitlana Kizim, Oksana Voloshyna, Irina Sarancha, Svitlana Nahorniak, Olena Stoliarenko **205**
ORGANIZATION OF ADAPTIVE TRAINING USING ARTIFICIAL INTELLIGENCE TECHNOLOGIES IN THE CONTEXT OF WAR

Nikolay Komitov, Veselin Mengov, Georgi Komitov, Evelin Shopov **213**
JOYSTICK CONTROL OF A 3D PRINTED ROBOTIC MANIPULATOR FOR STUDENT LEARNING

Tatyana Krumova **217**
PATIENT CLIENT CONSUMER BEHAVIOR IN PHYSICAL AND ONLINE PHARMACIES. A COMPARATIVE ANALYSIS OF PHARMACEUTICAL CARE AND ARTIFICIAL INTELLIGENCE

Iryna Kyrychenko, Artem Oliinyk, Kirill Smelyakov, Loreta Savulioniene, Paulius Sakalys **221**
COMPARATIVE ANALYSIS OF HEURISTIC ALGORITHMS FOR OPTIMIZING THE DISTRIBUTION OF MEDICAL EQUIPMENT IN A CRISIS

Oleg Latyshev, Nikolay Todorov Dolchinkov **225**
APPLICATION OF DIGITAL TELECOMMUNICATION ENVIRONMENT TO SOLVE LEGAL ISSUES

Georgi Markov, Borislav Nikolov **231**
DETECTION AND MITIGATION OF MALICIOUS ACTIVITIES BASED ON DNS QUERY ANALYSIS

Stela Mincheva, Veselka Stoyanova **237**
RESEARCH ON THE IMPACT OF THE USER EXPERIENCE FOR THE SUCCESS OF A VIRTUAL PRODUCT: BULGARIAN TRAVEL AGENCY WEBSITES

Ventsislava Nikolova-Minkova **243**
HISTORICAL DEVELOPMENT OF TECHNOLOGIES IN THE FIELD OF ARTIFICIAL INTELLIGENCE

Laura Ozoliņa, Arnis Cīrulis, Lauris Taube **251**
VEGETATION REALISTIC VISUALIZATION IN VIRTUAL REALITY SCENARIOS

Olha Palamarchuk, Iryna Haba, Halyna Shulha, Anna Khilya, Iryna Sarancha **257**
NEUROPLASTICITY AND DIGITAL TOOLS IN LIFELONG LEARNING: COGNITIVE CHALLENGES AND OPPORTUNITIES

Simeonka Petrova **265**
ANALYZING E-COMMERCE OF SMALL AND MEDIUM-SIZED ENTERPRISES IN THE EUROPEAN UNION: DEPENDENCIES AND TRENDS IN THE CONTEXT OF DIGITALIZATION

Mekhriniso Qudratova, Marat Rakhmatullayev, Sherbek Normatov, Laylo Sayfieva, Sarvinoz Berdibekova **271**
EXPANDED SELECTING CRITERIA OF RESEARCH DATABASES FOR UNIVERSITY LIBRARIES

Agnese Reine **277**
THE INTERSECTION OF ARTIFICIAL INTELLIGENCE AND EMPLOYMENT LEGAL RELATIONS: BALACING EMPLOYER INTERESTS WITH FUNDAMENTAL RIGHTS IN AI-DRIVEN EMPLOYMENT PRACTICES

Stefko Burdzhiev, Maria-Magdalena Burdzhieva **285**
NUCLEAR WEAPONS - CONSEQUENCES FOR THE BIOSPHERE IN CASE OF THEIR POTENTIAL USE

Bohdan Rozputnia, Liudmyla Shevchenko, Volodymyr Umanets, Serhii Yashchuk, Yuliia Sabadosh **293**
METHODOLOGICAL APPROACHES TO USING ARTIFICIAL INTELLIGENCE TO DEVELOP CREATIVE SKILLS IN FUTURE DESIGNERS

Zhaneta Savova, Antoniya Tasheva, Rosen Bogdanov **299**
ON THE SYSTEMATIC ENCODING OF P-ARY REED-SOLOMON CODES WITH AN ARBITRARY PRIME P

Laylo Sayfieva, Sherbek Normatov, Mekhriniso Qudratova, Sarvinoz Berdibekova, Temur Khudayberganov **307**
ASSESSING THE NEED AND POSSIBILITY OF USING RECOMMENDER SYSTEMS IN UNIVERSITY LIBRARIES

Igor Schukin, Raisa Smirnova **313**
THE METHOD OF COMPLETE BIFURCATION ANALYSIS FOR PREDICTING THE BEHAVIOR OF COMPLEX SYSTEMS

Mariya Shirokopetleva, Olena Shevchenko, Daria Pervieieva, Loreta Savulioniene, Paulius Sakalys **321**
A COMPARATIVE ANALYSIS OF NATIVE IOS FRAMEWORKS FOR DEVELOPING GRAPHICS SCENES IN AUGMENTED REALITY APPLICATIONS

Georgi Stanchev, Vanya Katsarska **329**
APPLICATION OF TURBO CODES IN UNMANNED AERIAL SYSTEMS

Dilyana Stoicheva **337**
IMAGE RECOGNITION IN THE TRAFFIC SIGN SYSTEM - SEMIOTIC AND LINGUISTIC ASPECTS

Svetlomir Stankov, Desislava Velinova **345**
APPLICATION OF A LARGE LANGUAGE MODEL FOR AIR POLLUTION ANALYSIS BY USING A RAG SYSTEM

Diyora Talipova **353**

MATHEMATICAL METHODS FOR EVALUATION OF WEBOMETRIC INDICATORS OF INFORMATION LIBRARY CENTERS

Oļegs Uzhga-Rebrov **359**
DECISION MAKING DECISION MAKING BASED ON FUZZY PREFERENCE RELATIONS

Velga Vevere, Inga Shina, Malalgodapitiya Gamage Darika Nirujani Nanayakkara, Iveta Linina, Rosita zvirgzdina **367**
INTEGRATING DIGITAL TECHNOLOGIES TO ENHANCE CSR STRATEGIES FOR RETAIL COMPANIES IN LATVIA

Roberts Volkovičs **375**
DATA CENTRE MONITORING MODEL UTILIZING ARTIFICIAL INTELLIGENCE, MACHINE LEARNING AND ANOMALY DETECTION ALGORITHMS

Roberts Volkovičs **383**
POLLUTION DETECTION MODEL UTILIZING ANOMALY DETECTION TECHNIQUES PERFORMING ANALYSIS OF SATELLITE DATA

Roberts Volkovičs **389**
MODEL FOR PROCESSING HISTORICAL TIMESERIES AND ESTABLISHING RULESET FOR ANOMALY DETECTION IN CURRENT SENSOR DATA AND GENERAL-PURPOSE FORECASTING FOR SMART FARMING IN LATVIA

Ibrohim Yuldoshev, Dilmurod Tuhtanazarov, Turdali Jumayev, Anvarjon Mahkamov **395**
MODELING AND NUMERICAL SOLUTION OF LIQUID FILTRATION PROCESSES IN MULTILAYER OIL FIELDS

II
INFORMATION TECHNOLOGIES

The Mediating Role of Green Work Commitment in the Relationship Between Green HR Practices, AI Elements, and Environmental Sustainability: A Quantitative Analysis

Muhammad Ramzan Ali
RISEBA University of Applied Sciences
Riga, Latvia
AJOU University in Tashkent,
Tashkent, Uzbekistan
Ramzan.ali@ajou.uz

Liga Peiseniece
BA School of Business and Finance
Riga, Latvia
liga.peiseniece@ba.lv

Elina Mikelsone
BA School of Business and Finance
Riga, Latvia
elina.mikelsone@ba.lv

***Abstract*- We examined the role that Green Work Commitment plays in the context of green HR practices, such as green hiring, green compensation, green training, AI components, and organisational sustainability. It is a quantitative research method that uses questionnaires as a data-collecting tool. The study population was the study population of employees associated with multinational corporations and essential sectors in Pakistan, such as Pakistan International Airlines, Procter & Gamble Pakistan, banks, educational institutions, and IT organisations. Likewise, key organisations such as Navoi Mining and Metallurgy Combinat JSC, POSCO International Textile, LUKOIL Uzbekistan Operating Company, Nestlé Uzbekistan, Huawei Uzbekistan, various banks, educational institutions, as well as the IT sector, collected data from Uzbekistan. In both cases, quantitative methods were used, and random and convenience sampling were used to elicit 373 responses. Descriptive statistics were performed in SPSS version 23 (mean, rates, and standard deviation), and inferential statistics in Smart PLS version 3.0. Based on these goals, 12 hypotheses were developed to investigate the relationships between green HR practices and environmental sustainability. Considering these hypotheses, ten had strong backing, while two had less strength.**

This study adds to the expanding body of information on Green HR practices by emphasising the mediating function of green work commitment in promoting environmental sustainability inside multinational firms in Pakistan. In this study, we outline the path for future research into the broader implications of Green HR practices for sustaining organisations across regions and industries. It would be interesting to study how green HR approaches evolve alongside AI aspects in future research, emphasising how employee engagement and organisational success are impacted by green work commitments. Furthermore, an analysis of how leadership and company culture impact green HR policies may provide more insight. To better understand how these techniques are applicable globally, a comparison can be made between emerging and developing economies.

Keywords: GHRM practices, Green Work Commitment, Environmental sustainability, Green hiring, Green training, Green compensation, sustainability, Pakistan, and Uzbekistan.

I. Introduction

As businesses increasingly prioritise environmental sustainability, balancing profit and ecological responsibility has become a global concern [1]. Human resource management based on green principles (or "green HRM") has emerged over the past decade as an important strategic lever to support organisations in their journey toward environmental sustainability [2]. All policies relating to human resource management should be green for employees' hiring, remuneration, training, and commitment that approach sustainable development. Artificial intelligence (AI) is an important factor that can enhance the efficiency of green HR practices while also preparing businesses to manage sustainability-related operations [3, 4]. This study addresses the gap in the literature about the relationship between green HR practices, elements of AI, and organisational sustainability, while also investigating green work engagement as a predictor of organisational sustainability.

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8578
© 2025 The Author(s). Published by Rezekne Academy of Technologies.
This is an open access article under the Creative Commons Attribution 4.0 International License.

Similarly, the environmental aspect emerged as a primary concern for enterprises worldwide. A growing number of businesses are using sustainable practices to lessen their environmental impact. According to Renwick, et al. [5], one of the foundational concepts that underpins sustainable practices in enterprises is green human resource management or Within the framework of GHRM, green recruiting, green compensation, and green training significantly influence employees' dedication to environmental sustainability. Green HRM encompasses policies and practices that foster environmental sustainability [6]. Additionally, the landscape of contemporary employment has altered the way HR practices absorb various technologies, particularly Artificial Intelligence (AI), which indicates the compelling need to address efficient evidence on how AI elements contribute to green HRM and environmental sustainability [7, 8]. This refers to the literature review of theoretical models and empirical studies of Green Work Commitment (GWC) as an intervening variable between green HR practices, AI aspects, and environmental sustainability in organisations, particularly in the MNCs sector and key sectors from Pakistan.

However, little is known about the mediation effect of Green Work Commitment in the relationship between green HR practices, AI elements, and environmental sustainability, especially in the context of Pakistan [8, 9]. This study aims to contribute empirical insights from multinational companies in Malaysia and the major industrial sectors of Pakistan to address the existing research gap regarding the unique challenges and opportunities for airlines, banking, education, and IT sectors [10, 11]. Given the pace of technological advancements and increasing environmental pressures on these sectors, there is a need to better understand AI-powered HRM approaches and their role in promoting sustainable modes of work [12, 13]. Therefore, filling this research gap will allow organisations to design more focused interventions that facilitate green work commitment, which ultimately contributes to sustainability efforts in the long run [7].

A. Research Questions

i. Are there any links between GHRM and AI elements with environmental sustainability?

ii. Is employee green commitment has a mediating role between Green HRM practices AI elements, and Organisational Environmental sustainability?

B. Research Objectives

i. To investigate the relation between GHRM AI factors, employee green commitment and environmental sustainability to provide a concise summary of the interrelationships.

ii. To investigate there is the mediating role of employee green commitment between GHRM AI elements and environmental sustainability.

C. Green HR Practices and Organisational Sustainability

HRM that is green consists of policies and practices aimed at stimulating the actions of green employees. This is grounded on the premise that HRM practices support the development of an organisational culture of sustainability. It has three components, i.e., green hiring, green compensation, and green training, which, when integrated, work together to perpetuate a sustainable working culture and environmental sustainability performance of the organisation in the long run [14, 15]. Various green human resources practices (such as green recruitment, selection, compensation, and training) are seen as significant mechanisms for organisations that can promote sustainable development [6, 14]. Green hiring refers to the efforts of hiring candidates who have a similar consciousness on environmental issues and possess sustainability-related skills [16]. Green compensation is defined as incentives and rewards given to employees due to their active contribution towards sustainability practices, while green training is about educating and informing employees, which enables them to practice sustainability of the environment.

Green HR practices are becoming increasingly important in fostering corporate environmental responsibility, according to recent studies [17], for example, researchers looked at how green initiatives may be incorporated into HRM and discovered that green HRM practices were positively correlated with better organisational sustainability outcomes. Aligning employee objectives with sustainable business practices is greatly aided by green recruiting, which gives preference to hiring people who share environmental principles [18]. According to Haakenstad, et al. [19], seventy-two percent of EU organisations have implemented green HR practices, with 46% stressing sustainability in their recruitment efforts. Green training programs are also important, with 67% of employees expressing a stronger sense of responsibility for environmental issues after obtaining sustainability training [20].

Environmental sustainability in organisations is defined by practices aimed at decreasing carbon footprints, reducing waste generation, and promoting energy efficiency [20, 21]. Eco-offices and sustainable organisations often put in place eco-office policies, carbon offsets, and supply chain sustainability measures [22]. According to earlier research, businesses with strong green HR practices typically achieve better environmental performance, regulatory compliance, and corporate social responsibility. Along with the aforementioned advantages, sustainable HR practices also improve stakeholder trust, employee engagement, and brand image [1].

D. Green Hiring

One of the definitions of "green hiring" is hiring individuals who care for and engage in an organisation's sustainability goals [4]. Studies have shown that employees who are part of communities that endorse green job principles are more committed to the company's environmental mission. The nature of green hiring also

develops [23, 24], which creates a workforce that is more likely to practice sustainable behaviours. To ensure new hires fit an organisation's sustainability mission, the literature also suggests incorporating environmental considerations in job descriptions and selection criteria [25].

E. Green Compensation

This type of compensation is referred to as "green compensation" [26, 27], as it creates motivation and motivates employees to act sustainably. Incentive programs, recognition initiatives, and bonus payments for eco-friendly behaviour promote employees' desire to adopt sustainable behaviour. Green compensation significantly impacts employee behaviour and strengthens an organisation's commitment to sustainability [28]. Integrating sustainability metrics into performance reviews will further help motivate employees to continue engaging in green behaviours [29].

F. Green Training

According to Saeed, et al. [30], the goal of green training is to provide workers with the knowledge and skills to take action toward environmental sustainability. Organisations make sure that their employees take part in the construction process and understand the importance of sustainability initiatives when they pay for a green training program. This is supported by studies showing that green training increases employee awareness of and participation in sustainability initiatives [3]. Training on domestic sustainable behaviours: (1) responsible use of resources; (2) conserving energy; (3) not wasting food. All of these types of training are linked to improvements in organisational sustainability performance [15, 31].

G. Role of AI in Enhancing Green HRM

AI solutions can positively impact Green HRM by optimising resource utilisation, automating sustainability-related chores, and improving decision-making [12]. AI-based HR analytics can evaluate the environmentally conscious behaviour of workers and determine measures to encourage them [32]. AI empowers greener operations and enhances the effectiveness of green HR practices [3].

The implementation of AI (artificial intelligence) into HR employment procedures has entirely transformed the way organisations manage sustainability tasks. AI-supported recruitment tools facilitate green hiring by recognising applicants with strong environmental commitment [24]. Utilising predictive analytics and AI-based performance monitoring can help organisations build effective green compensation plans. Also, AI-based learning systems customise green training plans for employees, which ultimately helps to make them more environmentally friendly and expand their skills [5]. AI continues to train and helps in automating sustainability reporting, monitoring staff engagement in green projects, and optimising resources for maximum environmental performance [23].

Green HR practices are progressively integrating artificial intelligence (AI) to improve operational efficiency and decision-making, particularly in the area of sustainability. AI tools that assess sustainability parameters, forecast environmental impacts, and optimise resource allocation include machine learning, predictive analytics, and data-driven automation [33].

The application of AI in energy management systems is a noteworthy illustration. Data on energy use can be analysed by AI systems, which can then offer real-time insights to cut waste [34]. Businesses can cut operating costs by up to thirty percent a year by implementing AI-driven energy-saving efforts [35]. Additionally, staff involvement in sustainability initiatives is being tracked and monitored with the aid of AI systems. AI can offer tailored suggestions for enhancing worker performance in environmental activities by evaluating data from sustainability objectives and green training initiatives [36]. By providing real-time feedback on their environmental performance, AI-based technologies like "smart" eco-feedback systems also encourage staff to adopt more environmentally friendly practices [37].

H. Mediating Role of Green Work Commitment

Norton, et al. [38] states that employee green work commitment tackles the extent to which employees are committed and willing to engage in environment-friendly behaviour at the workplace. As a mediator between the relationship of Green HR practices and organisational sustainability, it can channel the environmental knowledge or awareness of employees into action [15]. The correlation between green HR practices and sustainability outcomes is enhanced by employees committed to green initiatives, who are more likely to engage in sustainable behaviours [39].

Green Work Commitment (GWC) is the psychological attachment and dedication employees have towards an organisation's environmental goals [29]. A strong attitude towards an environmentally friendly workplace drives employees to take proactive steps as active participants in environmental improvement efforts, improved energy efficiency, and reduced workplace waste [40]. Research has shown that employees with high green commitment are more inclined to engage in voluntary sustainable behaviours. The mediation of GWC suggests that green HR practices may target employees who demonstrate commitment and act as change agents in the organisation to promote its environmental sustainability [15]. Furthermore essay from which material was obtained, such sustainability-oriented HR practices, which include HR practices that create supportive, strategic and operational policies and procedures to enhance the degree of employees' intrinsic motivation toward environmental sustainability, are shown to be dependent upon the support within the organization as well as top-management commitment towards creating a more sustainable organization [29].

The existing literature review identifies the importance of green HRM, AI components, and Green Work Commitment towards achieving environmental sustainability. Prior research suggests that green HR practices positively affect sustainability outcomes, and when they are combined with AI-driven HR interventions, the effects are further amplified. By promoting environmental awareness through HR policy adaptations that incorporate sustainability, organisations can create a culture of environmental sustainability that, in turn, contributes to a better future for both companies and the environment for years to come [24]. Consequently, this study investigates GWC with the organisational context of Pakistan and attempts to provide literature on the phenomenon existing between PO fit and sustainable organisation, and to give HR practitioners and academics well-being results that promote sustainability through effective organisational culture transcending PO fit. Furthermore, the results of this study could provide useful suggestions for policymakers and corporate decision-makers who are looking to develop AI-enabled GHRM solutions that conform to global sustainability goals [41, 42].

I. Research Conceptual Model

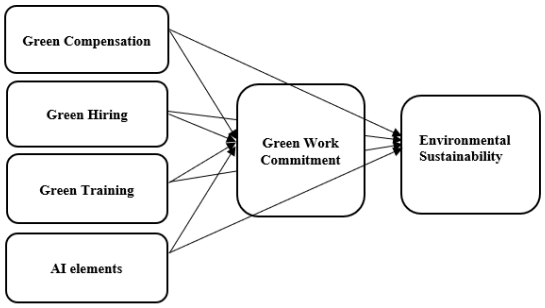


Fig. 1. Conceptual Framework.

J. Hypothesis Development

The relationships between green HR practices and environmental sustainability were then explored through the development of 12 hypotheses based on the research purpose, and relatively weaker support for 3 of them.

H1. *Green Hiring directly affects organization sustainability for the better.*

H2. *Green compensation has positive and straightforward connections with organisational sustainability.*

H3. *Green training and organisational sustainability are positively and directly related.*

H4. *AI elements have a positive and direct relationship with organisational sustainability.*

H5. *However, there is a positive and direct relationship between employee green commitment and green hiring.*

H6. *Green compensation has a significant and direct impact on employee-green commitment.*

H7. *The relationship between green Training and employee green commitment is positive and direct.*

H8. *Green AI elements have a direct and positive correlation with employee green commitment.*

H9. *We have positive and direct effect of employee green commitment and organisation sustainability.*

H10. *Green compensation and organisational sustainability are mediated by employee green commitment.*

H11. *Similar to the factor of employee green commitment that mediates the impact of green hiring on achieving organisational sustainability.*

H12. *Green training has a mediating effect with organisational sustainability through employee green commitment.*

The research investigates the influence of Green Work Commitment on the relationship between green HR practices (Green Hiring, Green Compensation, Green Training), AI Elements, and Environmental Sustainability. Data is primarily acquired using a standardised questionnaire inside a quantitative research framework. This study adopts a quantitative method using structured questionnaires as the main instrument of data collection [43]. Methods: Data were collected through a cross-sectional survey design to examine the role of green HR practices and AI capabilities on attaining environmental sustainability. The study population comprised employees from significant organisations [44], including Pakistan International Airlines, Procter & Gamble Pakistan, banks, educational institutions, and IT firms in Pakistan. Similarly, data were collected from key organisations in Uzbekistan, such as Navoi Mining and Metallurgy Combinat JSC, POSCO International Textile, LUKOIL Uzbekistan Operating Company, Nestlé Uzbekistan, Huawei Uzbekistan, banks, educational institutions, and IT firms. A combination of random and convenience sampling methods was employed to elicit 373 valid responses across both regions [45].

Structured questionnaires measuring green HR practices, AI integration, green work commitment, and organisational sustainability were distributed electronically. The questionnaire consisted of multiple sections assessing demographic information, perceptions of Green HRM initiatives, AI implementation, and sustainability outcomes. Descriptive statistics were calculated using SPSS version 23, including frequency distributions, means, and standard deviations to summarise responses [43, 44, 46]. Inferential statistical analyses were conducted using Smart PLS version 4.0, enabling Structural Equation Modelling (SEM) to test relationships among variables. A bootstrapping technique (5,000 resamples) was applied to assess mediation effects and confirm statistical significance.

II. Materials and Methods

A. Descriptive Statistics

We began by summarising the core characteristics of our dataset. for each variable (green hiring, green compensation, green training), basic descriptive statistics (mean as measure of central tendency, standard deviation, skewness and kurtosis as measures of dispersion) were calculated, AI elements, green work commitment, and organizational sustainability The data were found to be normally distributed, supporting the use of advanced statistical techniques in subsequent analyses. Understanding who our respondents are is key to interpreting our results. Our sample comprised individuals from various backgrounds. The demographic breakdown is stated as: Firstly, talking about gender, 55% Male and 45% Female. Secondly, there are age Groups that lie between the categories 25–34 years (30%), 35–44 years (40%), 45–54 years (20%), and 55+ years (10%). Further, there is the Education Level lies between Bachelor's Degree (50%), Master's Degree (35%), and PhD (15%). Furthermore, there are Years of Experience the people lie between 1–5 years (25%), 6–10 years (40%), 11–20 years (25%), 20+ years (10%). Lastly, I am reporting the information about the sector of respondents: Industry Sector Manufacturing (30%), IT (25%), Healthcare (20%), Finance (15%), others (10%). This diverse demographic profile adds context to our analysis and supports the broader generalizability of our findings.

B. Analysis and findings

To ensure that our measurement instruments were both reliable and valid, we assessed several key metrics used to measure the validity and reliability. Cronbach's Alpha of all constructs demonstrated excellent internal consistency [47]. For instance, Green Hiring scored 0.88 and Organisational Sustainability scored 0.91, both well above the 0.70 threshold. The Composite Reliability (CR) of all constructs had CR values higher than 0.70, confirming that the items within each construct consistently measure the intended concept. Average Variance Extracted (AVE) states that AVE values exceeded the recommended 0.50 for all constructs (e.g., 0.70 for Green Hiring and 0.73 for Organisational Sustainability) [48], ensuring that a substantial proportion of the variance in the observed measures is captured by the construct. Factor Loadings: Each item loaded strongly on its respective construct, with loadings ranging from 0.80 to 0.89 [49]. This supports convergent validity and indicates that the items are well-correlated with the underlying constructs.

Table 1 Measurement Model Summary

Construct	**Cronbach's Alpha**	**Composite Reliability (CR)**	**AVE**	**Factor Loadings (Range)**
Green Hiring	0.84	0.92	0.60	0.80 – 0.85
Green Compensation	0.81	0.90	0.65	0.86 – 0.88
Green Training	0.86	0.91	0.58	0.87 – 0.90
AI Elements	0.87	0.93	0.68	0.80 – 0.84
Green Work Commitment	0.90	0.94	0.70	0.83 – 0.86
Organizational Sustainability	0.91	0.95	0.73	0.85 – 0.89

C. Exploratory Factor Analysis (EFA)

An Exploratory Factor Analysis was conducted to uncover the latent structure of our measurement items [50]. The Kaiser-Meyer-Olkin (KMO) measure was above 0.7, and Bartlett's test of sphericity was significant ($p < 0.001$), confirming the suitability of our data for factor analysis. We retained only those items with factor loadings above 0.6, ensuring that our constructs were both clean and meaningful.

D. Structural Equation Modelling (SEM)

The researcher used Structural Equation Modelling to test our hypothesised relationships. Our model posited the following: Direct Effects mentioned in the study are Green Hiring, Green Compensation, Green Training, and AI Elements directly impact both Green Work Commitment and Organisational Sustainability. Green Work Commitment directly influences Organisational Sustainability [49, 50]. There also exist Mediation Effects, such as Employee Green Commitment mediates the relationship between green practices (and AI Elements) and Organisational Sustainability.

E. Hypothesis Testing

Testing of the following 12 hypotheses was performed using standardised regression weights (β), t-values, and p-values: H1. This written piece highlights the positive and direct relationship between green hiring and organisational sustainability. After performing the analysis, the results showed the mean values, p, and significance values that are $\beta = 0.30$, $t = 4.50$, $p < 0.003$. So these values verify that hypothesis 1 is supported. Hypothesis 2 stated that we now look into the relationship between green compensation with organisational sustainability and find that H1 is positively and directly related. Results for H2 are $t = 3.80$, $p < 0.02$, $\beta = 0.25$. Thus, these values uphold the hypothesis's significance. H3 stated that Green training and organisational sustainability are positively and directly correlated with this hypothesis. Results are $t = 4.20$, $p < 0.000$, $\beta = 0.28$. The hypothesis is thus confirmed by these values. H4 told us that there is a positive correlation between AI components and organisational sustainability. This hypothesis yielded $\beta = 0.35$, $t = 5.00$, and $p < 0.03$. So, based on these values, hypothesis 4 is accepted. H5 is related to green hiring and is positively and directly associated with employee green commitment, has findings $p < 0.00$. Exactly what these values indicate is that the hypothesis is supported. H6 is green compensation is positively directly associated with employee green

commitment. Thus, the hypothesis is in agreement with these values, resulting in $t = 3.90$, $p < 0.01$, $\beta = 0.27$.

H7 tells us that there is a direct positive connection between green training and employee green commitment. Analysis told us the values of $t = 4.10$, $p < 0.003$, $\beta = 0.30$, and these values about the hypothesis. Accordingly, the hypothesis is confirmed and supported by the given value. H8 is that there is a direct and positive relationship between AI components and employee green commitment. The results showed that $\beta = 0.34$, $t = 4.70$, $p < 0.001$. backed, and this stated that the hypothesis has high significance. H9 is that organisational sustainability has a positive and direct correlation with employee green commitment. The findings are stated that $t = 6.00$, $p < 0.001$, $\beta = 0.50$. Hence, this hypothesis is supported by these statistical analyses. H10 has a statement that employee green commitment is a mediator of organisational sustainability and green compensation. As the researcher conducted analysis and got the values $t = 2.80$, $p < 0.05$, indirect effect $\beta = 0.14$. These values indicate that the hypothesis is supported. H11 stated that employee green commitment mediates the green hiring and organisational sustainability relationship. As the researcher used SEM to identify the values and got the values $t = 2.50$, $p < 0.03$, indirect effect $\beta = 0.16$. Hence, the given hypothesis is supported by these values. Lastly, the H12 has the statement that employee green commitment mediates the effect of green training on organisational sustainability. For my last hypothesis, here we have the values $t = 2.00$, $p < 0.02$; indirect effect $\beta = 0.15$So the hypothesis was supported as per these values. Notably, green work commitment acted as a significant mediating factor in the relationship between organisational sustainability and green employee commitment policies, according to a recent analysis. The study details how, to incur more lasting economic and environmental benefits, businesses can align AI components with green hiring, compensation, and training practices.

Here's a table summarising the hypotheses, their results (β, t-values, p-values), and conclusions based on your provided information:

TABLE 2 HYPOTHESIS TESTING

Hypothesis	**β Value**	**t-value**	**p-value**	**Conclusion**
H1	0.30	4.50	< 0.003	supported.
H2	0.25	3.80	< 0.02	supported.
H3	0.28	4.20	< 0.000	supported.
H4	0.35	5.00	< 0.03	supported.
H5	-	-	< 0.00	supported.
H6	0.27	3.90	< 0.01	supported.
H7	0.30	4.10	< 0.003	supported.
H8	0.34	4.70	< 0.001	supported.
H9	0.50	6.00	< 0.001	supported.
H10	0.14	2.80	< 0.05	supported.
H11	0.16	2.50	< 0.03	supported.
H12	0.15	2.00	< 0.02	supported.

III. RESULTS AND DISCUSSION

They revealed that Green HR practices and AI factors have a significant influence on organisational sustainability, where Green Work Commitment (GWC) plays a significant mediating effect. By integrating AI-driven solutions with sustainability-focused HR practices, organisations can bring employees into the fold of green initiatives. The findings demonstrate how artificial intelligence promotes the efficacy of green human resource management practices through enhanced data-driven decision-making and sustainable workforce engagement, and these are aligned with the studies of [4, 13, 22, 39, 49].

IV. CONCLUSION

The findings provide empirical support for the positive role of strategic Green HRM on sustainability outcomes and the interplay between AI integration and strategic Green HRM as a driver of sustainability. Indeed, long-term sustainability goals depend on having employees committed to green initiatives. These findings highlight the need for using AI-based sustainability initiatives as a means to achieve both commitment from employees and a vision for the organisation in question. These findings contain insights that can help guide managers, policymakers, and researchers in seeking to create sustainable business models.

Future research could also investigate industry-specific effects, thus deepening our understanding of these relationships. The potential long-term benefits of Green Work Commitment for enhancing employee engagement and organisational success are worth further exploration within future studies considering the implementation of AI-powered HR practices. Furthermore, exploring the enhancing moderating role of leadership and organisational culture on the effect of green HR strategies on sustainability outcomes may also provide rich insights. The coherence of these approaches globally might be further elucidated through comparative studies across emerging and developed economies.

The study adds to the literature by building an integrated framework reflecting the impact of green HR practices on awareness towards environmental sustainability. It describes how these HR systems affect employee attitudes and behaviours that adopt environmentally sustainable practices. The study fills the research gap by collating insights from multinational organisations and key sectors from both Pakistan and

Uzbekistan, two country-level case studies on green HRM, environmental issues, and sustainability.

V. ACKNOWLEDGEMENTS

We wish to extend our gratitude to the researchers and practitioners whose work has greatly enhanced our understanding of the Green HRM domain. Also, I want to say thank you to my counsellors for their assistance and support throughout this research. Special thanks to my PhD scientific supervisors, family, and colleagues for their collaboration, as well as everyone who has come here for financial support. I also appreciate the participation of everyone in this project.

VI. REFERENCES

[1] D. W. Renwick, T. Redman, and S. Maguire, "Green human resource management: A review and research agenda," International Journal of Management Reviews, vol. 15, no. 1, pp. 1-14, 2013.

[2] C. J. C. Jabbour and F. C. A. Santos, "The central role of human resource management in the search for sustainable organizations," The International Journal of Human Resource Management, vol. 19, no. 12, pp. 2133-2154, 2008.

[3] G. Tang, Y. Chen, Y. Jiang, P. Paillé, and J. Jia, "Green human resource management practices: scale development and validity," Asia pacific journal of human resources, vol. 56, no. 1, pp. 31-55, 2018.

[4] S. Ahmad, "Green human resource management: Policies and practices," Cogent business & management, vol. 2, no. 1, p. 1030817, 2015.

[5] D. W. Renwick, C. J. Jabbour, M. Muller-Camen, T. Redman, and A. Wilkinson, "Contemporary developments in Green (environmental) HRM scholarship," ed: Taylor & Francis, 2016.

[6] V. Amrutha and S. Geetha, "A systematic review on green human resource management: Implications for social sustainability," Journal of Cleaner Production, vol. 247, p. 119131, 2020.

[7] S. Sharif, S. A. Malik, N. Arooj, and O. M. Albadry, "Human resource management (HRM) practices and organizational commitment in higher educational institution (HEI): a mediating role for work engagement," Global Knowledge, Memory and Communication, 2024.

[8] S. Cheema and F. Javed, "The effects of corporate social responsibility toward green human resource management: The mediating role of sustainable environment," Cogent Business & Management, vol. 4, no. 1, p. 1310012, 2017.

[9] D. Renwick, T. Redman, and S. Maguire, "Green HRM: A review, process model, and research agenda," University of Sheffield Management School Discussion Paper, vol. 1, pp. 1-46, 2008.

[10] M. A. Mohamed, I. H. Mohamud, A. M. Sahal, and M. A. Farah, "A bibliometric analysis of academic trends in human resource management practice from 2000 to 2023," Cogent Business & Management, vol. 11, no. 1, p. 2427217, 2024.

[11] T. N. Bauer and L. Aiman-Smith, "Green career choices: The influence of ecological stance on recruiting," Journal of business and psychology, vol. 10, no. 4, pp. 445-458, 1996.

[12] P. Tambe, P. Cappelli, and V. Yakubovich, "Artificial intelligence in human resources management: Challenges and a path forward," California Management Review, vol. 61, no. 4, pp. 15-42, 2019.

[13] N. Y. Ansari, M. Farrukh, and A. Raza, "Green human resource management and employees pro-environmental behaviours: Examining the underlying mechanism," Corporate Social Responsibility and Environmental Management, vol. 28, no. 1, pp. 229-238, 2021.

[14] L. Almada and R. Borges, "Sustainable competitive advantage needs green human resource practices: A framework for environmental management," Revista de Administração Contemporânea, vol. 22, no. 3, pp. 424-442, 2018.

[15] J. Dumont, J. Shen, and X. Deng, "Effects of green HRM practices on employee workplace green behavior: The role of psychological green climate and employee green values," Human resource management, vol. 56, no. 4, pp. 613-627, 2017.

[16] S. Rani and K. Mishra, "Green HRM: Practices and strategic implementation in the organizations," International Journal on Recent and Innovation Trends in Computing and Communication, vol. 2, no. 11, pp. 3633-3639, 2014.

[17] P. Agarwal, R. K. Upadhyay, Anuj, K. Ahalawat, R. Kukreti, and A. Akhtar, "Environmental performance in higher education and green HRM: the mediating role of organisational citizenship behaviour," International Journal of Management Practice, vol. 17, no. 6, pp. 713-734, 2024.

[18] V. Vasilev, "Sustainable Development Policies in Organizations through the Application of Green Human Resource Management Policies," Sustainable Development, vol. 3, no. 04, 2023.

[19] A. Haakenstad et al., "Measuring the availability of human resources for health and its relationship to universal health coverage for 204 countries and territories from 1990 to 2019: a systematic analysis for the Global Burden of Disease Study 2019," The Lancet, vol. 399, no. 10341, pp. 2129-2154, 2022.

[20] M. Aboramadan, Y. M. Kundi, and A. Becker, "Green human resource management in nonprofit organizations: Effects on employee green behavior and the role of perceived green organizational support," Personnel Review, vol. 51, no. 7, pp. 1788-1806, 2022.

[21] B. F. Daily, J. W. Bishop, and N. Govindarajulu, "A conceptual model for organizational citizenship behavior directed toward the environment," Business & Society, vol. 48, no. 2, pp. 243-256, 2009.

[22] A. A. Arulrajah and H. Opatha, "Analytical and theoretical perspectives on green human resource management: A simplified underpinning," 2016.

[23] C. J. C. Jabbour et al., "Who is in charge? A review and a research agenda on the 'human side'of the circular economy," Journal of cleaner production, vol. 222, pp. 793-801, 2019.

[24] N. Khan, A. Malik, and A. Khan, "Human resource analytics: A novel approach to bridge the gap between human resource functions and organizational performance," International Journal of Human Capital in Urban Management, vol. 9, no. 2, 2024.

[25] Y. Yuan, S. Ren, G. Tang, H. Ji, F. L. Cooke, and Z. Wang, "How green human resource management affects employee voluntary workplace green behaviour: An integrated model," Human Resource Management Journal, vol. 34, no. 1, pp. 91-121, 2024.

[26] D. B. Zoogah, "The dynamics of Green HRM behaviors: A cognitive social information processing approach," German Journal of Human Resource Management, vol. 25, no. 2, pp. 117-139, 2011.

[27] M. R. Ali, M. F. Akram, T. A. Urkinbayev, S. K. Tashtayeva, and G. T. Aripdjanov, "The Pathways to Achieve Green Economy and The Process of Sustainable

Development Goals," SGS-Engineering & Sciences, vol. 2, no. 02, 2023.

[28] N. T. Pham, H. T. Hoang, and Q. P. T. Phan, "Green human resource management: a comprehensive review and future research agenda," International Journal of Manpower, vol. 41, no. 7, pp. 845-878, 2020.

[29] Y. J. Kim, W. G. Kim, H.-M. Choi, and K. Phetvaroon, "The effect of green human resource management on hotel employees' eco-friendly behavior and environmental performance," International Journal of Hospitality Management, vol. 76, pp. 83-93, 2019.

[30] B. B. Saeed, B. Afsar, S. Hafeez, I. Khan, M. Tahir, and M. A. Afridi, "Promoting employee's proenvironmental behavior through green human resource management practices," Corporate Social Responsibility and Environmental Management, vol. 26, no. 2, pp. 424-438, 2019.

[31] D. I. Nawaz and D. M. K. Vokhidova, "Unlocking Organizational Excellence: The Impact of Training, Technology Adoption, Employee Engagement, and Leadership Support on Performance," International Journal of Intellectual Cultural Heritage, vol. 5, no. 1, pp. 104-121, 02/13 2025.

[32] R. Gholami, A. B. Sulaiman, T. Ramayah, and A. Molla, "Senior managers' perception on green information systems (IS) adoption and environmental performance: Results from a field survey," Information & management, vol. 50, no. 7, pp. 431-438, 2013.

[33] J. E. John and S. Pramila, "Integrating AI Tools into HRM to Promote Green HRM Practices," in International Conference on Information and Communication Technology for Competitive Strategies, 2023, pp. 249-259: Springer.

[34] V. Gupta and M. Arora, "Green human resource management and its sustainable organizational practices in hospitality industry in India," Journal of the Knowledge Economy, pp. 1-23, 2024.

[35] S. Ogbeibu et al., "Demystifying the roles of organisational smart technology, artificial intelligence, robotics and algorithms capability: A strategy for green human resource management and environmental sustainability," Business Strategy and the Environment, vol. 33, no. 2, pp. 369-388, 2024.

[36] M. Z. Shah and T. Ali, "Impact of marketing expenditures on sales of leading multinational & local pharmaceutical industries in Pakistan: A comparative study," Journal of Marketing and Management, vol. 14, no. 1, pp. 18-32, 2023.

[37] P. Shanthi, K. Prakash, R. Arun, C. Nirmala, M. Kousalya, and K. Sivaperumal, "Green HRM Practices and the Factors Forcing it: A Study on Health Care Entities in Chennai," International Journal of Professional Business Review: Int. J. Prof. Bus. Rev., vol. 8, no. 9, p. 25, 2023.

[38] T. A. Norton, H. Zacher, S. L. Parker, and N. M. Ashkanasy, "Bridging the gap between green behavioral intentions and employee green behavior: The role of green psychological climate," Journal of Organizational Behavior, vol. 38, no. 7, pp. 996-1015, 2017.

[39] P. Paillé, Y. Chen, O. Boiral, and J. Jin, "The impact of human resource management on environmental performance: An employee-level study," Journal of Business Ethics, vol. 121, no. 3, pp. 451-466, 2014.

[40] J. L. Robertson and J. Barling, "Greening organizations through leaders' influence on employees' pro-environmental behaviors," Journal of organizational behavior, vol. 34, no. 2, pp. 176-194, 2013.

[41] M. R. Ali and S. M. J. Iqbal, "Examining the mediating influence of green behavior on the impact of green HR practices on environmental sustainability," iRASD Journal of Management, vol. 4, no. 3, pp. 479-494, 2022.

[42] M. Ali, Z. Kadirova, and B. Ismoyilov, "Practicing Green HRM to Achieve Environmental Sustainability," in ENVIRONMENT. TECHNOLOGIES. RESOURCES. Proceedings of the International Scientific and Practical Conference, 2024, vol. 1, pp. 24-33.

[43] R. Bougie and U. Sekaran, Research methods for business: A skill building approach. John Wiley & Sons, 2019.

[44] J. F. Hair Jr, M. Sarstedt, L. Hopkins, and V. G. Kuppelwieser, "Partial least squares structural equation modeling (PLS-SEM) An emerging tool in business research," European Business Review, vol. 26, no. 2, pp. 106-121, 2014.

[45] J. F. Hair et al., "Executing and interpreting applications of PLS-SEM: Updates for family business researchers," Journal of Family Business Strategy, vol. 12, no. 3, p. 100392, 2021.

[46] J. Hair and A. Alamer, "Partial Least Squares Structural Equation Modeling (PLS-SEM) in second language and education research: Guidelines using an applied example," Research Methods in Applied Linguistics, vol. 1, no. 3, p. 100027, 2022.

[47] A. J. Gong, M. L. Bolsegui, E. E. Lee, S. C. Mathai, and C. R. Weiss, "Assessing the psychometric validity of the epistaxis severity score: internal consistency and test–retest reliability," American journal of rhinology & allergy, vol. 38, no. 1, pp. 38-46, 2024.

[48] D. Alarcón, J. A. Sánchez, and U. De Olavide, "Assessing convergent and discriminant validity in the ADHD-R IV rating scale: User-written commands for Average Variance Extracted (AVE), Composite Reliability (CR), and Heterotrait-Monotrait ratio of correlations (HTMT)," in Spanish STATA meeting, 2015, vol. 39, pp. 1-39.

[49] M. Shevlin and J. N. Miles, "Effects of sample size, model specification and factor loadings on the GFI in confirmatory factor analysis," Personality and Individual differences, vol. 25, no. 1, pp. 85-90, 1998.

[50] D. Hooper, "Exploratory factor analysis," 2012.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 23-30

Artificial Intelligence in Cybersecurity: Threats, Defenses, and Future Directions

Laylo Bakhronkulova
Research Scholar at AJOU University
Tashkent, Uzbekistan
laylo7883@gmail.com

Muhammad Ramzan Ali
Assistant Professor at AJOU University
Tashkent, Uzbekistan
Email: Ramzan.ali@ajou.uz

Zulfiya Khabirova
Associate Professor at AJOU Universit
Tashkent, Uzbekistan
Email: zulya.uz@gmail.com

Akimjonov Azimjon
Research Scholar at AJOU University
Tashkent, Uzbekistan
Email: stmustbk@gmail.com

Alimova Zebo
Research Scholar at AJOU University
Tashkent, Uzbekistan
Email: bb5911846@gmail.com

Abdumajidova Muslima
Research Scholar at AJOU University
Tashkent, Uzbekistan
Email:
muslimaabdumajidova23@gmail.com

***Abstract*— This study explores the usage of Artificial Intelligence and machine learning technology in modern cybersecurity. When cyberattacks becoming more frequent, organizations are turning to AI-powered solutions to improve their defense systems. Adoption of AI technologies like machine learning and deep learning is shown to improve the accuracy of threat detection, but data reliability, model interpretability, and bias in decision-making systems remain significant issues. Research has proven AI to be most successful in preventing large-scale attacks, i.e., DDoS, through the recognition of patterns in network traffic based on models like Recurrent Neural Networks (RNNs) and Convolutional Neural Networks (CNNs). The application of AI technologies, such as machine learning and deep learning, has been shown to improve the speed and precision of threat detection so that it becomes easier to identify and counteract previously unknown vulnerabilities. Despite these advantages, very low rates of organizations have fully implemented AI-driven security solutions, and confidence in AI decision-making still affects deployment. This article also highlights increasing incidents of AI-driven cyber attacks, such as AI-created malware, automated phishing, and deepfake identity theft, that are outrunning traditional security controls. This analysis also emphasizes the growing importance of application of AI in cybersecurity with underscoring its potential to strengthen defens systems against zero-day attacks and similar evolving threats. However, it also reviews some of the challenges that need to be addressed for more effective integration of AI models in cybersecurity, such as the reliability of the data that is being used for its' training. With the development in AI technologies, machine learning based models are expected to play an increasingly crucial role in protection of both businesses and individuals from sophisticated cyberattacks. And despite all the advantages, the full implementation of AI-driven security solutions remains low. What is more, concerns about the trustworthiness of AI decisions and the lack of transparency in AI models still remains.**

Keywords*— *Cybersecurity, Deep Learning, Anomaly Detection, Intrusion Prevention, Machine Learning, Neural Networks, Cyber Threats, Artificial Intelligence, Network Security, Adversarial Attacks.

I. INTRODUCTION

This article will systematically summarize how deep learning can be used to increase the security of cyberspace, especially in fields like intrusion prevention and anomaly detection and what kind of situation we already have in the world of IoT regarding the usage of AI and machine learning in cybersecurity.

Nowadays, network traffic has become so complex that only deep learning stands a chance of learning these intricate patterns. Its methodological advantage is in having the capacity not to be a sink for extra data, but to tackle new information with aplomb. Different architectures of deep learning Convolutional Networks (CNNs), Recurrent Neural Networks (RNNs), Autoencoders, and Generative Adversarial Networks (GANs)(see them all at work in the chapters above) are considered with the reasons for their ability to handle high-dimensional data and detect anomalies across different domains of cybersecurity provisos [16].The deep learning's advantages in anomaly detection are particularly marked in unsupervised

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8592
© 2025 The Author(s). Published by RTU PRESS
This is an open-access article under the Creative Commons Attribution 4.0 International License.

scenarios. In these favourable frames, it can seek to discern tiny departures from the norm of datasets without using labelled instances to guide its decisions. In its intrusion detection and prevention systems (IPS), deep learning improves the ability to identify and prevent attacks. As it is able to classify network traffic based on many different parameters, the accuracy of such systems increases while false positives decrease. But unanswered questions loom ahead, such as the need for big, high-quality databases that could be targets of adversarial attacks on systems and models' expansibility. This is an area where neither deep learning technology nor its applications have yet developed mature responses [26].

II. MATERIALS AND METHODS

A. Literature review

According to literature on deep learning in cybersecurity, it seems that all agree its potential to transform the fields of anomaly detection and intrusion prevention systems (IPS) is already evident. Traditional approaches like signature-based intrusion detection systems (IDS) are losing their effectiveness as cyberattacks are constantly evolving. Especially with zero-day exploits, which evade detection by such traditional methods [25]. In the face of increasingly sophisticated cyber threats, deep learning, with its unique capability to adapt and learn from large datasets, gives hope for the future. Thoroughly-trained deep learning models, such as Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs), Autoencoders and generative adversarial networks (GANs), have already been put to use successfully in cybersecurity tasks including anomaly detection and intrusion prevention. These models are excellent at identifying complex patterns and revealing tiny discrepancies; especially in high-dimensional and time-series data, such as network traffic or system logs produced over years [4]. For example, on time series data, RNNs have proved effective at learning temporal dependencies in the data and identifying anomalous peaks [22] while autoencoders used to distinguish between normal data representations. However, challenges remain such as the need for high-quality labelled datasets and interpretability of models [21]. Nevertheless, deep learning has achieved tangible success in real-world applications: intrusion detection in IoT networks, cloud security, and malware detection. Currently active research is concerned with improving model accuracy, reducing computational costs, and improving interpretability to increase the uptake of deep learning models in cybersecurity as a whole [26].

B. The Evolving Landscape of Cybersecurity Threats

The digital space is increasingly complex and the frequency of cyberattacks ever-on-the-rise. These attacks include everything from basic denial-of-service (DoS) attempts to highly sophisticated, concerted breaches meant to siphon valuable or harmful data or otherwise cause havoc on (or to) mission-critical infrastructure. Signature-based intrusion detection systems (IDSs), which detect known attack patterns are becoming less effective against the evolving threat landscape. As it turns out, signature-based solutions are only as good as they are at discovering new attacks; malicious actors have the capability to continuously adjust their techniques to facilitate new attacks, leading to attacks being adapted and re-used with new techniques that signature-based solutions simply was not designed to recognize. These attacks, known as zero-day exploits, target unknown vulnerabilities, making signature-based IDSs ineffective [25]. Additionally, the amount of network traffic generated is large, and the complexity of modern systems makes it harder for traditional methods to effectively analyse data and find malicious behavior interspersed among all the background noise. Meanwhile, these legacy approaches have their limitations [1]; increasing need for advanced, intelligent security systems that can classify both known and unknown threats [1]. Deep learning has the potential to learn complex patterns and adapt to new data, making it an exciting approach to tackle these shortcomings.

C. Deep learning Fundamentals in Cybersecurity

A sub-field of machine learning known as deep learning employs artificial neural networks with multiple layers to discover high-level abstractions in raw data. In cybersecurity, data tends to be high-dimensional and complex, making this ability of hierarchical representation learning inherently useful. Due to the strength of this technology several deep learning architectures have shown to be efficient in the entire for the cybersecurity area. Convolutional neural networks (CNNs) are specialized in handling structured data, such as images and network traffic patterns, and are very proficient in revealing spatial relationships and features in them [16]. Long short-term memory (LSTM) networks and gated recurrent units (GRUs), which are types of recurrent neural networks (RNNs), are designed to deal with sequential data, making them ideal candidates for time-series data such as network log or events that have temporal dependencies [13]. Autoencoders are unsupervised learning models that are particularly good at identifying anomalies by learning a compressed version of normal data (s) and flagging instances which vary significantly from this learned version [19]. On the other hand, generative adversarial networks (GANs) may produce synthetic data which can extend small datasets and enhance other deep learning models. These architectures are selected because their flexibility and pattern recognition abilities allow them to cope well with new dynamic and evolving threats in the fields of cybersecurity [28].

D. Anomaly Detection using Deep Learning

Anomaly detection, which refers to identifying unusual patterns or deviations from expected behaviour, is an important part of cybersecurity. Deep learning still provides large advantages over, for example, traditional methods in the potential to surf through complex datasets and spot slight discrepancies. In the case of anomaly detection in cybersecurity, with the presence of classified and unclassified data, the unsupervised and semi-supervised deep learning techniques are well suited to cybersecurity use cases since you can train on unlabelled and partially labelled data, which is a subject we discuss in our Summary [19]. For instance, given a normal network traffic, an autoencoder is trained to learn its compressed

representation. It then flags these deviations from the representation, which signify classical activities, as anomalies. Data learned from the logs of normal execution flows, used with deep learning models, can detect unexpected events or sequences of events possibly indicating malicious activity [27]. Deep learning for anomaly detection has been successfully applied not only for network traffic and system logs but also for user behaviour analysis, unusual access pattern detection, and anomaly detection of other data streams. Deep learning models such as recurrent neural networks (RNN) can be used to present the temporal dependencies of the signal and highlight abnormal behaviours changing over time in time series data. Yet some challenges remain, such as the existence of high-dimensional data and understanding the model outputs. More advanced deep learning architectures and more effective techniques are being investigated to bring the accuracy and explainability of deep networks up to closer limits, thus allowing their deployment in many applications [29].

E. Intrusion Prevention Systems (IPS) Enhanced by Deep Learning

Intrusion Prevention Systems (IPS) are essential in modern cybersecurity world, as they permanently monitor and check a network traffic to identify anomalies and block potential threats. Traditionally, IPS uses signature-based and heuristic methods to detect already known attack patterns. However, these conventional techniques often have difficulty recognizing new or evolving cyber threats, like zero-day attacks. To overcome these challenges, machine learning, especially deep learning, has proven to be a good method for improving the capabilities of IPS technology [1].

Deep learning-based IPSs leverage advanced neural network architectures to analyze vast amounts of network traffic in real time. Unlike traditional IPSs, which rely on predefined rules, deep learning models can autonomously learn from historical and already collected data to identify different patterns of suspicious behavior and therefore predict new patterns a well. These systems utilize various features, including packet headers, payload contents, and network flow characteristics, to classify incoming traffic as benign or malicious [5]. This ability makes deep learning-powered IPS capable to adapt to enhancing threats and attack patterns dynamically identifying those schemes that were previously unknown .

Neural networks commonly used for IPSs include deep neural networks, convolutional neural networks (CNNs), recurrent neural networks (RNNs), long short-term memory networks (LSTMs), autoencoders, and generative adversarial networks (GANs). CNNs have proven to be effective in extracting features from network packets, whereas RNNs and LSTMs are especially adept at identifying attack strategies that depend on time. Autoencoders and GANs are capable of identifying anomalies by learning standard traffic patterns and highlighting signs of intrusions [9].

Incorporating deep learning into Intrusion Prevention Systems (IPSs) offers many benefits, especially in enhancing detection precision. Conventional rule-based systems often produce a high volume of false positives, which demands ongoing manual adjustments to prevent unwarranted and baseless interruptions such as those made by hackers or other interrupters [14]. In contrast, deep learning models can highly minimize false positives by recognizing nuanced differences between legitimate behavior and harmful traffic patterns that may mean intrusions into the system and subsequent loose of data [16]. What is more, IPSs that utilize deep learning can manage and control substantial amounts of network data, making them well-suited for high-traffic settings like corporate or governmental networks and cloud infrastructures or other systems that permanently store a huge amount of private information [14][28][29].

A significant benefit of deep learning-based intrusion prevention systems (IPSs) is their capability to identify zero-day attacks, which are threats that have not been previously recognized and lack established signatures. In contrast, traditional IPSs depend on threat databases that are updated manually, creating a vulnerability gap until new attacks are detected [22][30]. Deep learning models can learn from past attack patterns and predict new variations, offering a proactive defense against new cyber threats [22].

Nonetheless, these systems face various challenges, with a significant concern being the considerable computational expense. Deep learning models demand a lot of processing power, particularly in high-bandwidth environments where prompt threat detection is crucial. Training and deploying such models always require modern and specialized hardware like graphics processing units (GPUs) or tensor processing units (TPUs), which can increase both the cost and complexity of implementation [2].

One of the challenges faced is the necessity for ongoing retraining. Cyber threats are constantly changing, and attackers often create new methods to circumvent current security protocols [14]. To stay effective, deep learning models need to be regularly updated with new data to identify emerging attack vectors. However, obtaining high-quality labeled data for training is a complex issue, as cybersecurity datasets frequently exhibit class imbalances, with benign traffic far outnumbering malicious samples. This problem might result in biased models that have difficulty detecting rare but highly significant attacks [13][26].

The future of deep learning-enhanced IPSs lies in hybrid security models, where deep learning is integrated with traditional security techniques to create more adaptive and reliable intrusion prevention mechanisms. Combining deep learning with rule-based systems, threat intelligence feeds, and behavioral analytics can create a multi-layered defense strategy capable of addressing a wide range of cyber threats [29].

In summary, deep learning has greatly improved the functionality of contemporary IPSs, providing enhanced accuracy, flexibility, and the ability to identify previously unknown threats. Nonetheless, issues such as computational demands, adversarial attacks, and the necessity for ongoing retraining need to be tackled to fully harness the advantages of deep learning in IPSs. As cyber threats continue to advance, the adoption of AI-driven IPS solutions will be increasingly vital for protecting digital infrastructure from complex cyberattacks.

F. Materials

To obtain a comprehensive and reliable data about the current situation of cybersecurity and the use of AI and machine learning technologies in this area we will use a range of different sources. A significant resource for this analysis is an open source article by Jacob Fox published on the Cobalt platform on October 10, 2024 [12]. This research provides information about the impact of AI on contemporary cybersecurity, especially how machine learning algorithms help in detecting and addressing new cyber threats. It provides a detailed statistics of different challenges of implementing AI-based security solutions in corporative environments. This article serves as a crucial foundation for understanding trends in use of AI throughout the world.

Additionally, we will refer to a scientific study made by the Check Point online platform team on October 18, 2024 [6]. This study offers a statistical analysis of cybersecurity threats recorded over the year, highlighting notable trends such as the rise of zero-day attacks and DDoS incidents in different parts of the world. It also provides information about how different organizations are integrating AI and machine learning to protect from these threats and offers some statistics about the effectiveness of various AI-driven security strategies.

Except these sources, we will also include data from various cybersecurity research papers and industry reports that cover essential topics like IDSs, IPSs and AI-enhanced network security solutions. Special attention will be given to studies that focus on the use of deep learning technologies, such as RNNs and CNNs. These studies provide valuable data and elaborate into how AI can improve security systems by detecting suspicious patterns in network traffic and enhancing the accuracy of real-time threat detection.

What is more, to fully understand all the challenges related to AI integration in cybersecurity, we will review reports that discuss issues like data reliability, model interpretability and bias in AI-driven decision-making systems [21]. By examining different viewpoints on some challenges, we are going to present a balanced perspective on both benefits and limitations of the use of AI in the cybersecurity field. By comparing information from Jacob Fox's article on the Cobalt platform and the cybersecurity statistical analysis by Check Point Research, we are going to develop a comprehensive understanding of the role of AI for data protection in modern days. [6],[12].

G. Analysis

In recent years, AI became an advanced tool for data protection and privacy, gaining popularity among lots of cybersecurity experts. A study by the Ponemon Institute found that around 70% of participants believe that AI is highly effective in identifying previously unknown threats [12]. What is more, 53% of security experts noted that their organizations still are only implementing AI-based security solutions that use machine learning techniques [12]. This increasing dependence on AI is vital, especially as the number of cyber threats targeting businesses globally continues to rise. Zero-day attacks especially are significant financial and security threats as cyberattacks have seen a dramatic rise in recent years [6]. Research from "Check Point Research" indicates a 75% increase in cyberattacks throughout the world during the third quarter of 2024 [6]. Such techniques as machine learning and deep learning are particularly highly effective in large-scale attacks, including DDoS attacks in software-defined networks [24]. Deep learning technologies, such as RNNs and CNNs, have already proven their capability to analyze network traffic and recognize suspicious behavior patterns [9]. For example, research emphasized the success of an Attentional LSTM-CNN model in identifying anomalies in quasi-periodic time series data, significantly enhancing cybersecurity threat detection [22].

Despite the rapid enhancement of AI in the cybersecurity field and studies indicating that AI can greatly improve the accuracy of IDSs, only 18% of organizations have fully integrated AI-based security systems in their infrastructures [12]. Experts have examined the latest developments in machine learning and deep learning techniques applied to IDS while also admitting the existence of some challenges that these systems may encounter [5]. Additionally, a study has introduced the PS-IPS framework—an Intrusion Prevention System that utilizes machine learning on programmable switches. This innovation enhances adaptability and efficiency, making it especially beneficial for securing critical infrastructures, such as energy grids, industrial control systems, and financial institutions [20]. Whilst AI-driven cybersecurity solutions are advancing, several challenges still persist. A primary concern is ensuring the reliability and trustworthiness of the data used to train AI models, and the interpretability of AI-driven decisions poses a significant issue, as opaque "black-box" models can lead to false positives or missed threats [21][15].Despite these obstacles, the future of AI in cybersecurity appears to be bright. Research suggests that the integration of AI and machine learning will further enhance threat detection methods, automate network traffic analysis, and strengthen defenses against zero-day attacks [23]. As AI models become more advanced and transparent, their role in cybersecurity is expected to expand in the future, providing stronger and better protection for both businesses and individuals [23].

In the third quarter of 2024, an average of approximately 1,870 cyberattacks per company were recorded, showing a 75% increase compared to the same quarter in the year 2023 and a 15% rise compared to the

second quarter of 2024. Simultaneously, around 74% of security professionals reported that their organizations suffer from cyberattacks involving artificial intelligence, whilst 75% of experts stated that they were forced to adjust their security strategies to better combat AI-driven cyber threats. The most heavily impacted regions were African countries, experiencing over 3,000 attacks per week throughout 2024, nearly 50% more than in 2023. [12][6]

Despite the increasing adoption of AI in cybersecurity, its inherent characteristics—such as easy access to shared data and system control—raise concerns. 63% of security professionals reported that they use AI primarily to create rule sets that reflect known security patterns and indicators (Ponemon Institute)[12]. Additionally, 50% stated that they use AI exclusively for training purposes. Furthermore, 85% of researchers agree that only machine intelligence-based technologies are capable of detecting and preventing AI-generated threats. [12]

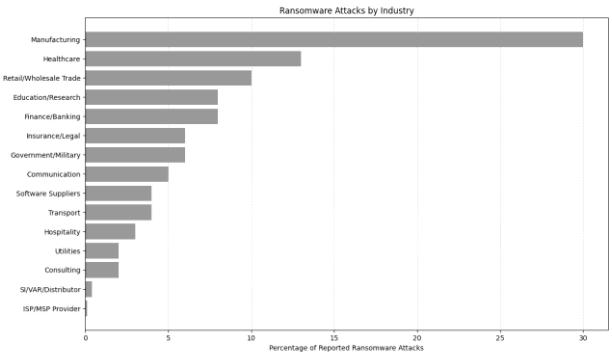


Fig 1. Statistics of ransomware attacks in 2024.

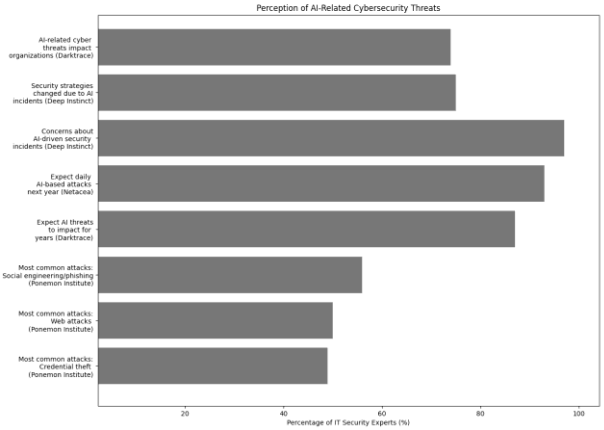


Fig 2. Perception of AI-related Cybersecurity Threads in 2024.

III. RESULTS AND DISCUSSION

While a review of recent research actually confirms the growing role of AI in both offensive and defensive cybersecurity trends, there are several important considerations to keep in mind when comparing the findings to technical specifications. For a more accurate comparison, we have presented a comparative table of deep learning models in cybersecurity which is represented as Table 1

Firstly, we can agree with the emphasis in the literature [13],[27] on the superior pattern recognition ability of deep learning algorithms in intrusion detection tasks. This is well aligned with the information given in Table 1, which shows that hybrid models offer high accuracy and performance for classification tasks. However, the literature often overlooks the practical limitations of these models — particularly in terms of resource consumption and inability to generalize well to temporal data.

Moreover, while RNN-based models such as LSTM and GRU are often praised for their ability to handle temporal sequences (e.g., system logs), although it is worth noting that they are difficult to train and suffer from vanishing gradient problems. This calls into question their scalability in real-time cybersecurity systems that must handle huge amounts of streaming data.

The application of unsupervised models, including autoencoders and GANs, is widely recognized for anomaly detection [16], [21]. Autoencoders are ideal for detecting outliers without labeled data. Nevertheless, it is worth avoiding over-reliance on such models due to their low interpretability, which is still a problem in environments where explainability is crucial, such as in the government or financial sector.

From Table 1 which presents advantages and disadvantages of various types of models with their application fields we can determine that recurrent neural networks (RNNs) such as LSTM and GRU are best suited for temporal dependency tasks, e.g., system log event analysis. RNNs are hard to train and suffer from vanishing gradients, restricting their stability and scalability. Autoencoders enable unsupervised learning along with outlier detection by means of abnormality detection. Yet they are low in interpretability and highly reliant upon the quality of data on which they are learned. GANs can potentially solve the class imbalance problem by creating synthetic instances and therefore improve the resilience of other models. They do, however, need a significant amount of computational power and are prone to training instability. Fully connected networks offer extremely high accuracy for classification problems and rather simple structures. They are not effective in learning long-term temporal patterns in the data and therefore are weaker in more complicated cases. Hybrid models, e.g., combinations of RNN and CNN, have the most potential. Such models can jointly process spatial and temporal features, which is particularly beneficial when faced with constantly changing threats. They need to be properly tuned and can be resource-intensive.

Overall, while existing research provides a solid foundation for understanding the role of AI in cybersecurity, it tends to overexaggerate the benefits while omitting or underestimating the practical limitations associated with implementing the models themselves. A more nuanced perspective - balancing, performance, interpretability, and resource requirements - is critical to creating effective and realistic defense systems, as shown in Table 1. Lastly, strategic selection and tuning of AI

models depending on the nature of cyber threats and data are required in creating an effective defense mechanism. Hybrid models particularly possess immense potential in offering overall analysis and high accuracy of threat detection.

IV. ACKNOWLEDGMENTS

We would like to express our heartfelt gratitude to the researchers, cybersecurity experts, and data scientists whose extensive efforts and pioneering research have significantly enhanced our understanding of deep learning applications in cybersecurity. Their commitment to advancing knowledge in artificial intelligence, threat detection, and risk management has been crucial in creating innovative solutions to address contemporary cyber threats. The methodologies, case studies, and experimental results they have shared have laid the foundation for further investigation and development in this rapidly changing field. We also wish to express our sincere appreciation to the various academic institutions, government agencies, private organizations, and research centers that have provided essential funding, infrastructure, and technical support for the studies mentioned in this paper. Their steadfast dedication to promoting research in cybersecurity and artificial intelligence has been crucial in driving new discoveries and improving existing methods to strengthen the security and resilience of digital systems. We also acknowledge the collaborative efforts of interdisciplinary teams, industry professionals, and practitioners who have worked diligently to connect theoretical advancements with practical cybersecurity applications. Their knowledge, insights, and contributions have been crucial in transforming AI-driven security innovations into practical solutions that safeguard organizations, governments, and individuals from new cyber threats. Furthermore, we recognize the ongoing efforts of open-access platforms, publishers, and peer reviewers who have promoted knowledge sharing and ensured that the latest research is accessible to the global cybersecurity community. The advancements in incorporating artificial intelligence into cybersecurity frameworks would not have been possible without the collective dedication of these individuals and organizations. We express our heartfelt thanks to everyone who has played a role in this field and anticipate further progress driven by their expertise and commitment to innovation in the future.

TABLE 1: COMPARATIVE TABLE OF DEEP LEARNING MODELS IN CYBERSECURITY

Model Type	**Application (Anomaly Detection/ Intrusion Prevention)**	**Advantages**	**Disadvantages**
CNN	Both	Also used for effective feature extraction, high accuracy in processing structured data like images and network traffic patterns. Detect spatial relationships and features well	Common challenges with machine learning models: Computationally intensive, require large datasets, not very good with sequential data.
RNN (LSTM, GRU)	Both	Effective for sequential data, retains temporal dependencies, good for time-series analysis such as network logs or system events	Hard to train, computational complexity, gradients can vanish.
Autoencoders	Primarily Anomaly Detection	Unsupervised learning, which is used when no labelled data is available, can also be used to find outliers; this process involves learning a compressed representation of normal data and alerting the system in case of deviations.	Reconstruction error is a complex metric that gives little insight, excellent performance relies heavily on the quality of normal data used to train.
GANs	Both	Trained on data until October 2023, Generates synthetic data to help tackle data imbalance problems to use and can also improve the robustness of certain deep learning models by polling data sets.	Training instability: High computational cost: Hard to train/evaluate.
Deep Feedforward Networks	Intrusion Prevention	Fairly simple architecture, high accuracy with a lot of training data, good for classification tasks.	Tend not to encode complex relationships over long time periods, may overfit more easily without sufficient regularization.
Hybrid Models (e.g., CNN-LSTM)	Both	It captures spatial and temporal features simultaneously which are key in complex cybersecurity use cases, utilizing the all strengths of CNN and RNN.	More complexity, more computational cost, needs proper design and tuning.

V. REFERENCES

[1] A. Abdallah, A. Alkaabi, G. Alameri, S. H. Rafique, N. S. Musa, and T. Murugan, "Cloud network anomaly detection using machine and deep learning techniques—recent research advancements," IEEE Access, vol. 12, pp. 56749–56773, 2024. [Online]. Available: https://doi.org/10.1109/ACCESS.2024.3390844.

[2] M. Z. Alom, T. M. Taha, C. Yakopcic, S. Westberg, P. Sidike, M. S. Nasrin, M. Hasan, B. C. Van Essen, A. A. S. Awwal, and V. K. Asari, "A state-of-the-art survey on deep learning theory and architectures," Electronics, vol. 8, no. 3, p. 292, 2019. [Online]. Available: https://doi.org/10.3390/electronics8030292.

[3] T. Al-Shehari, et al., "Enhancing insider threat detection in imbalanced cybersecurity settings using the density-based local outlier factor algorithm," IEEE Access. [Online]. Available: https://ieeexplore.ieee.org/document/10459083.

[4] V. Barba-Sánchez, et al., "Effects of digital transformation on firm performance: The role of IT capabilities and digital orientation," Heliyon, vol. 10, no. 6, 2024. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/38509885/.

[5] K. Bathiri and M. Vijayakumar, "Enhancing intrusion detection system (IDS) through deep packet inspection (DPI) with machine learning approaches," in 2024 International Conference on Advances in Data Engineering and Intelligent Computing Systems (ADICS), IEEE, 2024. [Online]. Available: https://ieeexplore.ieee.org/document/10533473.

[6] Check Point Research, "A closer look at Q3 2024: 75% surge in cyber attacks worldwide," Check Point Blog, Feb. 24, 2025. [Online]. Available: https://blog.checkpoint.com/research/a-closer-look-at-q3-2024-75-surge-in-cyber-attacks-worldwide/.

[7] F. Cerasuolo, et al., "Adaptive intrusion detection systems: Class incremental learning for IoT emerging threats," in 2023 IEEE International Conference on Big Data (BigData), IEEE, 2023. [Online]. Available: https://ieeexplore.ieee.org/document/10386129.

[8] S. Chakraborty, et al., "Interpretability of deep learning models: A survey of results," in IEEE SmartWorld, Ubiquitous Intelligence & Computing, Advanced & Trusted Computing, Scalable Computing & Communications, Cloud & Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI), IEEE, 2017. [Online]. Available: https://doi.org/10.1109/UIC-ATC.2017.8397411.

[9] J. N. Chukwunweike, M. Yussuf, O. Okusi, T. O. Bakare, and A. J. Abisola, "The role of deep learning in ensuring privacy integrity and security: Applications in AI-driven cybersecurity solutions," World Journal of Advanced Research and Reviews, vol. 23, no. 2, pp. 2550, 2024. [Online]. Available: https://doi.org/10.30574/wjarr.2024.23.2.2550.

[10] X. D. Do, H. D. Nguyen, and V. N. Tisenko, "Malicious URL detection based on machine learning," International Journal of Advanced Computer Science and Applications, vol. 11, no. 1, 2020. [Online]. Available: https://doi.org/10.14569/IJACSA.2020.0110119.

[11] H. N. Fakhouri, et al., "A comprehensive study on the role of machine learning in 5G security: Challenges, technologies, and solutions," Electronics, vol. 12, no. 22, p. 4604, 2023. [Online]. Available: https://doi.org/10.3390/electronics12224604.

[12] J. Fox, "Top 40 AI cybersecurity statistics," Cobalt Blog, Oct. 10, 2024. [Online]. Available: https://www.cobalt.io/blog/top-40-ai-cybersecurity-statistics.

[13] H. Gonaygunta, et al., "Enhancing cybersecurity: The development of a flexible deep learning model for enhanced anomaly detection," in 2024 Systems and Information Engineering Design Symposium (SIEDS), IEEE, 2024. [Online]. Available: https://doi.org/10.1109/SIEDS61124.2024.10534661.

[14] M. Z. Gunduz and R. Das, "Cyber-security on smart grid: Threats and potential solutions," Computer Networks, vol. 169, p. 107094, 2020. [Online]. Available: https://doi.org/10.1016/j.comnet.2019.107094.

[15] S. R. Hong, J. Hullman, and E. Bertini, "Human factors in model interpretability: Industry practices, challenges, and needs," Proceedings of the ACM on Human-Computer Interaction, vol. 4, no. CSCW1, pp. 1–26, 2020. [Online]. Available: https://doi.org/10.1145/3392878.

[16] R.-H. Hwang, M.-C. Peng, C.-W. Huang, P.-C. Lin, and N. Nguyen, "Unsupervised deep learning model for early network traffic anomaly detection," IEEE Access, vol. 8, pp. 30387–30399, 2020. [Online]. Available: https://doi.org/10.1109/ACCESS.2020.2973023.

[17] J. M. Kaplan, et al., Beyond cybersecurity: Protecting your digital business. Hoboken, NJ: Wiley, 2015.

[18] A. R. Khan, M. Kashif, R. H. Jhaveri, R. Raut, T. Saba, and S. A. Bahaj, "Deep learning for intrusion detection and security of Internet of Things (IoT): Current analysis, challenges, and possible solutions," Security and Communication Networks, vol. 2022, p. 4016073, 2022. [Online]. Available: https://doi.org/10.1155/2022/4016073.

[19] G. Kocher and G. Kumar, "Machine learning and deep learning methods for intrusion detection systems: Recent developments and challenges," Soft Computing, vol. 25, no. 15, pp. 9731–9763, 2021. [Online]. Available: https://www.researchgate.net/publication/352725425_Machine_learning_and_deep_learning_methods_for_intrusion_detection_systems_recent_developments_and_challenges.

[20] A. Y.-P. Lee, et al., "PS-IPS: Deploying intrusion prevention system with machine learning on programmable switch," Future Generation Computer Systems, vol. 152, pp. 333–342, 2024. [Online]. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4440724.

[21] W. Liang, et al., "Advances, challenges, and opportunities in creating data for trustworthy AI," Nature Machine Intelligence, vol. 4, no. 8, pp. 669–677, 2022. [Online]. Available: https://www.researchgate.net/publication/362752511_Advances_challenges_and_opportunities_in_creating_data_for_trustworthy_AI.

[22] F. Liu, et al., "Anomaly detection in quasi-periodic time series based on automatic data segmentation and attentional LSTM-CNN," IEEE Transactions on Knowledge and Data Engineering, vol. 34, no. 6, pp. 2626–2640, 2020. [Online]. Available: https://www.researchgate.net/publication/343492730_Anomaly_Detection_in_Quasi-Periodic_Time_Series_based_on_Automatic_Data_Segmentation_and_Attentional_LSTM-CNN.

[23] A. Manoharan and M. Sarker, "Revolutionizing cybersecurity: Unleashing the power of artificial intelligence and machine learning for next-generation threat detection," International Research Journal of Modern Engineering and Technology & Science, 2023. [Online]. Available: https://www.researchgate.net/publication/379308659_REVOLUTIONIZING_CYBERSECURITY_UNLEASHING_THE_POWER_OF_ARTIFICIAL_INTELLIGENCE_AND_MACHINE_LEARNING_FOR_NEXT-_GENERATION_THREAT_DETECTION.

[24] N. S. Musa, et al., "Machine learning and deep learning techniques for distributed denial of service anomaly detection in software-defined networks—current research solutions," IEEE Access, vol. 12, pp. 17982–18011, 2024. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=10418146.

[25] D. Nair and N. Mhavan, "Augmenting cybersecurity: A survey of intrusion detection systems in combating zero-day vulnerabilities," in Smart Analytics, Artificial Intelligence and Sustainable Performance Management in a Global Digitalised Economy, Emerald Publishing Limited, 2023. [Online]. Available: https://doi.org/10.1108/S1569-37592023000110A007.

[26] M. Ozkan-Okay, et al., "A comprehensive survey: Evaluating the efficiency of artificial intelligence and machine learning techniques on cybersecurity solutions," IEEE Access, vol. 12, pp. 12229–12256, 2024. [Online]. Available: https://doi.org/10.1109/ACCESS.2024.3355547.

[27] G. Pang, C. Shen, L. Cao, and A. Van Den Hengel, "Deep learning for anomaly detection: A review," ACM Computing Surveys, vol. 54, no. 2, Article 38, 2021. [Online]. Available: https://doi.org/10.1145/3439950.

[28] A. Yaseen, "The role of machine learning in network anomaly detection for cybersecurity," Sage Science Review of Applied Machine Learning, vol. 6, no. 8, pp. 16–34, 2023. [Online]. Available: https://journals.sagescience.org/index.php/ssraml/article/view/126.

[29] Z. Zamanzadeh Darban, et al., "Deep learning for time series anomaly detection: A survey," ACM Computing Surveys, vol. 57, no. 1, pp. 1–42, 2024. [Online]. Available: https://dl.acm.org/doi/10.1145/3691338.

[30] X. X. Zhu, et al., "Deep learning in remote sensing: A comprehensive review and list of resources," IEEE Geoscience and Remote Sensing Magazine, vol. 5, no. 4, pp. 8–36, 2017. [Online]. Available: http://dx.doi.org/10.1109/MGRS.2017.2762307.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 31-36

Review of the Cybersecurity Impact and Limitations of the Use of Artificial Intelligence in Transport

Todor Balabanov
Faculty of Telecommunications and Electrical Equipment in Transport
University of Transport
Sofia, Bulgaria
todor.balabanov@vtu.bg

Dimitar Dimitrov
Faculty of Transport Management
University of Transport
Sofia, Bulgaria
ddimitrov@vtu.bg

***Abstract*—Artificial intelligence opens new opportunities for adding value to industry, transport, and society. New technologies are everywhere and are becoming increasingly established in many aspects of life. AI applications are endless to discuss, develop, and deploy. This study looks at the most used applications of artificial intelligence in transport. On the other hand, cybersecurity is also a growing technical and technological concept. Many companies engaged in the development of technical and technological solutions with applications in transport have incorporated information technology into their business. This requires companies and organizations to implement more security measures. The need to protect data and information increases the requirements for cybersecurity, and it is also believed that artificial intelligence substantially impacts cybersecurity. Machine learning is already heavily induced in the latest technologies supporting cybersecurity. The article reviews the literature and explores the overall impact of artificial intelligence on cybersecurity.**

Keywords*— *Artificial Intelligence, Cybersecurity, Road Transport, Railway Transport.

I. INTRODUCTION

The development of artificial intelligence provides new opportunities for generating and managing processes and gives additional value to industry, transport, and society as a whole [1]. New technologies provide more and more opportunities for AI to find applications in many aspects of life. These applications are practically endless to discuss, develop, and implement in many areas. However, in transport, aspects of reliability and security are fundamental, especially regarding people's safety and health.

This study was provoked and aims to look at the most used applications of artificial intelligence in transport. On the other hand, cybersecurity is also a growing technical and technological concept. Many companies engaged in the development of technical and technological solutions with applications in transport have incorporated information technology into their business. This requires companies and organizations to implement more security measures. The need to protect data and information increases the requirements for cybersecurity, and it is also believed that artificial intelligence substantially impacts cybersecurity. Machine learning is already heavily induced in the latest technologies supporting cybersecurity. The article reviews the literature and explores artificial intelligence's overall impact on transport cybersecurity [2].

II. MATERIALS AND METHODS

As a basic definition, AI is connected to all machines acting in a way that seems intelligent [3] or exhibiting characteristics typical of human reasoning. However, this definition suffers from the lack of a universally accepted definition of "intelligence." Later, a new definition was developed based on the Turing test [4]: A machine is considered intelligent if it is indistinguishable from a human during interaction with an impartial observer.

More structured, detailed definitions are also known in [5]-[8] as they attempt to capture the broad nature of AI and its potential coverage. In some areas, such definitions sound too abstract, which means they are less likely to be widely accepted. Generally, standard definitions are characterized by a decrease in adoption, which leads to a lack of general agreement on what AI is.

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8581
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

According to [9], the closest definition of AI suitable for next-generation transport and transport engineering is AI is the discipline that brings together all the aspects that allow an entity to determine how to perform a task and/or make a decision based on the experience gained through sample observation and/or interaction with the environment, as well as possibly competing or collaborating with other entities.

This definition is based on the need to highlight the following aspects that are crucial when considering the application of AI in the field of transportation:

1) to be able to learn from examples (i.e., not to be a program code to solve a problem);

2) possibly working in an environment in conjunction with other objects;

3) performing a task that requires intelligence if performed by a human;

4) omits trivial automatism;

5) It can be either hardware or software (or hybrid).

The above allows us to deduce the connection between some of the most common concepts related to AI, including Deep Learning, Machine Learning, and AI itself.

Machine learning is a subfield within AI focused on techniques that can learn from examples and improve with experience without being explicitly programmed for a task. Within ML, artificial neural networks are borrowed from the structure of the human brain: ANNs have a layered structure of interconnected neurons (perceptrons) that interact with each other to perform a task. In recent years, technological evolution has made it possible to build more and more complex ANNs, such as the so-called. Deep Neural Networks are a class of ANNs with multiple layers of neurons, allowing them to extract functions from the data automatically. DNN enables DL, which "allows for the so-called. Computational models to be composed of multiple processing layers and to learn data representations with multiple levels of abstraction [10]."

The development of communication and information systems has led to the creation of so-called Intelligent Transport Systems, and computing systems and resources have opened new opportunities for intelligent solutions for traffic safety, comfort, and transport efficiency. Artificial intelligence is widely used to optimize traditional data-driven approaches in various research areas. A typical example is the application of the Vehicle-to-Everything system in land transport, which, combined with AI, collects and analyzes information from various sources, expanding the driver's perception and predicting traffic situations to avoid potential accidents [11]. In the same case, V2X communications are based on the sharing of information between:

- Vehicle-to-Infrastructure;
- Vehicle-to-Vehicle;
- Vehicle-to-Pedestrian;
- Vehicle-to-Self;
- Vehicle-to-Road side units

V2X communications are related to the following three aspects of management:

- efficiency and speed of movement, optimal routes, and minimization of traffic;
- safety, security, and comfort of travel and transportation;
- energy efficiency and ecology.

One important V2X use case is traffic information. Vehicle apps can use this information to intelligently perform tasks such as clearing congestion, making better use of electric vehicle charges, minimizing fuel consumption, and improving location-based services. The traffic dataset can be obtained from multiple sources, such as CCTV cameras, induction loops, information services, and vehicles. Designing highly accurate traffic forecasting algorithms using conventional traffic estimation techniques is challenging.

There are known overview studies dedicated to the application of AI in railways, all of which focus on a specific aspect of an application. For example, in [12], an overview of the latest applications of big data analytics in the context of railway engineering and transport has been carried out.

The [13] also provides a study of the available and potential use of AI in railway assets.

The [14] reviews and evaluates data-driven approaches applied in train dispatching management, which are grouped into statistical methods, graphical models, and ML.

[15] proposes a study on recent applications of ML in railway maintenance based on a taxonomy of existing literature.

Another study provided an overview of the applications of visual inspection technology based on image processing in the railway industry [16].

The [17] contains a systematic revision of the forecasting of urban spatiotemporal data flow; existing ML-based methods for urban flow forecasting are monitored, with some discussions about the difficulties and some ideas in this direction.

The [18] provides an overview of the rail system's sustainability, with a focus on quantitative approaches. The review discusses sustainability metrics and approaches, as well as data-driven and optimization-based approaches. Several growing future scientific topics are also identified.

The researchers [19] present a study of recent approaches to the problems of online rescheduling of rail traffic, including dynamic and stochastic aspects. According to the authors' conclusion, models based on optimization are the most used approaches.

In general, the use of AI in railways is an area that is to be developed more dynamically. On the one hand, there is a broad perspective on the application of AI. On the other hand, it is necessary to consider them in a complex way (including an accompanying analysis of the different sub-areas of the railway sector) [20]-[22].

The railway sector is a particularly relevant example of the possibility of a significant degree of automation of processes and the development of various targeted AI applications for railway systems, analysis of their models and distributions, etc. Given its specificity, AI applications can be distinguished into seven subfields, which can be defined as follows [23]:

Maintenance and Inspection covers all preventive and corrective activities designed to keep the system or subsystems in good operational condition. These activities are essential to avoid deterioration with possible safety consequences due to improper maintenance.

Safety and security are paramount for any transport system, as passengers expect transport to be safe and secure. Transport safety and security refers to all activities and means to reduce the risks of both unintentional and intentional causes of accidents that may directly or indirectly cause injury to persons and/or damage to physical assets.

Autonomous Driving and Control includes applications oriented toward creating trains capable of operating automatically without any (or only limited) human intervention and approaches aimed at optimizing the energy consumption of moving rolling stock. The International Association of Public Transport defines five Grades of Automation in terms of the operation of trains ranging from GoA0, meaning there is no automation, to GoA4, which awaits trains capable of operating automatically without onboard staff/driver. A more in-depth review of research and development of automatic train operation in rail transport can be found in [24].

Traffic Planning and Management combines all activities with effective and efficient capacity management, scheduling and control of rail operations, and resource allocation and management. This includes traffic forecasting and rescheduling, analysis of passenger and freight rail transport, assessment of traffic demand and capacity, train and crew timetables, and optimal use of rolling stock and energy to increase passenger and freight transport efficiency and competitiveness.

Revenue Management is the application of disciplined analytics that predict consumer behavior at micro-market levels and optimize product availability and price to maximize revenue growth.

Transport Policy deals with the development of a set of strategies and programs, which are established by governments and regulators, to achieve specific objectives related to social, economic, and environmental conditions and the functioning of the transport system.

Passenger Mobility refers to the movement of people using any means of transport. In this context, it refers to rail transport and the following characteristics of mobility: time taken to reach the destination; affordability and Accessibility, as rail options need to be affordable to ensure a successful transport service; and Safety, which is a fundamental prerequisite for rail mobility.

The study [25] systematizes scientific research, as shown in Fig. 1, where the information on the studies included in each sub-field of railway transport shall be presented.

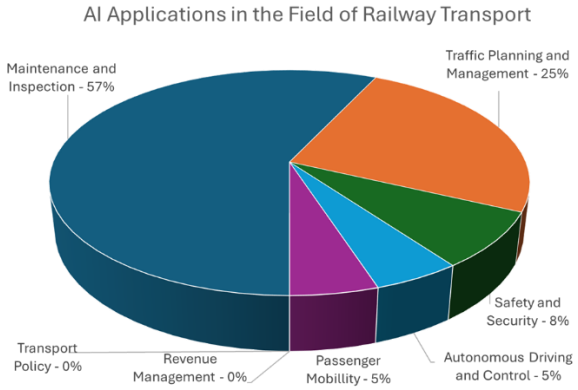


Fig. 1. AI Applications in the Field of Railway Transport.

"Maintenance and Inspection" is the main component, which makes up about 57% of the surveys: more than twice as many documents in "Traffic Planning and Management" and seven times as many documents in the field of "Safety and Security." Documents in the field of "Autonomous Driving and Control" as well as "Passenger Mobility" account for 5% each. So far, there is no open research interest in the "Revenue Management" and "Transport Policy" subfields.

The application of artificial intelligence in transport projects is a complex task that requires a comprehensive concept [26],[27]. The reasons are mainly related to the degree of use of information technology in transportation and the cost of AI. The creation of AI is directly related to significant engineering effort and cost.

Artificial intelligence is increasingly used in all modes of transport, but it is entering the sector with a slowdown. The biggest problem facing technologies related to artificial intelligence is the collection of data and its classification in order for the learning process to be effective. The goal is not to hinder the development and penetration of artificial intelligence but to prevent the risks of its use.

The application of artificial intelligence in managing transport projects is a complex and multi-parameter task, requiring data on traffic, the environment, transport events over time, etc. The data and information are accumulated, processed, and analyzed, which then form the basis for improving the performance of artificial intelligence.

The use of artificial intelligence in project management is a topical scientific problem that several authors consider methodological [28]-[32]. The issues discussed are a special case related to the design and construction of transport infrastructure, but this will, in any case, be an important element of the overall task and the challenges to its implementation.

Artificial intelligence is increasingly used in the management of transport projects. However, the most serious challenge for the technologies used is still collecting, analyzing, and classifying data to make the learning process more efficient [33].

Most of the transport projects are in the construction of transport infrastructure. The application of artificial intelligence in managing projects for the construction of transport infrastructure is mainly related to documentary analysis, remote analysis, forecasting, analysis of subcontractors, etc. The project architecture shows the team's relationships, tasks, and milestones in these cases. Artificial intelligence can be successfully used to account for this interaction and improve overall project management. The rapid development of artificial intelligence technologies implies improving the management of transport infrastructure projects.

The modernized version of the four-stage model for transport infrastructure planning requires planning based on long-term forecasts of expected traffic, applying mathematical models [34],[35]. The extended four-stage transport model is shown in Fig. 2. It also includes an "Artificial Intelligence" module, through which the accumulated data and trends are processed and analysed.

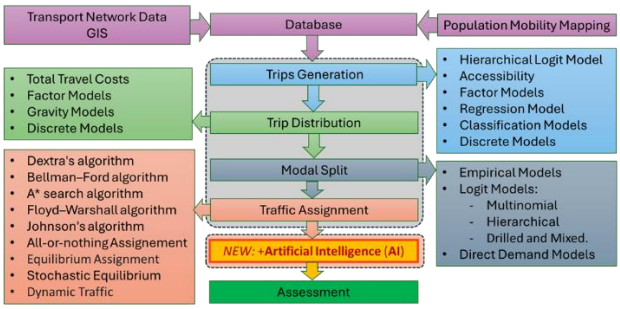


Fig. 2. A modernized version of the four-stage transport model for transport infrastructure planning.

The idea is to create large data sets related to transport, logistics operations, vehicles, types of cargo, cargo volume, speed of freight flows, carriers, routes, infrastructure, and workload by hours, days, and seasons to be used by artificial intelligence. The data collected is of different types – text, numbers, photos, video, voice, etc. It has been found that the most researched data are those related to transport accidents to improve safety [36]. In these cases, with the help of tools and techniques for analyzing text data and images, artificial intelligence can detect previously hidden problems. It should be noted that with flexible management of transport projects with an artificial intelligence application, higher efficiency is achieved [37],[38].

The transport sector is a complex system consisting of many coordinated business logic and processes to ensure a continuous, high-quality, and safe transport process. It is this complex information infrastructure consisting of many hardware and software elements, including the ability to use AI, that makes it sufficiently vulnerable to unintentional or deliberate negative information impacts that can disrupt operations, compromise sensitive data, and even threaten public safety, according to the classic scheme given in the figure below:

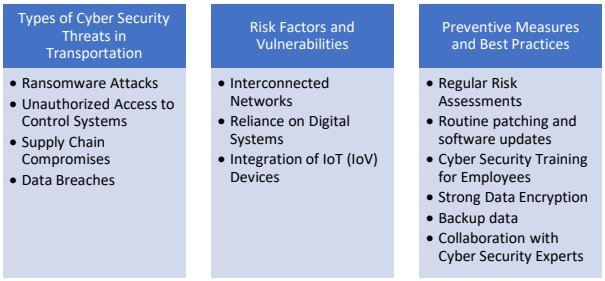


Fig. 3. Typical scheme for presenting cyber threats, risk factors and prevention in transport.

III. RESULTS AND DISCUSSION

The analysis of the work in the current study shows that AI can revolutionize the transportation sector, but it comes with challenges and considerations. In this regard, the following can be summarized regarding the use of AI in transport:

Benefits of AI in Transportation

AI improves traffic management, predictive maintenance, and logistics optimization, making transportation systems more efficient.

AI can improve safety by enabling autonomous driving, reducing human error, and improving traffic monitoring and accident detection.

AI helps optimize routes and reduce fuel consumption, creating a more sustainable transportation ecosystem.

Challenges and risks of using AI

AI involves collecting vast amounts of data and raising privacy questions.

AI systems can mistakenly recognize pedestrians or other vehicles, leading to potential accidents.

Implementing AI in transportation requires robust regulatory frameworks to ensure safety and ethical use.

Key Areas of AI Application

AI supports features such as perception, localization, mapping, scheduling, and control in self-driving cars.

AI improves intelligent traffic management systems, improving traffic and reducing congestion.

AI optimizes logistics operations, from route planning to predictive maintenance.

From a future perspective, the role of artificial intelligence in transportation is expected to grow, with advances in machine learning and IoT (IoV) leading to further innovation. However, addressing the challenges and risks associated with AI is crucial for its successful integration into the transport sector.

IV. CONCLUSION

This article summarizes and systematizes the problem of the application of artificial intelligence in the field of road transport, particularly railway transport, as an illustrative example of a high degree of automation of its management and functioning. Categorization has been made into seven railway sub-areas: maintenance and inspection, safety and security, autonomous movement and control, transport planning and management, revenue management, transport policy, and passenger mobility. This is an important step towards adopting AI in transportation, as it systematically provides a detailed and in-depth summary of available research focuses.

In this regard, the following conclusions are presented:

- AI reveals its strong impact on various activities related to forecasting. For example, in the field of maintenance and inspection, AI-enabled damage/defect predictions have been extensively studied. Similar situations are also found in areas such as forecasting the flow of transport passenger mobility and traffic situation forecasting in real-time traffic management.
- The use of intelligent systems provides additional support to improve maintenance operations, resulting in increased safety.
- AI can support optimization models to address large-scale real-life issues in planning, traffic management, maintenance, and inspection scheduling.
- AI applications can use a wide range of data from sensors, visuals/footage, and traffic movement logs, making AI's capabilities in transportation extremely diverse.
- Special emphasis is placed on the application of artificial intelligence in the management of transport projects, which is a complex and multiparametric task that requires extensive data on traffic, the environment, transport events over time, etc.
- Regarding Cybersecurity impact and limitations in transport, a scheme for the presentation of cyber threats, risk factors, and prevention is given.

AI is attracting increasing research interest, and therefore – it is realistic to expect that a greater focus on AI-based scientific and applied research will characterize the future of transport engineering, as well as its planning and management.

REFERENCES

[1] D. Burroughs, "The future of intelligence is artificial," Rail Journal, 2019. [Online]. Available: https://www.railjournal.com/in_depth/future-intelligence-artificial

[2] M. F. Ansari, B. Dash, P. Sharma, and N. Yathiraju, "The impact and limitations of artificial intelligence in cybersecurity: A literature review," Int. J. Adv. Res. Comput. Commun. Eng., vol. 11, pp. 81–90, Oct. 2022.

[3] A. Przegalińska, "State of the art and future of artificial intelligence," Policy Department for Economic, Scientific and Quality of Life Policies, Brussels, 2019.

[4] A. M. Turing, Computing Machinery and Intelligence, 2009, pp. 23–65.

[5] European Commission, "ANNEX to the communication from the commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal," 2019.

[6] B. Copeland, "Artificial intelligence," Encyclopedia Britannica, Jun. 28, 2024. [Online]. Available: https://www.britannica.com/technology/artificial-intelligence

[7] European Commission and Joint Research Centre, Artificial Intelligence – A European Perspective. Luxembourg: Publications Office, 2018.

[8] V. Vatakov, E. Pencheva, and E. Dimitrova, "Recent advances in artificial intelligence for improving railway operations," in Proc. 30th Nat. Conf. Int. Participation (TELECOM), 2022.

[9] N. Bešinović et al., "Artificial intelligence in railway transport: Taxonomy, regulations, and applications," IEEE Trans. Intell. Transp. Syst., vol. 23, pp. 14011–14024, Sep. 2022.

[10] Y. LeCun, Y. Bengio, and G. Hinton, "Deep learning," Nature, vol. 521, pp. 436–444, 2015.

[11] W. Tong, A. Hussain, W. Bo, and S. Maharjan, "Artificial intelligence for vehicle-to-everything: A survey," IEEE Access, vol. PP, pp. 1–1, Jan. 2019.

[12] F. Ghofrani, Q. He, R. M. P. Goverde, and X. Liu, "Recent applications of big data analytics in railway transportation systems: A survey," Transp. Res. Part C Emerg. Technol., vol. 90, pp. 226–246, 2018.

[13] Y. Jain et al., "A survey on railway assets: A potential domain for big data," in Proc. Int. Conf. Issues Challenges Intell. Comput. Techn. (ICICT), 2019.

[14] C. Wen et al., "Train dispatching management with data-driven approaches: A comprehensive review and appraisal," IEEE Access, vol. 7, pp. 114547–114571, 2019.

[15] M. C. Nakhaee, D. Hiemstra, M. Stoelinga, and M. van Noort, "The recent applications of machine learning in rail track maintenance: A survey," in Lecture Notes Comput. Sci., vol. 11495, pp. 91–105, 2019.

[16] S. Liu, Q. Wang, and Y. Luo, "A review of applications of visual inspection technology based on image processing in the railway industry," Transp. Saf. Environ., vol. 1, pp. 185–204, 2019.

[17] P. Xie et al., "Urban flow prediction from spatiotemporal data using machine learning: A survey," Inf. Fusion, vol. 59, pp. 1–12, 2020.

[18] N. Bešinović, "Resilience in railway transport systems: A literature review and research agenda," Transp. Rev., vol. 40, pp. 457–478, 2020.

[19] F. Corman and L. Meng, "A review of online dynamic models and algorithms for railway traffic management," IEEE Trans. Intell. Transp. Syst., vol. 16, pp. 1274–1284, 2014.

[20] SNCF, "Making your rail journey better with predictive maintenance," 2020. [Online]. Available: https://www.sncf.com/en/network-expertise/rolling-stock-division/how-predictive-maintenance-improves-rail-travel

[21] V. Fragnelli and S. Sanguineti, "A game theoretic model for re-optimizing a railway timetable," Eur. Transp. Res. Rev., vol. 6, pp. 113–125, 2014.

[22] X. Gibert, V. M. Patel, and R. Chellappa, "Deep multitask learning for railway track inspection," IEEE Trans. Intell. Transp. Syst., vol. 18, pp. 153–164, Jan. 2017.

[23] F. Flammini et al., RAILS Deliverable D1.1: Definition of a Reference Taxonomy of AI in Railways, 2020.

[24] J. Yin et al., "Research and development of automatic train operation for railway transportation systems: A survey," Transp. Res. Part C Emerg. Technol., vol. 85, pp. 548–572, 2017.

[25] R. Tang et al., "A literature review of artificial intelligence applications in railway systems," Transp. Res. Part C Emerg. Technol., vol. 140, p. 103679, 2022.

[26] European Parliament, "Artificial intelligence in transport," 2019.

[27] Ministry of Transport, Information Technology and Communications of the Republic of Bulgaria, "Concept for the development of artificial intelligence in Bulgaria until 2030," 2022.

[28] H. Dam, T. Tran, J. Grundy, A. Ghose, and Y. Kamei, "Towards effective AI-powered agile project management," 2018.

[29] I. Taboada, A. Daneshpajouh, N. Toledo, and T. Vass, "Artificial intelligence enabled project management: A systematic literature review," Appl. Sci., vol. 13, p. 5014, Apr. 2023.

[30] R. Costa, Á. Dias, R. Gonçalves, L. Pereira, and S. Abreu, "Artificial intelligence in project management: Systematic literature review," Int. J. Technol. Intell. Plan., vol. 13, p. 1, Jan. 2022.

[31] S. Ong and S. Uddin, "Data science and artificial intelligence in project management: The past, present and future," J. Mod. Proj. Manag., vol. 7, 2020.

[32] D. I. Tselentis, E. Papadimitriou, and P. van Gelder, "The usefulness of artificial intelligence for safety assessment of different transport modes," Accid. Anal. Prev., vol. 186, p. 107034, 2023.

[33] V. Holzmann and M. Lechiara, "Artificial intelligence in construction projects: An explorative study of professionals' expectations," Eur. J. Bus. Manag. Res., vol. 7, pp. 151–162, May 2022.

[34] D. Dimitrov and I. Petrova, "Use of artificial intelligence in transport project management," Mech. Transp. Commun., vol. 21, no. 3, 2023.

[35] D. Dimitrov, I. Petrova, P. Zlateva, and D. Velev, "Artificial intelligence application in agile transport project management," 2023.

[36] K. Dong, I. Romanov, C. McLellan, and A. F. Esen, "Recent text-based research and applications in railways: A critical review and future trends," Eng. Appl. Artif. Intell., vol. 116, p. 105435, 2022.

[37] A. Tubman, "The use of artificial intelligence in international decision-making processes in project management," May 27, 2022.

[38] M. R. Davahli, The Last State of Artificial Intelligence in Project Management, 2020.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 37-41

Using Bayesian Methods to Predict Users' Information Needs in a Digital Library

Fayzi Bekkamov
Library information systems department Tashkent University of Information Technologies named after Muhammad al-Khwarizmi
Tashkent, Uzbekistan
bfayzi93@gmail.com

Mumin Babajanov
Modern Information and Communication Technologies department International Islamic Academy of Uzbekistan
Tashkent, Uzbekistan
mum1975@mail.ru

Mansur Berdimurodov
Modern Information and Communication Technologies department International Islamic Academy of Uzbekistan
Tashkent, Uzbekistan
mansur_alisherovich@mail.ru

***Abstract*— In digital library, identifying users' information needs and providing them with relevant resources is of critical importance. Users' characteristics, personal preferences, and demographic information play a key role in determining their information needs. Machine learning based methods are widely utilized to recommend resources that align with users' information requirements, significantly enhancing the efficiency of information retrieval systems. The Bayesian method is one of the most effective methods for predicting users' information needs. This approach is based on the principle of conditional probabilities and enables the prediction of future information needs by analyzing users' past search behaviors and interaction patterns. The Bayesian model offers several advantages, including the ability to process large datasets, high classification accuracy, and computational efficiency. Due to these benefits, it is extensively applied in digital library to optimize information retrieval and recommend relevant resources to users. This article examines the fundamental principles of the Bayesian method in the context of digital library, highlighting its advantages and limitations. Furthermore, the effectiveness of this model in identifying users' information needs and recommending appropriate resources is analyzed. The findings of this research contribute to the improvement of digital library, enhancing user search experiences and optimizing resource recommendations.**

Keywords*— *digital library, Bayes methods, personal preferences, information requirements, predict, resource, recommender systems, rating, metadata similarity, probability.

I. INTRODUCTION

Information needs are influenced by a combination of users' search histories, demographic attributes, and individual preferences. To effectively predict and address these needs, various machine learning techniques have been employed, among which the Bayes method is widely recognized for its efficacy in probabilistic classification and recommendation systems [1, 2].

The Bayes method, derived from Bayesian probability theory, is a powerful statistical classification technique that is utilized for computing the probability of a user seeking particular information, based on the past data or experiences. The technique is particularly adept at predicting users' information needs because it is developed upon analyzing various variables such as their earlier search histories, patterns, interests, and contextual variables.

The application of Bayesian techniques for information need prediction generally includes a number of key steps:

Data collection and preprocessing: the first task is to gather users' search queries, browsing history, and other available interaction data. Raw data is cleaned and preprocessed to eliminate noise and irrelevant information so that the model learns from meaningful and quality input.

Pattern extraction: in this stage, the system scans the processed data for recurring patterns, behavior, or keywords that indicate the interests of the user and possible information needs. These patterns are relevant as they allow the system to make educated predictions regarding what the user might be interested in, given their past behavior.

Bayesian Classification: the second step is to apply Bayesian classification principles for the categorization of the search queries and interactions. Bayesian classification utilizes a probabilistic method that updates the probability of a user's information needs being met based on new data or evidence. The system calculates the probability that a specific query falls under a specific category or topic, based on previous probabilities and the evidence gathered from previous searches.

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8586
© 2025 The Author(s). Published by RTU PRESS
This is an open-access article under the Creative Commons Attribution 4.0 International License.

The use of Bayes methods in information retrieval simultaneously optimizes the relevance and effectiveness of the results. With expectations of what is most likely to be searched or what the user will require, the system is able to make useful suggestions or rule out search results. This, besides enhancing the use experience, helps in the development of intelligent, context-aware search engines and recommender systems that are capable of continuously changing based on users' feedback and behaviour [3, 4].

By leveraging the Bayes method, modern information retrieval systems can enhance user experience by providing tailored content recommendations, improving search result accuracy, and predicting future information-seeking behaviors. This approach has been extensively applied in various domains, including digital libraries, e-commerce, and personalized content delivery platforms, underscoring its significance in the field of information science and artificial intelligence [5, 7].

II. MATERIAL AND METHODS

Its application in library information systems significantly enhances the quality and efficiency of service provision through systematic analysis of user behavior and classification of users according to informational needs. The probabilistic character of this approach is particularly effective in large-scale environments where a great amount of user interaction data can be utilized to determine patterns and preferences more precisely [6].

Central to the Bayes approach is Bayes' Theorem, a foundation idea in probability theory that allows for the computation of the probability of an event given prior knowledge and new evidence. In information systems, this would involve estimating the probability that an observed user query or activity reflects a particular information category or need.

By representing uncertainty and revising beliefs in a dynamic manner as new evidence arrives, the Bayesian model allows for adaptive decision-making and sophisticated user profiling. This allows library systems to dynamically adjust resource recommendations, improve search result relevance, and tailor the user experience as a whole [6, 8, 9]

The general form of the Bayes method is:

$$P(C_i \mid X) = \frac{P(X \mid C_i) \cdot P(C_i)}{P(X)} \qquad (1)$$

where,

$P(C_i|X)$ – is the probability that the user belongs to category C_i given the features X;

$P(X|C_i)$ – is the likelihood of observing features X if the user belongs to category C_i;

$P(C_i)$ - is the prior probability of users belonging to category C_i;

$P(X)$ - is the overall probability of users exhibiting features X.

To predict a user's information needs, the probability calculations are based on the following user characteristics:

X_1 - genres of books read by the user;

X_2 - keywords searched by the user;

X_3 - authors searched by the user;

X_4 - topics read by the user.

If C represents user need categories (e.g., dissertations, scientific articles, theses), the probability is calculated using:

$$P(C_t \mid X_1, X_2, X_3, X_4) = \frac{P(X_1, X_2, X_3, X_4 \mid C_t) P(C_t)}{P(X_1, X_2, X_3, X_4)} \quad (2)$$

Assuming that features are independent of each other, the formula simplifies to:

$$P(C_1 \mid X_1, X_2, X_3, X_4) = \frac{P(X_1 \mid C_1) P(X_2 \mid C_1) P(X_3 \mid C_1) P(X_4 \mid C_1) P(C_1)}{P(X_1) P(X_2) P(X_3) P(X_4)}$$

(3)

Here, each feature is computed independently, simplifying the method and ensuring efficiency.

If the feature set is $X = \{x_1, x_2, \ldots, x_n\}$ then:

$$P(X|C_k) = P(x_1|C_k) \cdot P(x_2|C_k) \cdot \ldots \cdot P(x_n|C_k) \qquad (4)$$

The Bayes method calculates probabilities for each class C_k and selects the class with the highest probability as the predicted classification:

$$C_{predict} = \arg max = P(C_k|X) \qquad (5)$$

In an library information system context, a scientific researcher searching for academic papers or textbooks can be classified using the Bayes method as follows: Let

C_1 - scientific articles;

C_2 - textbook;

The user's query consists of:

x_1- scientific, x_2- article, x_3- research, x_4- news.

The classification of search results using the Bayes method is presented in Table 1.

TABLE 1 CLASSIFICATION USING THE BAYES METHOD

Keyword (user's query)	C_1 (class)	C_2 (class)
x_1	40	10
x_2	35	25
x_3	50	5
x_4	10	40
Total	135	80

The class probabilities are calculated as:

$$P(C_1) = \frac{135}{135+80} \approx 0{,}63$$
$$P(C_2) = \frac{80}{135+80} \approx 0{,}37$$

The likelihoods for each keyword given the class are computed as follows:

$$P(x_1|C_1) \approx 0{,}296$$
$$P(x_1|C_2) \approx 0{,}125$$
$$P(x_2|C_1) \approx 0{,}259$$
$$P(x_2|C_2) \approx 0{,}3125$$
$$P(x_3|C_1) \approx 0{,}370$$
$$P(x_3|C_2) \approx 0{,}0625$$
$$P(x_4|C_1) \approx 0{,}074$$
$$P(x_4|C_2) \approx 0{,}5$$

Using the Bayes method, we compute:

$$P(C_1|X) = P(C_1) \cdot P(x_1|C_1) \cdot P(x_2|C_1) \cdot P(x_3|C_1) \cdot P(x_4|C_1) \approx 0{,}0019$$

$$P(C_2|X) = P(C_2) \cdot P(x_1|C_2) \cdot P(x_2|C_2) \cdot P(x_3|C_2) \cdot P(x_4|C_2) \approx 0{,}00045$$

The query is classified under “scientific article”.

The Bayesian method is a probabilistic framework for user information need determination that follows statistical inference to analyze and categorize their queries. Such an approach fundamentally centers on computing the posterior probability that a given query corresponds to a certain category of information based on prior knowledge and observed data. Therefore, by carefully estimating the likelihood of other user intents, the Bayesian model can classify queries with reasonably high accuracy.

III. Results and Discussion

This probabilistic inference process, nevertheless, enables the system to incorporate historical user activity and contextual attributes within its decision-making. It is therefore not merely looking for keywords associated with a query but contextualizing queries within a general informational framework, enabling more subtle and useful categorization. This then offers a way of fetching highly relevant resources and can also be utilized in the development of smart, user-oriented information retrieval systems that can adapt to various and ever-changing needs of users.

Figure 1 illustrates a comprehensive information model specially made for predicting user information needs in the context of a library information system based on the ideas of Bayesian inference. The model operates via a systematic sequence of processes that begin with the systematic inspection of user-generated search queries. It proceeds to screen and retrieve the most pertinent information resources from a vast and heterogeneous digital library.

Through constant observation and interpretation of user activity, the model applies probabilistic inference to predict the likelihood of specific information needs. Through the inclusion of Bayesian inference techniques, the system can iteratively improve its predictions based on new data so that it can dynamically adapt to the changing user preferences, behaviours, and context situations of individual users [10].

Therefore, the system not only enhances the efficiency and relevance of information retrieval but also significantly increases the accuracy and individualization of resource recommendations. This dynamic approach ensures that users are presented with on-time and contextually appropriate information, hence improving the overall effectiveness of the digital library environment for meeting user needs [11].

One of the main strengths of the Bayesian classification method over other statistical and machine learning classification methods lies in its extensive computational efficiency. The Bayesian process is particularly good for large-sized information environments due to its capacity to process and analyze enormous text databases with fantastic speed and with minimal computational power.

This is because the algorithm relies on relatively simple probabilistic computation, which allows for fast training and classification even for high-dimensional data. Furthermore, the probabilistic nature of the Bayesian method to inference provides a principled approach to handling uncertainty and missing information. By making posterior probabilities dependent on prior evidence and knowledge, the model provides for sound and confident decision-making, even in challenging and dynamic information retrieval situations [12].

These properties make the Bayesian approach especially suitable for application in massive information retrieval systems, such as digital libraries, web search engines, and recommendation websites, where speed, scalability, and timely response to noisy user activities are critical to system performance and user satisfaction.

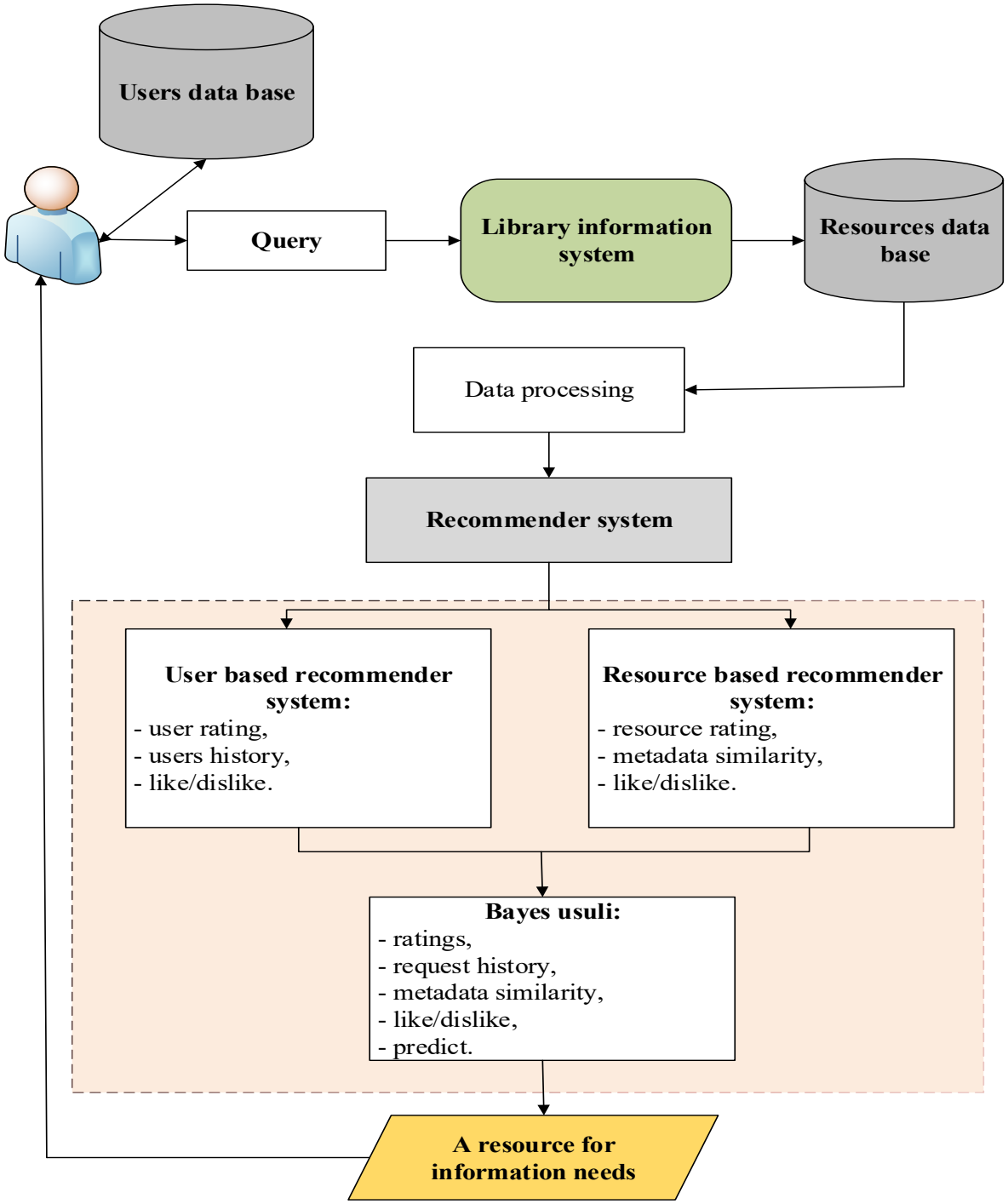


Fig. 1. An information model for identifying and recommending information needs of users in the library system.

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8586
© 2025 The Author(s). Published by RTU PRESS
This is an open-access article under the Creative Commons Attribution 4.0 International License.

IV. CONCLUSIONS

The application of Bayesian methods in library information systems significantly enhances the accuracy and efficiency of information retrieval and recommendation processes. By leveraging conditional probability principles, Bayesian models can effectively predict users' information needs based on their past search behaviors and interaction patterns. This method enables the classification of user queries with high precision, improving the personalization of content recommendations and search result relevance.

One of the key strengths of the Bayesian approach is its computational efficiency, allowing it to process large-scale datasets rapidly while maintaining high classification accuracy. The ability to independently compute features simplifies the classification process and ensures scalable implementation in library information systems environments. Furthermore, Bayesian inference dynamically adapts to changing user behaviors, making it a robust tool for optimizing information retrieval systems.

Through probabilistic modeling, the Bayesian method enhances user experiences by providing more accurate and tailored content recommendations. Its effectiveness has been demonstrated in various domains, including library information systems, e-commerce platforms, and personalized content delivery systems. Given its advantages, the Bayesian method remains a critical tool in the advancement of modern information retrieval and recommender systems, contributing to more effective and user-centered library services.

V. REFERENCES

[1] M. Condliff, D. Lewis, D. Madigan, and C. Posse, Bayesian mixed-effects models for recommender systems. ACM SIGIR Workshop on Recommender Systems: Algorithms and Evaluation, 1999

[2] W.Jin, User interest modeling and collaborative filtering algorithms application in English personalized learning resource recommendation. Soft Comput 2023. https://doi.org/10.1007/s00500-023-08700-0

[3] M. Rakhmatullaev, S. Normatov, F. Bekkamov, Fuzzy Relations Based Intelligent Information Retrieval for Digital Library Users, Environment. Technology. Resources. 14th international scientific and practical conference. June 15-16, 2023, Rezekne Academy Of Technologies, Rezekne, Latvia

[4] A.Rustamov, F.Bekkamov, Recommender systems: an overview, Scientific reports of Bukhara State University, 2021/3(85)

[5] C.Yang, Q. Fan, T. Wang et al., RepoLike: a multi-feature-based personalized recommendation approach for open-source repositories. Front Inf Technol Electron Eng 20(02):86–101, Springer 2019

[6] K. Miyahara, and M. J. Pazzani, Collaborative filtering with the simple Bayesian classifier. Pacific Rim International Conference on Artificial Intelligence, 2000

[7] F. Bekkamov, Y. Sharifov, Extended User Profiling Approaches for Recommendation Systems, Environment. Technology. Resources, 15th International Scientific and Practical Conference. June 27-28, 2024, ‘’Vasil Levski’’ National Military University, Veliko Tarnovo, Bulgaria

[8] S. Farshidi, K. Rezaee, S., Mazaheri . et al. Understanding user intent modeling for conversational recommender systems: a systematic literature review. 2024. https://doi.org/10.1007/s11257-024-09398-x

[9] S. Rendle, C. Freudenthaler, Z. Gantner, and L. Schmidt-Thieme, BPR: Bayesian personalized ranking from implicit feedback. Uncertainty in Artificial Intelligence (UAI), pp. 452–451, 2009.

[10] Ф.А. Беккамов, М.А. Рахматуллаев, Система поиска научной и образовательной информации с анализом сведений о пользователях, Информатизация образования и методика электронного обучения: цифровые технологии в образовании, Материалы VIII Международной научной конференции, 24-27 сентября 2024 г. Красноярск

[11] M. Rakhmatullaev, S, Normatov, F. Bekkamov, Tavsiya etish tizimlarining umumiy tahlili, Raqamli Transformatsiya va Sun’iy Intellekt ilmiy jurnali, Volume 1, Issue 4, December 2023

[12] T. Ha, S. Lee, Item-network-based collaborative filtering: a personalized recommendation method based on a user’s item network. Inf Process Manage 53(5):1171–1184, Springer 2017

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 43-48

Digital Tourism Marketing Channels: A Post-Covid Comparative Analysis of Consumers' Preferences

Hrisitna Boycheva
Department "Marketing and Strategic Planning
University of National and World Economy
Sofia, Bulgaria
hboycheva@unwe.bg

***Abstract* — The following article examines the post-Covid digital transformation in tourism distribution channels. Its focus is on the shift in consumers' preferences when choosing and booking a trip, because of the integration of technological innovations. The analysis includes the questions: where do consumers acquire information about the tourism products offers when choosing a destination, an accommodation and a transport mean before and after the pandemic; what are their motives for choosing a tourism product; what are the main characteristics (geographic, demographic, socio-economic, geodemographic and psychographic) of consumers that influence the decision to reserve a tourism product and how do they carry out the process of booking tourism products after the Covid-19 pandemic. Scientific research in the field of e-commerce and in tourism marketing channels over the last three years has been focused either on digital transformations in the industry or on the shift in consumers` preferences after the Covid-19 pandemic. However, there is a lack of in-depth scientific research on the post-Covid digital transformation of tourism marketing channels in Bulgaria. The significance of the topic for the EU tourism policy, for the Bulgarian tourism sector and for local authorities and destination management organizations and the gap in research on the changes in consumer preferences after the pandemic in Bulgaria gave me a reason to focus on this study.**

***Keywords* —channels, consumers, digital, marketing.**

I. INTRODUCTION

Tourism contributes significantly to European economic growth and is in the focus of several European, national and local policies. That can be explained due to its cross-sectoral economic and social dimensions and the high share of micro, small and medium-sized enterprises operating in the sector. According to the World Tourism Organization`s data, the industry generated 10% of the EU's GDP and provided around 23 million job positions in 2019. During the Covid-19 pandemic, tourism was one of the most affected sectors, because of the travel restrictions, airlines worldwide grounded their planes, while hotels, restaurants, and tourist attractions remained closed. The result was unprecedented losses (80% drop) in terms of revenue and jobs (11 million jobs) according to EC data [1].

The digitalisation of tourism marketing channels reflects changes in consumer behaviour, technological innovation and the opportunities they provide for recovery of the industry after the pandemic. Primary, digital marketing [2] channels enable tourism providers to attract consumers by creating positive image in social media, the main source for recovery [3], via influencers` recommendations, travel bloggers` feedback, customers` generated content in social media, online shared feedback (Google Local Guides, websites` users feedback, social media feedback). Social media is probably the most powerful and effective channel for tourism promotional and communication [4] channel.

Even before the COVID-19 pandemic tourism services providers put their focus on the online distribution channels and promotions [5]. But because of the travel restrictions and the lower demand that trend tent to become a key marketing tool [3] for overcoming those challenges during the pandemic [6]. So that at the post-Covid period online bookings of tourism products remain one of the main channels for reservation, chosen by the tourists, and a main source of income for the services providers. Along with that consumers` willingness to travel was also boosted by the augmented and virtual reality integrated on the tourism services providers` websites or social media channels; the easy and fast access to reliable information about destinations, transport means, accommodation and other

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8589
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

tourism services; and the flexibility of prices and dates available online, as most of the services providers rely on direct sales after the pandemic [2]. Digital marketing channels have made the booking process more customer-friendly, as tourists have 24/7 access to reservation systems from the convenience of their home or at any other location. They can easily and at no cost switch between various booking options and channels, supported by chatbots during the process.

The relevance of the topic is justified primarily by the fact that EC adopts several strategic documents, such as European Agenda for Tourism 2030, Transition Pathway for Tourism, Europe's Digital Decade, that emphasize the importance of digital innovation in tourism for building a crisis-resistant ecosystem. Furthermore, the industry recovery after COVID-19 pandemic has been boosted by the digitalization because of the tourists` changing requirements.

Scientific research in tourism marketing channels over the last three years have been focused either on digital transformations in the industry and shifts in consumer behaviour on one hand, or on the strategies that companies adopt to overcome the negative impacts of the Covid-19 pandemic at the other. However, in-depth scientific research on the post-Covid digital transformation of tourism marketing channels in Bulgaria can hardly be found. The significance of the topic for EU tourism policy, for Bulgarian tourism sector and for local authorities and destination management organizations gave me reason to focus on this study.

II. Materials and Methods

The subject of the study is the post-Covid shift in tourism product consumers` buying patterns. So that the object of the study is the tourism product consumer. For the purpose of the research qualitative data has been gathered for investigating consumers` behaviour. The qualitative research is more flexible and concentrated, prioritizing the quality and the depth of the collected data [7]. It samples specific groups and gathers meaningful data. So qualitative research has been chosen for the current study. The results of the qualitative research are developed under the statistical analysis which links what is known and what has been learned through the research. An online questionnaire was developed, and an anonymous survey was implemented to collect primary data. That method has been chosen because it is efficient, quick and not expensive, which makes the process of data collection faster and cost effective [8]. The online survey in fact is not a pure representative of the survey method, because some of its forms have specific features of the interview method (for example, the strict sequence in asking and answering the questions included in the relevant questionnaire). An important characteristic feature of the online survey is that the relationship and information exchange between surveyors and respondents are also an object of the digital transformation. The online survey has a higher degree of "perceived confidentiality" than other forms of data collection and higher "speed of fieldwork" [9]. However, the second indicator is an advantage of the online survey only in relation to other survey methods. Another advantage of the method under consideration over the other types of surveys is the low costs of its implementation [10].

In that regard, two online surveys were conducted. The first one illustrates consumers` booking patterns during the pandemic. Its timeframe is October-November 2021. A thousand respondents were selected by non-probability sampling procedure. Their demographic characteristics are diverse: women are 57,3% and 42,7% are men, divided into four age groups – 18-29 years old (16,3%), 30-39 years old (30,3%), 40-49 years old (32%) and 50-65 years old (21,4%). The post Covid online survey which was carried out in October-November 2024 and then a non-probability sampling procedure was applied among 1,000 consumers of tourism products 59,4% of who are women and 40,6% men. Respondents are distributed as follows: 18-29 years old – 17,1%, 30-39 years old 29%, 40-49 years old – 30,7%, and 50-66 years old – 23,2%. The logic and technology of the study include comparative analysis of the model of consumer behaviour when choosing and booking tourism products during and after the global pandemic. When processing quantitative data in the current article descriptive statistics and comparative analysis were envisaged while for further studies correlation analysis and regression analysis will be explored for answering the questions whether younger generations are more influenced by social media or whether the older generations rely more on the recommendations of friends and relatives or traditional media and channels. The correlation analysis will also be focused on answering the question whether there is a difference between men and women reliance on online search.

III. Results and Discussions

The first research question was "How do you prefer to book tourism products during/post Covid-19 pandemic?" and five options to choose between were given. As was expected, there is a significant drop in the number of respondents who didn't travel in 2021, as they were 24.2% and in 2024 that number decreased by 21%, as only 3% of the respondents didn`t travel. That could be explained with the pandemic travel restriction in 2020-2021 and the consumers` health concerns.

Table 1 Consumers` Preferences for Tourism Distribution Channels

How do you book tourism products during/post Covid-19 pandemic?	**Comparison**		
	2021 (during)	***2024 (post)***	***Change***
Websites for reservation	36.2%	44.1%	7.9%
Directly through tourism services providers	26.2%	38.3%	12.1%
Through travel agency	12.4%	13.8%	1.4%
I don`t travel	24.2%	3%	-21%
Other	1%	0.8%	-0.2%

As was expected, there is a significant drop in the number of respondents who didn't travel in 2021, as they

were 24.2% and in 2024 that number decreased by 21%, as only 3% of the respondents didn`t travel. That could be explained with the pandemic travel restriction in 2020-2021, the consumers` health concerns and the uncertainty due to Covid-19. Data shows that the most preferable booking channel during and post Covid-19 pandemic were the websites for reservation. 36.2% of tourists chose that channel and in 2024 an increase of 7.9% of those who preferred the websites for reservations has been registered as their number reached 441 out of 1 000. Furthermore, the highest increase (12.1%) was registered in those who book directly through tourism service providers from 26.2% in 2021 to 38.3% in 2024. Tourists who booked through travel agent were 12.4% of the respondents in 2021 and their number rose by 1.4% to reach 13.8 percent in 2024. 1% of the surveyed chose other booking channel in 2021 and 0.8% of the surveyed did the same in 2024.

When asked to specify up to 3 concreate channels used by the tourists to gather information about different components of the tourism trip the respondents in 2021 rated the channels as follows: (1) Independent online search – 69.9%, (2) Friends and relatives' recommendations – 61.7%, (3) Social media – 48.3%, (4) Tourism services providers` websites – 25.8%, (5) Travel agencies` websites – 18.1%, (6) Travel agencies` catalogues and printed advertising materials – 16.3%, (7) Tourism services providers` advertising materials – 13.6%, (8) Other – 0.8%.

TABLE 2 CONSUMERS` PREFERENCES FOR MARKETING CHANNELS FOR GATHERING INFORMATION

Marketing channel	**Comparison**		
	2021	***2024***	***Change***
Independent online search	69.9%	62.2%	- 7.7%
Friends and relatives' recommendations	61.7%	41.4%	- 20.3%
Social media	48.3%	59.1%	10.8%
Tourism services providers` websites	25.8%	28.3%	2.5%
Travel agencies` websites	18,1%	21.1%	3%
Travel agencies` catalogues and printed advertising materials	16.3%	15.7%	- 0.6%
Tourism services providers` advertising materials	13.6%	12.8%	- 0.8%
Other	0.8%	0.9%	0.1%

The results of the survey in 2021 show that the highest percentage of respondents (69.9%) gather information independently online, using Google and various types of websites/travel blogs – Booking, Trivago. Recommendations from friends/relatives were ranked as the second most powerful promotion channel when choosing tourism products with 61.7%. In third place respondents put social media (48.3%). Direct search at tourism services providers` websites acquired 25.8% of consumers followed by the online channels of travel agency (18.1%). Aligned with the global trends lower percentage of respondents use catalogues and printed advertising materials of travel agencies for information when choosing tourism products – 16.3%, followed by 13.6% of respondents who use catalogues and advertising materials of hoteliers/transport companies and 0/8% chose other channels, not listed above.

The ratio between the above channels illustrates that post Covid-19 pandemic consumers` preferences are mainly for digital channels when gathering information for future travel and the online channels play a powerful role when choosing tourism products, as the results of the consumers` survey in 2024 are the following: (1) Independent online search – 62.2%, (2) Social media – 59.1%, (3) Friends and relatives' recommendations – 41.4%, (4) Tourism services providers` websites – 28.3%, (5) Travel agencies` websites – 21.1%, (6) Travel agencies` catalogues and printed advertising materials – 15.7%, (7) Tourism services providers` advertising materials – 12.8%, (8) Other – 0.9%.

Data proves that after the pandemic consumers moved to more digitalized channels when they choose tourism products with the social media channels becoming more influential for the tourists` behaviour. That can be explained with all the options provided by digital marketing channels for comparing products, prices, tourism packages, the variety of promotions and deals online, the accessibility of the information (24/7 at any location), the feedback provided online and the influencers` recommendations reshaping consumers` preferences.

Tourism products consumers` buying patterns are associated with the booking process. In 2021 during the Covid-19 pandemic 85.4% of tourists chose websites or mobile apps for reservations, such as Booking, Esky, Trivago, for their bookings. That percentage increased to 91% in 2024 which makes the websites for reservations the main distribution channel for tourism products. The second-place ranked booking channel are the websites and mobile apps of the tourism services providers – 45.3% of the respondents preferred that channel in 2021 which is 12.1% lower than the percentage of those who booked through the same channel in 2024 (57.4%). Tourists who made their reservations through websites or mobile apps of travel agencies represent 38% of the surveyed in 2021 which had 3.4% increase in similar bookings in 2024 (preferred by 41.4% of the respondents). In contrast 19.4% of tourism products consumers preferred to reserve such services at travel agents` offices in 2021. Their number decreased in the following years to reach 14.7% in 2024. Those who didn't choose digital channels in 2021, booked on the phone call with a tourism services supplier or a tourism agent, were respectively 17.6% and 14.6%.

The data in Table 3 can be related to the digital marketing channels preferred by the respondents to choose tourism products. Consumers had the opportunity to search tourism offers online and compare tourism products elements, prices and promotions, afterwards tourists can easily contact the selected providers and reserve by phone call.

As a consequence of the pandemic there was higher uncertainty related to travel and that can explain why consumers preferred more personal customer service

because it provides higher security and reliability of the reservation. In the next 3 years due to the higher extent of digitalization of the tourism marketing channels, such as virtual and augmented reality, contactless check-in and checkout processes and the chatbot options integrated on the companies` websites or mobile apps led to decrease in the number of tourists who book tourism products on the phone. In 2024 13.2% and 11.7% respectively reserved their trip on phone call with a service provider or a travel agency. The less preferable distribution channels are the offices of the tourism products providers. They accounted for 7.5% in 2021 and 6.9% in 2024. That can be easily explained by the nature of tourism as is related to the movement of people from their usual environment. So, it is the territorial distance between tourism services providers and the consumers that makes the direct offices bookings less accessible for the consumers.

Analysing the data of the surveys, some general trends related to the reservation process of tourism products can be highlighted. The respondents were asked how they prefer to book tourism products and multiple answers were accepted. In that regard an accumulative percentage of 72 tourists preferred indirect distribution channels and chose tourism agencies` services, compared to 155.8% who reserved their travel on their own in 2021. That trend was stable in the next few years and in 2024 travel agents were even less preferable, as they gain 67.8% of consumers` preferences which is a 5.8% decrease. In contrast there was a 12.7% increase of the tourists who organized their travel individually in 2024 – gaining 168.5% of the multiple answers. After the pandemic tourism consumers prefer to book different components of their travel by themselves, although travel agencies still acquire a significant percentage of the reservations, they tend to be a less preferable distribution channel.

TABLE 3 CONSUMERS` PREFERENCES FOR TOURISM DISTRIBUTION CHANNEL

Consumers` preferences for tourism distribution channels	**Comparison**		
	2021	***2024***	***Change***
Platform for reservations (Booking, Esky, Trivago)	62,5%	63.8%	1.3%
Mobile app for reservations	22,9%	27.2%	4.3%
Tourism services providers` website	31,3%	38%	6.7%
Tourism services provider`s mobile app	14%	19.4%	5.4%
On phone calls with a hotelier or a transport company	17,6%	13.2%	-4.4%
At tourism services providers` offices	7,5%	6.9%	- 0.6%
Travel agent website	30%	33.7%	3.7%
Travel agent`s mobile app	8%	7.7%	- 0.3
At tourism agencies` offices	19,4%	14.7%	- 4.7%
On phone call with travel agent	14,6%	11.7%	- 2.9%

Furthermore, the data can be arranged according to consumers` preferences for direct and indirect distribution channels. The ratio illustrates that indirect booking channels are twice preferable by the consumers than direct reservation channels. Along with that it can be concluded that websites, as a reservation channel, are three times preferable than the mobile apps of the same organisations. Traditional distribution channels in tourism are rarely preferable by the consumers and the percentage of those willing to choose them for reservation is decreasing in the years after the pandemic.

Considering consumers` preferences for marketing channels when choosing and booking tourism products the platforms for reservation can be accepted for the most powerful channel for increasing sales for the Bulgarian tourism market. Because of that the current study identifies the most preferable platforms used by the tourist.

Table 4 illustrates that Booking.com is the most preferable reservation channel among the Bulgarian tourism products consumers. It acquires almost 60% of the preferences while all the other options gain less than 40%. Tourists ranked global platforms for reservations on the first three places – 1) Booking, 2) Airbnb and 3) Trivago. Consumers` preferences for those channels registered a slight increase during the studied period. In 2021 Esky is ranked on the fourth place but fell one position to number five in 2024. Esky is the only one platform which is specialized in offering airplane tickets while all the others are used for accommodation bookings. In 2021 the website for discounts and offers Grabo was ranked at fifth place but in 2024 it gained 1.3% more of the consumers` preferences and went ahead Esky. Pochivka.bg is a Bulgarian website offering accommodation services primary by citizens, apart hotels or guest houses (micro and small tourism services providers). While in 2021 6% of the respondents didn`t use platforms for reservations, in 2024 that percentage decreased to 4.4%.

TABLE 4 PLATFORMS FOR RESERVATION

Most preferable platforms for booking tourism products	**Comparison**	
	2021	***2024***
Booking	58,4%	59.1%
Airbnb	16,7%	17.2%
Trivago	6,8%	7.4%
Esky	6,1%	4.2%
Grabo	3,8%	5.1%
Pochvka.bg	1,2%	1.9%
Other	1,0%	0.7%
I don`t use platforms for reservations	6,0%	4.4%

In both surveys tourism products consumers were asked about their own perceptions related to the impact of Covid-19 pandemic on the digitalization of the tourism industry. In 2021 84.3% of the respondents considered that digital transformation in tourism was fastened during the

pandemic, as 23.6% of the tourists completely agreed and 60.7% agreed. In contrast 11.8% disagreed and 3.9% completely disagreed. As a comparison in 2024 the respondents who thought that Covid-19 pandemic made tourism industry more digitalized were 92.4%, with 38.9% completely agreed which is a significant raise (15.3%), 53.5% agreed while those who disagreed were 6.4% and 1.2% completely disagreed with the above statement.

Bulgarian consumers of tourism products have increased their thrust into online reservation. Only 21% prefer to book on the phone or at tourism companies` offices because of lack of thrust into digital channels (7% completely agreed and 14% agreed). While in 2021 the percentage of those who didn`t thrust, online reservation was 30.8% – with 8.8% completely agreed and 22% agreed. The increased thrust can be seen into the raise of those who completely don`t agreed with the statement by 6.4%, as seen below in Table 5.

IV. Conclusions

Bulgarian economy faces several challenges related to the inflation rate, low income, poor infrastructure, lack of digital innovation and high dependence of certain sectors one of which is tourism. While being a main source of employment and income tourism sector in Bulgaria suffers to align tourism offers with consumers` preferences in an effective manner. So that what is important is how the pandemic changed the buying behaviour as it contributed for the technology adoption in Bulgaria. Namely, Covid-19 pandemic fostered the digitalization in tourism industry, as it did in many other industries across the country. Consumers constantly moved towards digital booking channels as it can be seen by the above analysis but the tourism services providers fall behind adopting technological advancements because of lack of finance and digital innovation capacity. The findings of the study have the potential to enable tourism services providers to concentrate their efforts on certain communication and reservation channels while minimizing their cost and maximizing the profits by adequate price policy and higher compliance with the consumers` preferences.

Table 5 Consumers Thrust into Online Reservations

I don`t thrust online reservations and I prefer to book on the phone or at tourism companies` offices	**Distribution of respondents**			
	Completely agree	***Agree***	***Disagree***	***Completely disagree***
2021	8.8%	22%	40.9%	28.3%
2024	7%	14%	44.3%	34.7%

Bulgarian tourism supply must embrace technological advancement as there is a permanent shift towards online channels. Covid-19 pandemic fastened digital transformation of Bulgarian tourism industry by reshaping consumers` preferences. The comparative analysis shows that tourists are more willing to choose and book tourism products on their own through digital marketing channels. Another trend is that indirect bookings are far preferable than direct ones. Online reservation platforms are the most preferable marketing channel for Bulgarian tourist with Booking being the most favourable channel.

It can be assumed that services providers need to consider and benefit by offering their products at online platforms because of their wider reach and lower costs. Along with that they have to contact promotional offers (Grabo) and national reservation platforms (Pochivka.bg) to address consumers preferences.

While online indirect channels are main booking channel, there are still consumers who do not prefer to book through digital channels, so that services providers must invest and continue to operate traditional distribution channels.

Tourism services providers will more effectively reach their customers if using social media (Facebook and Instagram) for influencing and inspiring their travel behaviour. Along with that sufficient amount and efforts need to be put in SEO optimization of tourism suppliers own websites, content creation, Google and Meta Ads.

One of the limitations of the current study is the lack of theoretical framework. It will be overcome by future study by implementing Technology Acceptance Model (TAM) for understanding tourism consumers` motivation and their trust in digital marketing channels.

References

[1] European Comision, “Tourism industries – employment”, Eurostat, 2024. [Online]. Available: http://https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Tourism_industries_-_employment. [Accessed: Feb. 17, 2025].

[2] E. M. Sánchez-Teba, J. García-Mestanza and M. Rodríguez-Fernández, “The Application of the Inbound Marketing Strategy on Costa del Sol Planning & Tourism Board. Lessons for Post-COVID-19 Revival,” Sustainability, vol. 12, no. 9926, p. 1+, November 2020. [Online]. Available: ResearchGate, https://www.researchgate.net/publication/347212382_The_Application_of_the_Inbound_Marketing_Strategy_on_Costa_del_Sol_Planning_Tourism_Board_Lessons_for_Post-COVID-19_Revival#fullTextFileContent [Accessed Feb 11, 2025], https://doi.org/10.3390/su12239926.

[3] S. Nunes and P. Cooke, “New global tourism innovation in a post-coronavirus era,” Eur. Plan. Stud., vol. 29, pp. 1-19, 2020.

[4] D. R. Toubes, N. A. Vila and J. A. Fraiz Brea, “Changes in Consumption Patterns and Tourist Promotion after the COVID-19 Pandemic,” J. Theor. Appl. Electron. Commer. Res., vol. 16, no. 5, p. 1332+, April 2021. [Online]. Available: MPDI, https://www.mdpi.com/0718-1876/16/5/75 [Accessed Jan 30, 2025], https://doi.org/10.3390/jtaer16050075.

[5] Q. Liu, X. Zhang, S. Huang, L. Zhang and Y. Zhao, “Exploring consumers’ buying behavior in a large online promotion activity: The role of psychological distance and involvement,” J. Theor. Appl. Electron. Commer. Res., vol. 15, no. 1, p. 66+, January 2020. [Online]. Available:

ResearchGate, https://www.researchgate.net/publication/333609550_Exploring_Consumers'_Buying_Behavior_in_a_Large_Online_Promotion_Activity_The_Role_of_Psychological_Distance_and_Involvement [Accessed Feb 2, 2025], DOI: 10.4067/S0718-18762020000100106.

[6] A. Gruzd, "Tenure and promotion in the age of online social media," Proc. Am. Soc. Inf. Sci. Technol., vol. 48, pp. 1-9, 2011.

[7] F. Anyan, "The Influence of Power Shifts in Data Collection and Analysis Stages: A Focus on Qualitative Research Interview," Qual. Rep. vol. 18, p. 36, 2013.

[8] J. A. Holstein and J. F. Gubrium, "Context: Working it Up, Down, and Across," in Qualitative Research Practice, Sage Publication: London, 2004; pp. 297–311.

[9] K. Nunkoosing, "The problems with interviews," Qual. Health Res., vol 15, pp. 698-706, 2005.

[10] S. B. Merriam, Qualitative Research: A Guide to Design and Implementation, Josseybass: San Francisco, 2009, pp. 27-34.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 49-55

Analysis of User Satisfaction of Academic Digital Libraries: A case of Uzbekistan

Sarvinoz Berdibekova
Library information systems department Tashkent University of Information Technologies named after Muhammad al-Khwarizmi
Tashkent, Uzbekistan
sarvinozberdibekova@gmail.com

Sherbek Normatov
Library information systems department Tashkent University of Information Technologies named after Muhammad al-Khwarizmi
Tashkent, Uzbekistan
shb.normatov@gmail.com

Dildora Juraeva
Computers systems Department Tashkent University of Information Technologies named after Muhammad al-Khwarizmi
Tashkent, Uzbekistan
jdildora19@gmail.com

Mehriniso Qudratova
Information library systems department Tashkent University of Information Technologies named after Muhammad al-Khwarizmi
Tashkent, Uzbekistan
qudratovamehr@gmail.com

Laylo Sayfieva
Library information systems department Tashkent University of Information Technologies named after Muhammad al-Khwarizmi
Tashkent, Uzbekistan
sayfiyevalaylo05@gmail.com

***Abstract*—This study was conducted to examine user satisfaction with academic digital libraries in Uzbekistan. A survey was carried out among academic users from various higher education institutions, including students and faculty members. The survey aimed to identify key factors such as information quality, system usability, service efficiency, and the availability of digital resources. The results indicated that the majority of users consider academic digital libraries beneficial for research and study purposes, with high ratings for accessibility and resource diversity. However, certain shortcomings were identified, particularly in system navigation and technical support services, which require improvements. The study highlights the necessity of continuous development in digital library infrastructure to enhance user experience. These findings provide valuable insights for policymakers and educational institutions striving to improve digital library services in Uzbekistan.**

Keywords— ***Academic Libraries, Digital Libraries, Information Quality, Library Services, Library Resources, User Satisfaction, System Quality, Service Quality, UniLibrary system.***

I. INTRODUCTION

Today, libraries have become not only a place to provide information resources, but also innovative centers that provide services to users through modern technologies. The level of user satisfaction with an academic digital library is a key factor affecting the effectiveness and long-term success of libraries. A digital library provides services and opportunities aimed at ensuring the information needs of its users, including availability, resource quality, and ease of use of the system. Measuring user satisfaction is a key way to obtain important data for continuous improvement and development of user-oriented services. The development of information management technologies and information systems has led to significant changes in the educational environment and the library system. In Uzbekistan, academic digital libraries are increasingly integrated into higher education institutions in order to improve the scientific and pedagogical experience.

Understanding user interaction with the system and their satisfaction with library services helps to identify areas where service quality needs to be improved. Samadi et al. also emphasized the need to evaluate the effectiveness of digital libraries through user interaction and satisfaction. A study conducted at the University of Tehran identified information quality, system quality, and service quality as important factors that directly affect user satisfaction [1]. Meanwhile, a study conducted by Nordin et al. evaluated the effectiveness of digital reference services in university libraries and found that user satisfaction is directly related to service quality. Their findings highlight the importance of library services being responsive, having good communication skills, and providing services that meet user expectation [2]. Furthermore, a study conducted by Norizan Anvar et al. focused on how the user experience (UX) of library

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8583
© 2025 The Author(s). Published by RTU PRESS
This is an open access article under the Creative Commons Attribution 4.0 International License.

websites affects the effectiveness of digital libraries. The results of the study indicate that users' experience with a digital library website is directly related to its usability, ease of use, and overall value [3]. Pratiwi et al. used the System Usability Scale (SUS) to assess the usability and effectiveness of information systems in digital libraries. Their study found that the INLISLite digital library system was moderately usable and some users had difficulty using the system. The results of this study confirmed the importance of improving usability and user satisfaction for digital libraries [4].

User satisfaction assessment is important for optimizing digital library services and meeting the needs of academic users. A study by Bopape et al. found that researchers in public libraries in the Limpopo province of South Africa found that they should regularly assess user needs and adjust services accordingly. This finding is consistent with the trend in modern academic digital libraries, where user needs assessment is important for improving service quality [5]. The study conducted by Kishor and Bhakt also emphasized the need to study the information needs of library users and provide them with appropriate services. The results of the study show that the methods of searching for information by library users depend on their level of education, specialization and access to technology. It is also noted that increasing the level of information access of users is important for effective use of electronic library resources and services [6].

There are also a number of other studies investigating factors that influence user satisfaction in academic libraries. Emmanuel Baffour Gyau et al. assessed user satisfaction at Jiangsu University Library and found that users were highly satisfied with the library's support for teaching and research, how users were treated, and the overall quality of service. These results can help academic libraries improve their service quality and increase user satisfaction [7]. In a 2020 study, N. Soltani-Nejad and colleagues developed a model to identify factors that influence user satisfaction with digital libraries. The study found that ease of use of a digital library and the quality of digital resources are key factors in user satisfaction. Greater satisfaction leads to greater engagement, including recommending the library to others and reusing it. In addition, system quality, service quality, and information quality play a crucial role in shaping users' perceptions and attitudes toward digital libraries [8]. Mra Kadir et al. focused on improving the effectiveness of digital library services used by university students in 2023. They developed an empirical model to examine the relationships between information quality, system quality, service quality, and digital library collections with student satisfaction. Mediating factors such as perceived usefulness and ease of use were included to test their effects on user satisfaction. Their study highlights the importance of these factors in improving digital library services [9]. Jeong Hyun-chun and colleagues identified 18 non-contact services in academic libraries in Korea and categorized them as supported information access, supported learning and research, and supported support opportunities. This study identified five key factors for improving non-contact services. Convenience, responsiveness, security, reliability, and personalization. They found that reliability affects satisfaction with research support, but convenience and reliability are key when accessing information and learning support [10]. Nur Azima Azib et al. found that system quality and service quality are the most influential factors on user satisfaction. They suggested that libraries improve these aspects to improve user experience [11].

V.V.K.Suryanarayana Merti in his study recommended conducting regular orientation sessions to provide students with detailed information about library services and resources and conducting frequent in-house trainings for library staff [12]. Zakaria Abkari in his study noted that there are serious shortcomings in the library of Nar-Bit University, such as excessive noise and outdated textbooks, which negatively affect the study and research activities of students. He suggested updating the library collection with the latest textbooks, improving the electronic library, and reducing furniture and noise to increase efficiency [13]. Rahmatullaev M. suggested that in today's information-rich environment, where it is necessary to determine the information needs of users based on many parameters, fuzzy modeling is a practical way to work with expert knowledge. This helps to identify more structured needs of users and makes library services more effective [14].

II. MATERIALS AND METHODS

The main objective of this study was to analyze the level of user satisfaction with academic digital libraries in Uzbekistan.

The specific objectives of the study are as follows:

a) To analyze and assess the level of use of digital library services among university students and staff.

b) To identify factors affecting user satisfaction with available digital resources and services.

c) To study the frequency and preferences of digital library users in higher education institutions in Uzbekistan.

The study used a survey method to collect data from a diverse group of participants, including undergraduate students, graduate students, teaching assistants, senior lecturers, associate professors, and professors. The study involved 54 participants, which provided valuable information about user satisfaction and patterns of use of digital libraries in academic settings.

The survey included the following questions:

- What is your age?
- What is your gender?

- What is your academic degree?
- For what purposes do you use the library?
- What types of resources do you usually use in the electronic library?
- Does the collection of the library at your institution satisfy your information needs?
- How do you evaluate the service quality provided by traditional library staff?
- Is the working schedule of the library at your institution convenient for you?
- What are your thoughts on the electronic resources and online services available in the library at your institution?
- What new services or resources would you like to be added to the library at your institution?

III. RESULTS AND DISCUSSION

This section analyzes the factors influencing user satisfaction of university digital libraries. The study results are based on the respondents' experiences, highlighting their preferences and problems when using digital resources. In addition, users' opinions on library services are summarized and recommendations are given to eliminate existing shortcomings.

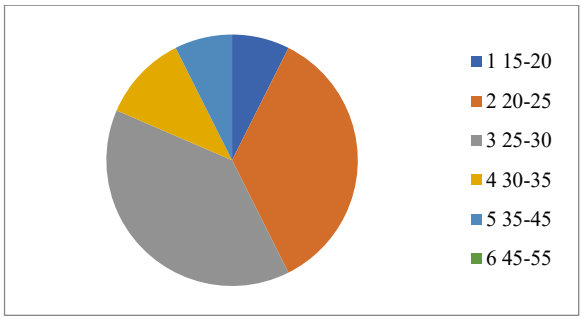


Fig. 1. Age Distribution of the Respondents.

Fig. 1 presents the age distribution of the respondents. The majority of the participants fall within the 25-30 age group, representing 38.9% of the total respondents. The second largest group consists of individuals aged 20-25, accounting for 35.2%. The 30-35 age group follows with 11.1% of the respondents. Both the 15-20 and 35-45 age categories contribute equally, each representing 7.4%. Notably, no respondents fall within the 45-55 age range. Overall, the data indicates that the sample is predominantly composed of younger adults, with the highest concentration in the 25-30 age bracket. The majority of the participants are female, accounting for 75.9% of the total sample, whereas males make up only 24.1% of the respondents.

Fig. 2 illustrates the academic degree categories of the respondents. The largest group consists of undergraduate students, making up 46.3% (25) of the total sample. Master's students and senior lecturers each account for 16.7%, sharing the second-largest representation. PhD students make up 9.3%, while associate professors represent 5.6% of the respondents. Assistant lecturers contribute 3.7%, and the smallest group is professors, comprising only 1.9%. Overall, the data indicates a higher participation from students, particularly undergraduates, compared to faculty members and senior academic staff.

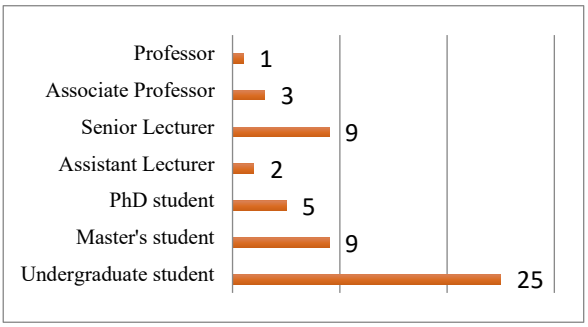


Fig. 2. Academic Degree Categories of the Respondents.

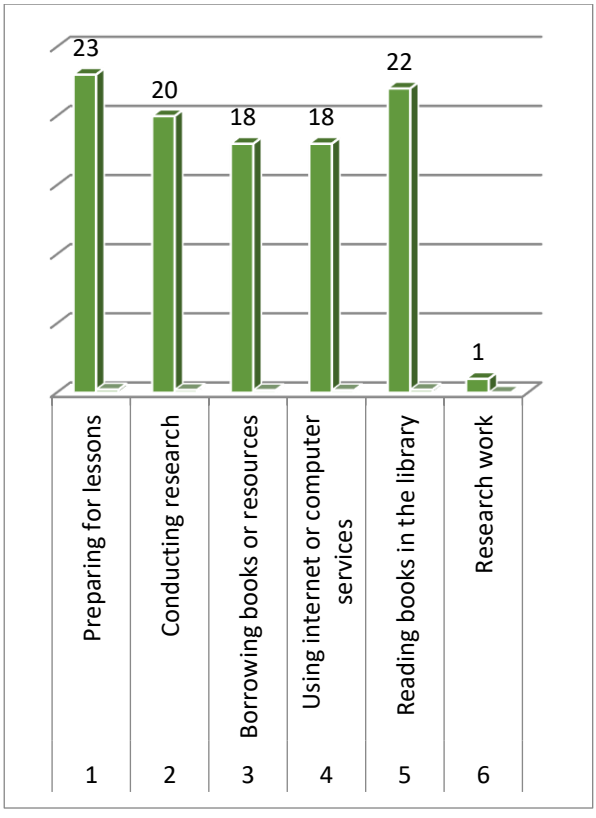


Fig. 3. Purpose of visits to Library.

Fig. 3 shows the distribution of purposes for library visits among respondents. The most common reason for visiting the library is preparing for lessons, accounting for 22.55% (23) of the total responses. Conducting research follows closely with 19.61% of the respondents.

Both borrowing books or resources and using internet or computer services are tied, each representing 17.65% of the total. Reading books in the library is another prominent reason, making up 21.57% of the responses. Lastly, only 0.98% of the respondents visit the library specifically for research work. Overall, the data reveals that the majority of respondents visit the library for academic and educational purposes, with the highest focus on lesson preparation and research activities.

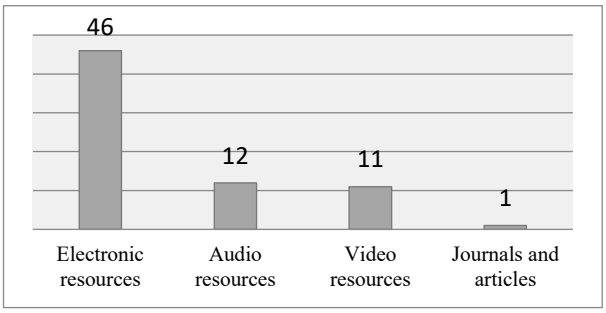


Fig. 4. Using e-library resources of the Respondents.

Fig. 4 shows the distribution of use of electronic library resources among respondents. According to it, the most frequently used resource is electronic resources, accounting for 65.71% (46) of the total responses. Electronic resources include e-books, scientific articles, digital publications and other information materials, and these resources are considered the most effective and convenient among users. Audio resources are used by 17.14% of respondents. These resources include audiobooks or other information materials in audio format, and they are mainly suitable for users who prefer to read or listen. Video resources are used by 15.71% of respondents. These resources include video tutorials or scientific videos and are useful for users who want to gain knowledge through reading or watching. Only 1.43% of respondents who are familiar with journals and articles use them as electronic library resources. These resources may be necessary for scientific research or special studies, but they are less in demand among general users. Thus, electronic resources are the most popular in library use, while other resources (audio, video, magazines, and articles) are used less frequently.

Also, when asked the question "Does the literature in the library of the institution where you study or work meet your needs?", 53.7% of respondents answered "Yes", indicating that the literature in the library fully meets their information needs. This means that the books, scientific articles, magazines and other resources in the library provide sufficient and necessary information for users. Respondents consider library resources to be useful for scientific research, reading and other purposes. 35.2% of respondents answered "No", indicating that the library does not fully meet their needs. These users do not consider the resources available in the library to be sufficient and believe that there is no information or literature they need. Perhaps these users are unable to find additional materials, new publications or specialized literature in the library for their special research or study. 11.1% of respondents chose the "I do not know" option, indicating uncertainty. This group of users could not express a clear opinion about the literature in the library. This probably refers to users who use the library resources less or do not have a clear idea of how they can meet their needs. In general, these data show that the majority of respondents consider the library collection to be adequate for their needs, that is, they believe that they can obtain the information they need through the resources available in the library. However, a significant part, namely 35.2% of respondents, do not consider the library collection to be sufficient and they could not find the necessary literature in the library. At the same time, these results indicate the need to develop the library collection and adapt its resources to the needs of users. The data also indicate that the library resources need to be updated or expanded to cover unmet needs.

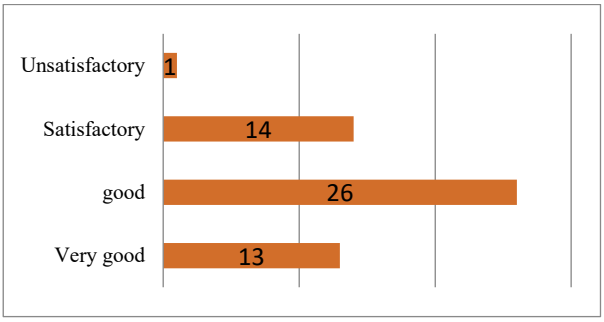


Fig. 5. Respondents' evaluation of the service quality of traditional library staff.

Fig. 5 shows respondents' ratings of the quality of services provided by traditional library staff. 48.1% (26) of respondents rated the service provided by library staff as "good". This indicates that most users are satisfied with the services provided by the library and consider them to be of good quality. High ratings of service quality indicate that the service is efficient, helpful to users, and appropriate. 24.1% of respondents described the service as "very good". These users rate the library services as of high quality and are completely satisfied with the services. This means that the library staff is meeting the needs of the users perfectly and providing a high level of service quality. 25.9% of respondents rated the service as "satisfactory". Users in this group are satisfied with the quality of library services, but they see some shortcomings or areas that need improvement in the service. They believe that some aspects of library services can be improved or expanded. 1.9% of respondents considered the service to be "unsatisfactory". This small group of users are not at all satisfied with library services and they believe that the quality of library services is very low or does not fully meet their needs. Overall, these data show that the majority of respondents are satisfied with the services provided by library staff. Most of them rated the quality of service as "good" or

"very good", which indicates that the library's service system is working effectively and is satisfactory for users. Also, some respondents rated the service as "satisfactory", which also indicates that the quality of services can be improved. Only a small part, namely 1.9% of respondents, consider library services to be "unsatisfactory", which indicates the need to improve library services.

When asked "Are the library hours of the institution where you study or work convenient for you?", the majority of respondents, 81.5%, considered the library's working hours convenient. This indicates that most users find the library's working hours convenient for their needs and they can find a convenient time to use the library. However, 18.5% of respondents rated the library's working hours as inconvenient. Users in this group said that the library's working hours did not fit their schedule or were not convenient for them. They indicated that additional time or flexible working hours were required to fully utilize library services. Overall, the data shows that the majority of respondents are satisfied with the library's working hours, which means that the library's working hours are comprehensive and flexible for users. Although a small proportion, 18.5% of users, expressed dissatisfaction with the library's working hours, this situation indicates the need to further optimize the library's working hours system.

Fig. 6 depicts respondents' opinions on electronic resources and online services. 44.4% (24) of respondents rated electronic resources and online services as "Good". This indicator shows that the majority of library users are satisfied with these services. A "Good" rating indicates a positive opinion that the quality of services meets the needs of users and is provided as intended. 29.6% of respondents rated the services as "satisfactory". These users consider the library services to be satisfactory, but note that some aspects need to be improved. Such users probably feel that some features or the convenience of the services need to be improved. 16.7% of respondents rated the services as "excellent". Users in this group rate the library resources and online services at the highest level and state that they are completely satisfied with them. This indicator shows that the library provides the highest quality of services. 5.6% of respondents rated the services as "unsatisfactory", indicating that this subgroup is not fully satisfied with the quality of the library's services. They note significant shortcomings in the services or their failure to meet the needs of users. 1.9% of respondents rated the services as "very poor". Users in this group consider the library services to be of very low quality and see a need to improve the services. Overall, these data show that the majority of respondents have a positive opinion of electronic resources and online services. Most users rated the services as "Good" or "Satisfactory". However, some users were dissatisfied with these services, noting that there is a need to improve the quality and adapt the services to the needs of users.

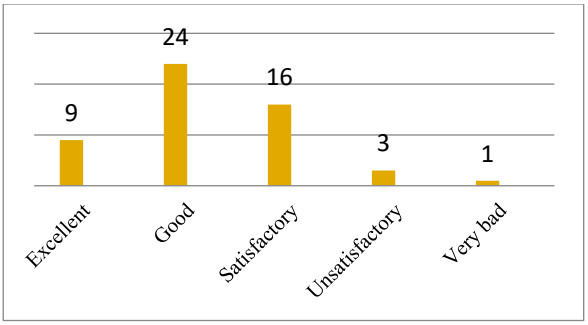


Fig. 6. Respondents' opinions on electronic resources and online services

In addition, in response to the question of what new services or resources they would like to see, added to the library of their institution, users have expressed many offers. The most common requests were to increase the availability of electronic literature, organize training sessions on subscribing to and using scientific databases, create a special area for scientific researchers, provide access to an international digital library, introduce advanced search services, introduce modern information and library services, develop a recommendation system, expand the collection of foreign scientific literature, etc.

The survey results provide valuable information about the current state of academic digital libraries in Uzbekistan and user satisfaction with their services. The results show that although the majority of users are satisfied with the availability of electronic resources, there is still significant room for improvement. The main factors affecting user satisfaction include the use of digital materials, the quality of services provided by library staff, the ease of use of the system, and the convenience of working hours. One of the most important conclusions is that most respondents consider e-resources to be extremely useful, with 65.71% often using e-books, articles, and other digital materials. However, a significant proportion of users expressed concerns about the availability of certain scientific databases and access to the most current foreign literature, suggesting that even when digital libraries offer a wide range of materials, their collections may not fully meet the research and teaching needs of all users. By expanding access to international digital libraries and expanding subscriptions that are considered scientific databases, solving this issue will significantly improve user satisfaction.

Furthermore, this study highlights the importance of training sessions to improve digital literacy among students and teachers. Many respondents suggested holding seminars and workshops to teach users how to effectively navigate digital library resources, use search tools, and access scholarly databases on a subscription basis. Such efforts could narrow the gap between

available resources and users' ability to use them effectively.

Another important aspect that respondents discuss is the need for advanced research services and recommendation systems. Many academic digital libraries in Uzbekistan are still based on basic research capabilities and do not always produce effective and relevant results. Implementing AI-based search algorithms and personalized recommendation systems can provide more accurate and targeted information, significantly improving user experience.

The survey also identified issues related to the library environment and facilities. While many users expressed satisfaction with the opening hours and quality of services provided by existing library staff, some suggested improvements such as dedicated study areas for researchers, better noise control, and improved research facilities. Creating dedicated research spaces and providing a more conducive environment for research can meet the needs of graduate students and faculty who require a calm and professional environment. Finally, respondents emphasized the importance of modernizing library services in line with international standards. The introduction of innovative library technologies, such as artificial intelligence-based cataloging, real-time support chatbots, and mobile-enabled digital library platforms, can further optimize the accessibility of library resources.

Overall, this study shows the need to further improve digital library services in Uzbekistan. Although users perceive the benefits of academic digital libraries, addressing identified challenges such as limited access to academic databases, the need for study sessions, enhanced search capabilities, dedicated research areas, and streamlining of services would significantly improve user satisfaction and the overall effectiveness of digital libraries. By introducing these recommendations, universities and university establishments may ensure that their digital libraries remain precious and relevant in the development landscape in development. In addition, the Unilibrary system is a platform for a digital library implemented in higher education establishments in Uzbekistan. This system is intended to provide students and teachers with access to various academic resources, supporting both training and scientific research. Academic digital libraries in Uzbekistan are always at the development stage concerning the implementation of user satisfaction mechanisms. Although the UniLibrary system offers essential services and resources to meet user needs, there are currently no structured mechanisms, such as surveys or questionnaires, to evaluate user satisfaction. Therefore, introducing such mechanisms would be crucial for further improving the system and gaining a better understanding of user demands.

IV. CONCLUSION

This study examined user satisfaction with academic digital libraries in Uzbekistan, analyzing awareness, usage, and key influencing factors. The results show that while most users appreciate the availability of digital resources, there are significant challenges with resource availability, service quality, and use of library systems. Most respondents expressed a need for more electronic literature, improved access to scholarly databases, and training in the use of digital resources. In addition, users emphasized the importance of improving library services, including the introduction of advanced search tools, modern recommendation systems, and specialized research platforms. Based on the results, the following recommendations were proposed to improve the efficiency of the academic digital library of Uzbekistan and increase user satisfaction:

a) Expand digital resources - increase the availability of electronic books, journals, and research articles to meet the diverse needs of students, faculty, and researchers.

b) Subscribe to international databases to access high-performance global research to support academic activities and improve research outcomes.

c) Training and seminars. We will organize regular training, webinars and seminars on the effective use of digital library services and research resources.

d) An advanced research system and recommendations to provide artificial intelligence-based research tools and personalized recommendations to improve the efficiency of information retrieval.

e) Dedicated research spaces - creating library specialties so that academic researchers can do their work in a resource-rich environment to achieve their goals.

f) Improve library service. Improved user experience, including more responsive library staff, extended opening hours and simplified billing and login processes.

g) Integration with global digital libraries. We will strengthen partnerships with international digital libraries to ensure wider access to high-quality research materials.

h) Improve user-centered services – Regularly evaluate user feedback to optimize the functionality of the digital library and ensure that services meet the changing needs of academic users.

Implementation of these recommendations will help enhance the role of academic digital libraries in supporting education and research in Uzbekistan. A digital library that addresses existing problems and includes improvements for users can be more effective, accessible, and valuable to the university community.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my university and faculty members for their continuous support and guidance throughout my studies, especially to my supervisor, Mr. Normatov Sh. B., whose valuable insights, encouragement, and constructive feedback were given to me during this research. I would also like to thank my classmates and friends for their help and

motivation, which made the research process more enjoyable and manageable.

REFERENCES

[1] Samadi and M. N. Masrek, "Evaluating digital library effectiveness: A survey at University of Tehran," in *2013 International Conference on Advanced Computer Science Applications and Technologies*, Dec. 2013, pp. 80–84.

[2] S. K. Nordin, N. A. Kassim, and K. Baharuddin, "Evaluating digital reference service in university libraries," in *2012 IEEE Symposium on Business, Engineering and Industrial Applications*, Sep. 2012, pp. 202–206.

[3] N. Anwar, E. Rahmandita, and Y. Kurniawan, "User Experience (UX): A comparative study between public and private institution library website in Indonesia and Malaysia," in *2022 8th International HCI and UX Conference in Indonesia (CHIuXiD)*, vol. 1, Nov. 2022, pp. 82–87.

[4] P. Y. Pratiwi, I. M. A. Pradnyana, and N. K. W. Damayanti, "Usability analysis on digital library information system using System Usability Scale (SUS)," in *2023 International Conference on Electrical and Information Technology (IEIT)*, Sep. 2023, pp. 293–298.

[5] S. Bopape, M. M. Mahlatji, M. Dikotla, M. Ntsala, and L. Makgahlela, "Identifying the information needs of public library and information services users in Limpopo province," *South African Journal of Libraries and Information Science*, vol. 83, no. 1, pp. 1–10, 2017.

[6] N.Kishor and V. U. Bhakt, "Changing scenario of information needs of library users with special reference to Women B.Ed institutions in Jhunjhunu City," *International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)*, vol. 3, no. 1, pp. 88–93, 2023. doi: 10.48175/IJARSCT-9013.

[7] E. B. Gyau, J. Liu, and O. Kwakye, "Evaluation of user satisfaction with academic libraries services based on students' perspectives," *Open Access Library Journal*, vol. 8, no. 8, pp. 1–17, 2021.

[8] N. Soltani-Nejad, F. Taheri-Azad, N. Zarei-Maram, and M. K. Saberi, "Developing a model to identify the antecedents and consequences of user satisfaction with digital libraries," *Aslib Journal of Information Management*, vol. 72, no. 6, pp. 979–997, 2020.

[9] M. R. A. Kadir, A. Z. H. Samsudin, and M. R. Seman, "Analysis of user satisfaction of academic digital library: An empirical model with mediating effects."

[10] J. H. Chun et al., "Beyond the desk: Enhancing user satisfaction with contactless services in South Korean academic libraries," *The Journal of Academic Librarianship*, vol. 51, no. 1, p. 102986, 2025.

[11] N. A. Azib, R. Abu, S. K. Rafie, and N. S. Mohd Tokiran, "Evaluating user satisfaction with digital library services: A study of academic libraries in higher education institutions," *International Journal of Research and Innovation in Social Science (IJRISS)*, vol. 8, no. 12, p. 4511, 2024. doi: 10.47772/IJRISS.2024.8120379.

[12] V. V. K. S. Murthy, "Evaluating user satisfaction with digital library services: A study of academic libraries in higher education institutions," *International Journal of Library and Information Science*, vol. VIII, no. XII, p. 14, 2024. [Online]. Available: http://www.iaeme.com/IJLIS/index.asp.

[13] Z. Abukari, "User satisfaction of resources and services of libraries: A case study of the Narh-Bita College, Tema, Ghana," *Library Philosophy and Practice (e-journal)*, no. 2743, 2019. [Online]. Available: https://digitalcommons.unl.edu/libphilprac/2743.

[14] M. Rakhmatullaev, S. Normatov, and F. Bekkamov, "Fuzzy relations based intelligent information retrieval for digital library users," in *ENVIRONMENT. TECHNOLOGIES. RESOURCES. Proceedings of the International Scientific and Practical Conference*, vol. 2, Jun. 2023, pp. 80–83.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 57-64

Methodology for Analysing LMS Data to Predict Student Dropout Risk in Higher Education

Linda Luīze Barbare
Institute of Applied Computer Systems
Riga Technical University
Riga, Latvia
linda-luize.barbare@rtu.lv

Aleksejs Jurenoks
Institute of Applied Computer Systems
Riga Technical University
Riga, Latvia
aleksejs.jurenoks@rtu.lv

Magone Una Rauba
Institute of Applied Computer Systems
Riga Technical University
Riga, Latvia
magone-una.rauba@rtu.lv

Zane Višķere
Institute of Applied Computer Systems
Riga Technical University
Riga, Latvia
zane.viskere@rtu.lv

***Abstract*—Nowadays, educational institutions use Learning Management Systems (LMS) to support students in the learning process. LMS technical data analysis enables the monitoring of student activities and early identification of those at risk of failing a course. Data gathered during the educational process facilitates the adaptation of learning content to meet each student's individual needs. By leveraging this data, institutions can implement adaptive education, allowing study programs to be structured based on personalized learning pathways, intelligent recommendation systems, and dynamic curriculum adjustments. Additionally, by analyzing student model data, it is possible to assess dropout risks. As a result, research on student attrition rates has gained increased attention. This paper examines the methodology for analyzing Moodle LMS data to adaptively detect factors influencing student dropout risk. The research explores the potential of analyzing log file data generated by Moodle LMS to identify student model parameters and their impact on student success throughout the entire educational process. By utilizing learning patterns and engagement indicators, activity log data from more than seven hundred students at Riga Technical University's Moodle e-learning system was analyzed. The research aimed to identify correlations and relationships between several factors, including the availability of resources for students, the number of graded activities, activity types, views, and other relevant data. By analyzing correlations between fluctuations in students' learning achievements and behavioral patterns in e-learning platforms, the study aims to identify key indicators and metrics for predicting dropout tendencies. The findings suggest that a decline in engagement, the presence of negative patterns, or the absence of consistent learning behaviors serve as reliable indicators of students at risk of dropping out.**

Keywords — learning management system, student dropout, e-learning, education theories

I. Introduction:

The growing availability of educational data has an increasing topicality in Educational Data Mining (EDM) and Learning Analytics (LA) [1] – [4]. LMSs platforms such as Moodle generate large volumes of data related to student activities. Analysing this data can reveal patterns in student engagement and predict dropout risks. [4], [5]. The goal of this paper is to describe a methodology of analysing Moodle LMS logs to identify factors influencing student dropout risk and to support early intervention strategies. [1], [4], [5]. Analysing student activity logs in LMS is a non-invasive method that relies on behaviour-related data to predict student success by examining student interactions within the LMS, such as access times, resource utilization, and participation in activities, without requiring personal or sensitive data [1].

RQ1: Does LMS log data correlate with pedagogical and cognitive aspects on e-learning?

RQ2: What specific behavioural patterns in Moodle LMS log data are most indicative of a heightened dropout risk?

Studies prove that low engagement metrics such as time spent on tasks, participation in discussions and

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8613
© 2025 The Author(s). Published by RTU PRESS
This is an open-access article under the Creative Commons Attribution 4.0 International License.

forums, and interaction with course materials in online courses is a strong indicator of student dropout [1], [2]. Even more, it has been concluded, that students who perform poorly in the early stages of a course are at higher risk of discontinuing their studies [6], [7] Majority of studies focus on log activity metrics but do not focus on identifying reasons for student disengagement, leaving a gap in understanding the factors that impact participation and motivation in online learning environments.

Related studies:

A systematic literature review was conducted to identify factors related to student dropout. To ensure the exploration of the latest methodologies in this research domain, particularly considering the increased adoption of online learning due to the COVID-19 pandemic, studies published between 2019 and 2025 were selected. The literature search was conducted by using keywords: ***learning management system (LMS), student dropout, e-learning, education theories.***

Initial search string "dropout AND Moodle OR learning AND management AND system AND prediction" returned 141 papers in Scopus that were narrowed down to 75 after adjusting selection criteria (in English, peer-reviewed articles, relevance to LMS and dropout prediction, etc.) After reviewing titles and abstract, 30 articles were identified to be directly relevant to research domain. Studies that have been included in review were focusing on Higher education institutions (HEI) and can be categorized by 2 main topics explored: machine learning techniques and models in dropout prediction and engagement metrics and key factors influencing dropout.

Student dropout has been critical research area for HEI as it directly impacts institutions' financial health and is a key aspect to foster society's progress and economic development [6], [7], [12], [13]. Recently there has been an increase of number of studies where student dropout risk is predicted using computer science and machine learning technologies [1], [7] – [11], [13], [14]. It has been identified, that in research domain related studies machine learning techniques such as Decision Trees, Random Forests, Logic Regressions, K-Nearest Neighbour (KNN), Clustering, Neural Networks, etc., are widely used to analyse LMS data for real-time data monitoring to track students' activity and interaction with course content providing valuable insights on student performance [1] – [17]. As established in literature, multiple tools have been proposed for dropout prediction, however many of tools in market tend to be too general and are not modified accordingly to educational institution specifics – such as teaching field, course length, internal organization policies and grading [7], [15] Increased adaptation of online and mixed-learning environments has highlighted the need for more advanced, AI-driven tools to support student success [7], [15]

Many studies use combined machine learning technique models and deep learning algorithms to achieve higher accuracy rates. The ensemble model by Rabelo and Zarate combines results from Logistic Regression, Neural Networks, and Decision Tree techniques developing a conceptual model that is primary based on previous knowledge – surveys from dropout students, knowledge from literature review from to domain related works. It was able to predict dropouts with 98.1% accuracy [7]. Similar study done by Tamada, Gusti, et al, compares seven machine learning algorithms (Random Forest, Decision Tree, Gradient Boosted Trees, Logistic Regression, Naive Bayes, Deep Learning, and Support Vector Machine) on analysing 761 high school student data at 20%-40%-60% course completion stages total across 8 classes within a 2-year period. Highest accuracies were achieved using methods Deep Learning (90.33% at 60% course completion stage) and Random Forest (88.42% at 40% course completion stage) [16].

Framework introduced by Shoaib and Sayed proposes combining pre-processing techniques using Convolutional Neural Network (CNN) for hidden pattern extraction with ensemble model to implement AI-driven education technologies. The model was able to categorize students into "No Risk," "Low," "Moderate," and "High" risk levels and predict the risk of dropout with 93% accuracy. Results were validated against actual student outcomes, demonstrating its reliability in real-world scenarios [6]. Another study analysed 12 000 log file entries using CNN [12]. Study suggested that machine learning classifiers alone do not provide efficient mechanisms on student performance prediction and achieving high accuracy with a large data set is challenging, however proposed model scored average accuracy of 98.6% [12]. The study by Sáiz-Manzanares and Rodríguez-Díez was conducted on single course with 49 students as a result the UBUMonitor tool was developed – a desktop app that connects to Moodle via REST API and WEB services to visualise log activities [15].

Studies propose various key metrics that impact dropout rates, including behavioural and engagement patterns, socio-demographic factors, teaching methods, and student personality traits [10]. These insights provide an understanding of how different factors impact dropout rates across various HEIs and regions. Study by Al-Kindi, Al-Khanjari, et al, was conducted in Sultan Quabos university and analysed records from "Introduction to computer science course" with 29 students (in total 273 906 log files) within semester. Four main key factors were extracted: Engagement (E), behaviour (B), Personality (Pers.) and Performance (P) to identify specific patterns. EBPersP model concluded that the most influential factor on performance was personality, followed by behaviour and engagement, implicating that understanding the student's personality traits can lead to more effective teaching strategies. [5] In research [13], it was established that older students tend to drop out more, but in [12] a strong correlation for higher drop out risk was found for students between the age of 20-29. However, the HEI type differed – research [12] was conducted in Arab Online University, while [13] was executed in mixed type HEI

(Face to face (F2F) and massive open online courses (MOOC)) France.

Building a ML model for student performance prediction necessitates the collaborative efforts of specialists in education, digital curriculum design, applied statistics, and computer science. László Bognár and Tibor Fauszt involved experts in these fields and found that introducing chapter-level indicators can increase the accuracy of predictions compared to using only course-level or site-level indicators [17].

Most of the research studies focus on Moodle logs activity and engagement as behavioural metrics, but do not specifically underline the reasons for student disengagement. Research is mainly conducted on engagement activity in combination with demographic or financial factors but exclude feedback from students and educators.

Pedagogical and cognitive aspects on e-learning

Online learning offers the advantage of education accessibility and flexibility [1] – enabling students to engage with any available online course at any time from any location. This enhances learning opportunities, while also is beneficial to the educators by expanding target audience reach and optimizing resource utilization. However, stable internet connection and access to digital devices has been identified as restrictive challenge in terms of e-learning accessibility [19]. Digital learning is a sustainable approach to global education challenges providing equity and inclusivity by ensuring digital connectivity and quality content delivery [18].

The increasing integration of technologies in education has prompted digital pedagogy methods to shift from traditional pedagogical frameworks such as Vygotsky, Piaget, etc., and calls for more student-centred approach [19] encouraging students to actively participate in knowledge construction [18], [20]. However, dependency on students' self-regulated learning that allows learners to navigate their progress without direct supervision and peer support [19] might result in cognitive overload and reduced engagement [18], [21], [22] that leads to higher dropout rates [8] and low academic scores [19] in comparison to traditional face to face classes. Therefore, it is crucial to timely allocate risk factors to provide additional support and mitigate dropout rates [20].

The central key to academic success and building learning experiences is effective student interaction with education content in an e-learning environment. [21] Pedagogically, e-learning environments encourage active participation through various interactive methods such as collaborative technologies, gamification, forums, etc., and promote self-regulated learning allowing students to guide their education process based on learning style and preferences through digital platforms [19], [21]. Cognitively, e-learning environments must provide deep learning experiences that can be achieved through content personalization and meaningful interactions rather than surface-level engagement [18], [21]. In the year 1989 Moore described three types of interaction: Learner-Teacher (LT), Learner-Content (LC), and Learner-Learner (LL) which outlines forms of engagement in an online environment. The Community of Inquiry (CoI) framework, which was influenced by Moore's research, emphasizes the importance of cognitive presence, where students can actively engage in critical thinking and problem-solving rather than passive content consumption. Furthermore, the Self-Determination Theory (SDT) by Yuerong and Na (2024) emphasizes that personal motivation and engagement in e-learning strongly correlate with three psychological needs: autonomy, competence, and relatedness [19], [21]. The Adaptive Structural Learning and Technology Acceptance Model (ASL-TAM) by Zheng, Lou, et al, also emphasizes students' relatedness to the topic and identifies three key dimensions – perceived ease of use, perceived usefulness, and system adaptability – as critical factors that shape student engagement and satisfaction with online learning platforms [22]. Another element that has a crucial role in student engagement levels is interactive learning methods such as forums, problem-solving tasks, adaptive learning pathways, etc., that foster cognitive presence [20], [21]. Scaffolding strategies, such as guided inquiry and structured feedback loops promote an increase in cognitive engagement and can assist students in structuring knowledge through reflective discourse [21]. If e-learning environments fail to provide meaningful scaffolding, it can result in students developing misconceptions and disengagement from further learning process [21]. Effective e-learning environments must combine interactive strategies, multimedia resources, and frequent engagement through forums and assignments to improve performance and reduce dropout [21]. However, it is suggested, that if there is an absence of direct social and teaching presence from educators in online learning courses, that can be mitigated through artificial intelligence-driven analytics that provide real-time feedback and personalized learning recommendations [21].

The studies show that student engagement varies based on multiple factors not only including students' personal traits and preferences but also digital accessibility and online course content and instructional quality [19]. Flexibility in online learning environments can enhance academic performance, however, challenges such as reduced peer and educator interaction, digital and lack of motivation can negatively affect student engagement and therefore increase dropout rates [19]. It is suggested that online learning environment courses should implement interactive strategies, multimedia resources, and frequent LT, LC, and/or LL interactions through various digital collaboration tools to enhance both performance and engagement [19], [21].

While e-learning provides adaptability and accessibility, learning outcomes depend on pedagogical

design and used methods, cognitive support strategies, and

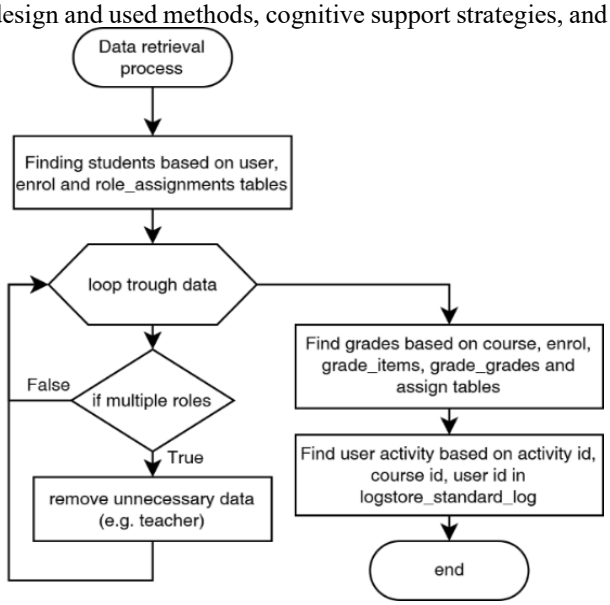


Fig. 1. Data retrieval process.

interaction strategies. Aligning e-learning environments with digital pedagogy strategies would result in enhanced learning outcomes and reduced dropout rates [18] – [22].

II. Materials and Methods

Data mining is the process of discovering new knowledge in large amount of already existing information, this process is based on traditional statistical analysis, mathematics and machine learning [23]. This process supports data driven decision making which in turn supports predictive analytics based in historic data by use of classification, regression or time series [23]. Predictive analytics uses past data to forecast future events, based on patterns extracted from data [23]. In this research, time series are used as base for predictions.

During data mining Moodle data, multiple steps had to be taken to achieve the results – data retrieval, data preparation, model building and pattern mining and analysing [23]. During the retrieval of data, data is mainly selected from logstore_standard_log (that contains course element views and corresponding user IDs), User (contains Users name, surname and contact information), Enrol (contains user enrolment in course date), Course (contains course name, course start and end date), role_assignments (contains users assigned roles for a course), grade_items (contains information about if assignment contains multiple grades), grade_grades (contain individual assignment grades, MIN and MAX assignable grade), Assign (contains assignment course information, Assignment name, deadlines) tables [24].

Due to large data amount in this particular case logstore_standard_log table (which is part of events API) is stored in separate data base together with other event related tables as per industry standard for cases when information needs to be split between multiple databases [25] – [27]. This made the data retrieval a multistep process (Fig. 1). First, all students who learn in a particular semester are found based on course, enrol, and user tables, and then their data is found in their respective databases to limit unnecessary data retrieval by using WHERE clauses. In further preparation process data is cleaned from data that could not be efficiently filtered out during the initial retrieval due to performance issues such as reaching environments timeout limit for single request length, cleaning included unnecessary log line removal (e.g., general course page views), duplicate records are removed or consolidated by regrouping to contain as little duplicate information as possible [28].

A two-week period (t_{learn}) was used to define participation windows. [29], [30]. Based on learning time frame length ($t_{learn\ len}$,(1)), student activities are looked at in time frames, which created one of the indicators for student non-participation ($t_{np\ activity}$). Students missing multiple time frame (t_{learn}), can be considered at high risk of dropping out, as knowledge retention (forgetting curve) needs to be considered. Additionally, the curriculum life span evaluation (t_{buffer} and $t_{u\ buffer}$) must be performed, as missing multiple learning periods may make it impossible to adjust the learning plan to the student's needs, potentially leading to dropout ((2), (3), comparison (4)) [29], [30]. Next step is to look at students grades more closely, where a conclusion that, if student has used up all learning process buffer (5) they are at a higher risk for not completing this subject, is made, as well as if their overall grades are under passing grade increased by standard deviation they are at high risk of dropping the course as additional improvements to grades are needed (t_{impr}, (6), (7), (8), comparison (9)) [29].

TABLE 1 KEY VARIABLES

Variable	Description
$t_{course\ len}$	Length of course in weeks
$t_{activity}$	Total activity length
$t_{learn\ len}$	One learning time frame length
t_{buffer}	Course buffer time, based on course length and a constant
$t_{np\ acitivity}$	Non-participated activity count, in other words, times not participated
$t_{u\ buffer}$	Used buffer time for non-participated activities
$t_{lo\ buffer}$	Leftover buffer time based on time needed to finish activities
$\sum grade$	Sum of all students' grades
$grade\ count$	Student grade count
$avg\ grade$	Average grade for student
$std\ dev$	Standard deviation
$passing\ grade$	Grade to pass the course
t_{impr}	Time needed to improve grades
$t_{upd\ buffer}$	Updated buffer value based on needed improvements
Δval	Difference between students' average grade and average grade in course
$avg\ pos$	Average position
Δpos	Difference between students grade position and average position in course
t_{corr}	Buffer time correction
$t_{f\ buffer}$	Final buffer time

During experiments additional corrections were made based on student grade rating ((10), (11), comparison (12)) in the particular course to increase the precision of prediction, so that there are less false positives for low-risk students (Fig. 2). These initial findings created a prediction of how likely the student is to finish a certain course, after which based on course information (e.g, ECTS) additional adjustments could be made to adjust for course importance.

The table (Table 1) defines key variables used in the dropout prediction model, covering time-based metrics for course engagement, buffer calculations and grade-based indicators for assessing student performance. These variables enable the model to evaluate learning participation patterns and identify students at risk of dropping out.

Additionally, to methodology we need to look at the calculations that make these predictions possible.

$$t_{learn\ len} = \frac{t_{course\ len}}{t_{activity}} \quad (1)$$

(1) Describes calculation of course learning time frame length. Where $t_{learn\ len}$ is one learning time frame length, $t_{course\ len}$ is the total course length, $t_{activity}$ is total course activity length.

$$t_{buffer} = t_{course\ len} \cdot 0.3 \quad (2)$$

(2) Represents course buffer time calculation, where 0.3 is course buffer time constant based on research [29], [30].

$$t_{u\ buffer} = \frac{t_{course\ len}}{t_{activity}} \cdot t_{np\ acitivity} \quad (3)$$

(3) Calculated used buffer time, where $t_{np\ acitivity}$ is non-participated activity count.

$$if\ t_{u\ buffer} > t_{buffer}\ then\ student\ is\ hight\ risk \quad (4)$$

(4) Shows the comparison used to determine high risk students based on buffer usage (1) (2) (3).

$$t_{lo\ buffer} = t_{buffer} - t_{u\ buffer} \quad (5)$$

(5) Calculates leftover buffer based on non-participated activity count. This shows current situation per student on already predicted need for learning process buffer usage.

$$avg\ grade = \frac{\sum grade}{grade\ count} \quad (6)$$

(6) Calculates average grade for this student.

$$t_{impr} = (passing\ grade + std\ dev - avg\ grade) \cdot t_{learn\ len} \quad (7)$$

(7) Calculates the buffer time necessary to improve grades, where passing grade is course passing grade.

$$t_{upd\ buffer} = t_{lo\ buffer} - t_{impr} \quad (8)$$

(8) Updates leftover buffer based on passing grade.

$$if\ t_{impr} > 0\ then\ if\ t_{upd\ buffer} > t_{buffer}\ then\ student\ is\ hight\ risk \quad (9)$$

(9) Shows comparison for high risk based on need for improvements.

$$t_{corr} = \Delta val \cdot \frac{\Delta pos}{avg\ pos} \cdot t_{learn\ len} \quad (10)$$

(10) Shows experimentally determined formula for correction value for buffer.

$$t_{f\ buffer} = t_{upd\ buffer} - t_{corr} \quad (11)$$

(11) Calculates buffer after correction.

$$\begin{aligned} &if\ |pos_{max} - pos_{stud}| > |pos_{min} - pos_{stud}|\ then \\ &\quad if\ avg\ grade < passing\ grade + std\ dev\ then \\ &\quad\quad if\ avg\ grade_{pos} < course\ avg\ grade_{pos}\ then \\ &\quad\quad\quad Formula\ 10\ and\ Formula\ 11\ and \\ &\quad\quad\quad if\ t_{f\ buffer} < 0 \\ &\quad\quad\quad then\ student\ is\ hight\ risk \\ &else\ no\ value\ correction \end{aligned} \quad (12)$$

(12) Compares whether student grades indicate that resulting buffer should be corrected by using (10) and (11) (Fig. 2).

Validation process used Riga Technical University Faculty of Computer Science, Information Technology and Energy data from learning year 2023/2024 autumn semester. Experiments main task was to check the dropout risk based on data available in e-learning platform. Data was collected with 1 month intervals.

During the experiment, predictive model determined risk factor which was then compared to actual situation based on semester results. The results are categorised in three categories – predictive results match the outcomes, predictive results show a false positive (student should pass the course, but they don't), predictive results show a false negative (student should not pass, but they pass the course).

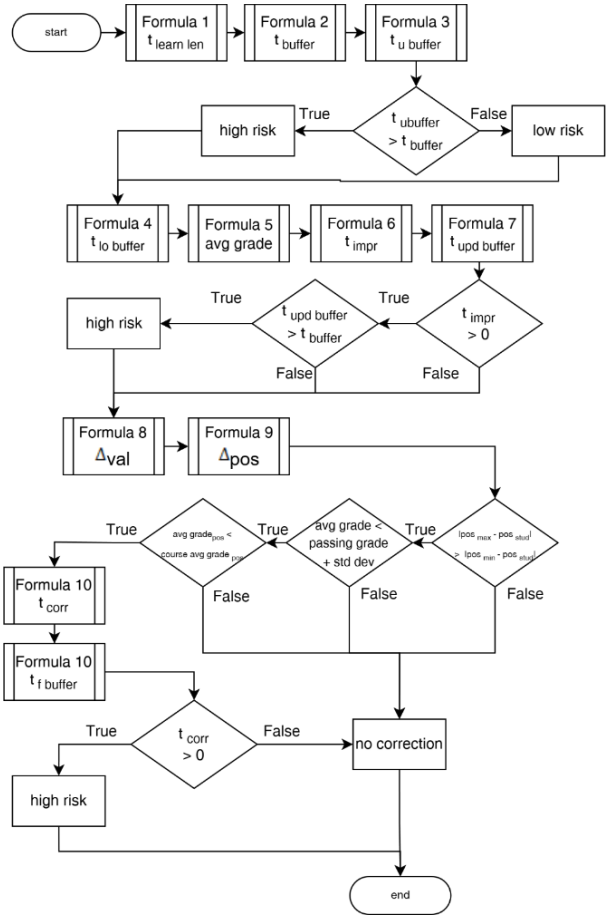


Fig. 2. Prediction process.

III. Results and Discussion

In first iteration, near the start of the course, the results 41% matched, 38% showed false positive and 21 % false negative. Second iteration determined 42% accurately, 40 % false positive and 18% false negative. Third iteration showed significant improvement in accuracy with 64% accurate predictions, 22% false positive and 14% false negative. In last iteration near the end of course the method showed 76% accurate results, 16% false positive and 8% false negative.

Based on during the experiment acquired data, it is possible to see that the method can identify course fail probability when 50% of the course has passed. Experiment showed that there are situations when it' is not possible to identify drop out risk without knowing study course complete requirements (e.g. false positive case context – it is not possible to identify the cause without knowing the requirements e.g. exam or activity weights). As a result, the research proves that just using LMS technical data the model can identify risk groups, but it's necessary to develop study course activity criteria (coefficients) that would help in model decision making.

The model's effectiveness is limited by its reliance on complete and consistent LMS data as well as set course curriculum and cannot account for unrecorded external influences such as personal or motivational factors. Enhancing model precision will require the development of course-specific coefficients and ECTS.

IV. Conclusions

The increasing adoption of digital education technologies, particularly e-learning environments like Moodle, have transformed the way how the student activities and engagement are being analysed. By examining log file data, institutions can early identify at-risk students and provide personalized support such as individual learning plans, additional support, etc., to mitigate dropout levels.

This research analysed activity log data from over 700 students at Riga Technical University's Moodle e-learning environment and focused on identifying key engagement metrics and patterns that corelate with dropout tendencies, aiming to provide actionable insights for educators for timely intervention.

The study proposes a data-driven methodology for analysing Moodle log data that combines analysis of time-series with buffer time calculations and grade-based corrections to predict dropout risks.

Findings demonstrate that low engagement – non-participation within defined learning time frame (t_{learn}) – and low grades below to passing thresholds are strong predictors of potential dropout. These findings align with previous results from to domain related studies highlighting the importance of early engagement and performance analytics in online courses. This research concludes that decline in engagement and inconsistency in participation strongly corelates with negative academic performance and risk of dropping out of course. To mitigate potential risks, timely intervention based on engagement analytics is crucial.

Future research should focus on understanding the reasons behind decline in student engagement in context of course content quality and terms of pedagogical and cognitive aspects. Additionally, further investigation on the long-term impact of digital pedagogy strategies on learning outcomes is necessary. By implementing continuous improvements and aligning online course content with digital pedagogy strategies, HEIs can bridge the gap between technology and student success, fostering sustainable education and improve retention rates.

V. Acknowledgments

This study was partly supported by Project No. 5.2.1.1.i.0/2/24/I/CFLA/003 –Implementation of consolidation and governance changes at Riga Technical University, LiepU, RTA, LJA, and LJK for advancement towards excellence in higher education, science, and innovation.

References

[1] J. Pecuchova and M. Drlik, "Enhancing the Early Student Dropout Prediction Model Through Clustering Analysis of Students' Digital Traces," IEEE Access, vol. 12, pp. 159336–159367, 2024, [Online] Available: IEEE Xplore.

https://ieeexplore.ieee.org/document/10736593 [Accessed Mar. 04, 2025.], https://doi.org/10.1109/ACCESS.2024.3486762

[2] I. D. Stanciu, Á. Hernández-García, M. Á. Conde, and N. Nistor, "Decoding a decade. Trends and evolution in learning analytics: A comprehensive synthesis," Computers in Human Behavior, vol. 165, p. 108526, Apr. 2025, [Online] Available: ScienceDirect https://www.sciencedirect.com/science/article/pii/S0747563224003947?via%3Dihub [Accessed Mar. 04, 2025.], https://doi.org/10.1016/j.chb.2024.108526

[3] S. Sarker, M. K. Paul, S. T. H. Thasin, and Md. A. M. Hasan, "Analyzing students' academic performance using educational data mining," Computers and Education: Artificial Intelligence, vol. 7, p. 100263, Dec. 2024, [Online] Available: ScienceDirect https://www.sciencedirect.com/science/article/pii/S2666920X24000663?via%3Dihub [Accessed Mar. 04, 2025.], https://doi.org/10.1016/j.caeai.2024.100263

[4] I. Mwalumbwe and J. Mtebe, "Using Learning Analytics to Predict Students' Performance in Moodle Learning Management System: A Case of Mbeya University of Science and Technology," The Electronic Journal of Information Systems in Developing Countries, vol. 79, no. 1, pp. 1–13, Mar. 2017, [Online] Available: Wiley Online Library https://onlinelibrary.wiley.com/doi/10.1002/j.1681-4835.2017.tb00577.x [Accessed Mar. 04, 2025.], https://doi.org/10.1002/j.1681-4835.2017.tb00577.x

[5] I. Al-Kindi, Z. Al-Khanjari, and Y. Jamoussi, "Extracting student patterns from log file Moodle course: A case study," International Journal of Evaluation and Research in Education (IJERE), vol. 11, no. 2, Art. no. 2, Jun. 2022, [Online] Available: IJERE https://ijere.iaescore.com/index.php/IJERE/article/view/23242 [Accessed Mar. 04, 2025.], https://doi.org/10.11591/ijere.v11i2.23242

[6] M. Shoaib, N. Sayed, J. Singh, J. Shafi, S. Khan, and F. Ali, "AI student success predictor: Enhancing personalized learning in campus management systems," Computers in Human Behavior, vol. 158, p. 108301, Sep. 2024, [Online] Available: ScienceDirect https://www.sciencedirect.com/science/article/abs/pii/S0747563224001699?via%3Dihub [Accessed Mar. 04, 2025.], https://doi.org/10.1016/j.chb.2024.108301

[7] A. M. Rabelo and L. E. Zárate, "A model for predicting dropout of higher education students," Data Science and Management, vol. 8, no. 1, pp. 72–85, Mar. 2025, [Online] Available: ScienceDirect https://www.sciencedirect.com/science/article/pii/S2666764924000341?via%3Dihub [Accessed Mar. 04, 2025.], https://doi.org/10.1016/j.dsm.2024.07.001

[8] H. S. Park and S. J. Yoo, "Early Dropout Prediction in Online Learning of University using Machine Learning," JOIV : International Journal on Informatics Visualization, vol. 5, no. 4, pp. 347–353, Dec. 2021, [Online] Available: JOIV https://joiv.org/index.php/joiv/article/view/732 [Accessed Mar. 04, 2025.], https://doi.org/10.30630/joiv.5.4.732

[9] M. M. Tamada, R. Giusti, and J. F. de M. Netto, "Predicting Students at Risk of Dropout in Technical Course Using LMS Logs," Electronics, vol. 11, no. 3, Art. no. 3, Jan. 2022, [Online] Available: MDPI https://www.mdpi.com/2079-9292/11/3/468 [Accessed Mar. 04, 2025.], https://doi.org/10.3390/electronics11030468

[10] Z. Song, S.-H. Sung, D.-M. Park, and B.-K. Park, "All-Year Dropout Prediction Modeling and Analysis for University Students," Applied Sciences, vol. 13, no. 2, Art. no. 2, Jan. 2023, [Online] Available: MDPI https://www.mdpi.com/2076-3417/13/2/1143 [Accessed Mar. 04, 2025.], https://doi.org/10.3390/app13021143

[11] M. Vaarma and H. Li, "Predicting student dropouts with machine learning: An empirical study in Finnish higher education," Technology in Society, vol. 76, p. 102474, Mar. 2024, [Online] Available: ScienceDirect https://www.sciencedirect.com/science/article/pii/S0160791X24000228?via%3Dihub [Accessed Mar. 04, 2025.], https://doi.org/10.1016/j.techsoc.2024.102474

[12]]M. Sayed, "Student Progression and Dropout Rates Using Convolutional Neural Network: A Case Study of the Arab Open University," Journal of Advanced Computational Intelligence and Intelligent Informatics, vol. 28, no. 3, pp. 668–678, May 2024, [Online] Available: ResearchGate https://www.researchgate.net/publication/380726606_Student_Progression_and_Dropout_Rates_Using_Convolutional_Neural_Network_A_Case_Study_of_the_Arab_Open_University [Accessed Mar. 04, 2025.], https://doi.org/10.20965/jaciii.2024.p0668

[13] M. Phan, A. De Caigny, and K. Coussement, "A decision support framework to incorporate textual data for early student dropout prediction in higher education," Decision Support Systems, vol. 168, p. 113940, May 2023, [Online] Available: ScienceDirect https://www.sciencedirect.com/science/article/abs/pii/S0167923623000155?via%3Dihub [Accessed Mar. 04, 2025.], https://doi.org/10.1016/j.dss.2023.113940

[14]]V. Realinho, J. Machado, L. Baptista, and M. V. Martins, "Predicting Student Dropout and Academic Success," Data, vol. 7, no. 11, Art. no. 11, Nov. 2022, [Online] Available: MDPI https://www.mdpi.com/2306-5729/7/11/146 [Accessed Mar. 04, 2025.], https://doi.org/10.3390/data7110146

[15] M. C. Sáiz-Manzanares, J. J. Rodríguez-Díez, J. F. Díez-Pastor, S. Rodríguez-Arribas, R. Marticorena-Sánchez, and Y. P. Ji, "Monitoring of Student Learning in Learning Management Systems: An Application of Educational Data Mining Techniques," Applied Sciences, vol. 11, no. 6, Art. no. 6, Jan. 2021, [Online] Available: MDPI https://www.mdpi.com/2076-3417/11/6/2677 [Accessed Mar. 04, 2025.], https://doi.org/10.3390/app11062677

[16]]M. Tamada, R. Giusti, and J. Magalhaes Netto, Predicting Student Performance Based on Logs in Moodle LMS. p. 8. 2021, [Online] Available: IEEE Xplore https://ieeexplore.ieee.org/document/9637274 [Accessed Mar. 04, 2025.], https://doi.org/10.1109/FIE49875.2021.9637274

[17] L. Bognár and T. Fauszt, "Factors and conditions that affect the goodness of machine learning models for predicting the success of learning," Computers and Education: Artificial Intelligence, vol. 3, p. 100100, Jan. 2022, [Online] Available: ScienceDirect https://www.sciencedirect.com/science/article/pii/S2666920X22000558?via%3Dihub [Accessed Mar. 04, 2025.], https://doi.org/10.1016/j.caeai.2022.100100

[18] R. Huang, M. A. Adarkwah, M. Liu, Y. Hu, R. Zhuang, and T. Chang, "Digital Pedagogy for Sustainable Education Transformation: Enhancing Learner-Centred Learning in the Digital Era," Front. Digit. Educ., vol. 1, no. 4, pp. 279–294, Dec. 2024, [Online] Available: Springer Nature Link https://link.springer.com/article/10.1007/s44366-024-0031-x [Accessed Mar. 04, 2025.], https://doi.org/10.1007/s44366-024-0031-x

[19] C. N. Akpen, S. Asaolu, S. Atobatele, H. Okagbue, and S. Sampson, "Impact of online learning on student's performance and engagement: a systematic review," Discov Educ, vol. 3, no. 1, p. 205, Nov. 2024, [Online] Available: Springer Nature Link https://link.springer.com/article/10.1007/s44217-024-00253-0 [Accessed Mar. 04, 2025.], https://doi.org/10.1007/s44217-024-00253-0

[20] L. Yuerong, M. Na, Y. Xiaolu, and S. S. Alam, "Self-determination and perceived learning in online learning communities," Sci Rep, vol. 14, no. 1, p. 24538, Oct. 2024, [Online] Available: Nature https://www.nature.com/articles/s41598-024-74878-4 [Accessed Mar. 04, 2025.], https://doi.org/10.1038/s41598-024-74878-4

[21] M. A. Al Mamun and G. Lawrie, "Cognitive presence in learner–content interaction process: The role of scaffolding in online self-regulated learning environments," J. Comput. Educ., vol. 11, no. 3, pp. 791–821, Sep. 2024, [Online] Available: Springer Nature Link https://link.springer.com/article/10.1007/s40692-023-00279-7 [Accessed Mar. 04, 2025.], https://doi.org/10.1007/s40692-023-00279-7

[22] Z. Li et al., "Students' online learning adaptability and their continuous usage intention across different disciplines," Humanit Soc Sci Commun, vol. 10, no. 1, pp. 1–10, Nov. 2023, [Online] Available: Nature https://www.nature.com/articles/s41599-023-02376-5 [Accessed Mar. 04, 2025.], https://doi.org/10.1057/s41599-023-02376-5

[23] D. Delen, Predictive Analytics: Data Mining, Machine Learning and Data Science for Practitioners, 2nd ed. 2020. [Online]. Available: https://www.oreilly.com/library/view/predictive-analytics-data/9780135946527/ [Accessed: Mar. 04, 2025]
[24] "Moodle 4.3 Database." [Online]. Available: https://www.examulator.com/er/4.3/ [Accessed: Mar. 04, 2025.]
[25] "Moodle2erd.png (3854×2641)." [Online]. Available: https://docs.moodle.org/dev/images_dev/5/5a/Moodle2erd.png [Accessed: Mar. 04, 2025.]
[26] "Large installations - MoodleDocs.". [Online]. Available: https://docs.moodle.org/405/en/Large_installations [Accessed: Mar. 05, 2025]
[27] "Events API - MoodleDocs." [Online]. Available: https://docs.moodle.org/dev/Events_API [Accessed: Mar. 04, 2025.]
[28] J. Han, M. Kamber, and Pei, Data Mining: Concepts and Techniques, 3rd ed. Morgan Kaufmann, 2011. [Online]. Available: https://www.oreilly.com/library/view/data-mining-concepts/9780123814791/ [Accessed: Mar. 04, 2025.]
[29] S. Jurenoka, "Development of Methods and Models for Generating the Adaptive Curriculum Based on the Student Knowledge Level," PhD, Riga Technical University, Latvia, Riga, 2023. [Online] Available: RTU Press https://ebooks.rtu.lv/product/development-of-methods-and-models-for-generating-the-adaptive-curriculum-based-on-the-student-knowledge-level/?lang=en [Accessed Mar. 04, 2025.], https://doi.org/10.7250/9789934229541
[30] S. Jurenoka and J. Grundspenkis, "Development of Methods and Models for Generating an Adaptive Learning Plan Based on the User's Level of Knowledge," BJMC, vol. 11, no. 1, 2023, [Online] Available: Baltic J. Modern Computing https://www.bjmc.lu.lv/fileadmin/user_upload/lu_portal/projekti/bjmc/Contents/11_1_06_Jurenoka.pdf [Accessed Mar. 04, 2025.], https://doi.org/10.22364/bjmc.2023.11.1.06

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 65-75

Drivers and Barriers to AI Adoption in Retail Enterprises: A Systematic Literature Review and Conceptual Framework

Linmu Cui
Faculty of Business Administration
Turiba University
Riga, Latvia
linmu.cui@gmail.com

Aldis Bulis
Faculty of Business Administration
Turiba University
Riga, Latvia
aldis.bulis@turiba.lv

***Abstract*—The emergence of artificial intelligence (AI) technology has profoundly changed the value chain of the retail industry. However, there is a significant gap between the potential value of AI and its actual implementation in retail operations, which highlights the practical challenges of integrating AI into daily operations. Since the introduction of ChatGPT in 2022, the number of studies on the application of AI technology has surged. This study aims to systematically explore factors that promote and hinder AI adoption in retail businesses. The study employed a systematic literature review, focusing on peer-reviewed academic articles in English published between 2015 and early 2025. This review specifically covers the topics of AI technology. The results of this study identify five major drivers, including cost reduction, improving service quality, marketing activities, external factors, and supporting decision-making. In addition, seven major barriers were identified, including perceived ease of use, uncertainty in returns, lack of talent, digital environment, investment and cost, data privacy and ethics issues, and organization and culture. This study also developed a conceptual framework based on the Technology Acceptance Model (TAM) to describe the mechanisms in which driving and impediment factors take effect. This study assists researchers in assessing the current state of research on AI adoption. As attention to AI technology grows, the importance of integrating evaluations of existing systems becomes evident.**

Keywords*— *Artificial Intelligence Adoption, Driving Factors and Barriers, Retail Industry, Systematic Literature Review

I. INTRODUCTION

A. Research Background

Although artificial intelligence is neither a new discipline nor a new academic research field, the results of recent technological developments show that artificial intelligence is being widely accelerated and affecting more and more fields [1]. Recent research on innovation, entrepreneurship, and emerging technologies highlights how technology-driven businesses are leveraging these advancements to transform their entrepreneurial practices and drive growth [2]. In November 2022, Microsoft-backed OpenAI launched its generative AI chatbot prototype ChatGPT, and the technology reached its peak of popularity [3]. Furthermore, artificial intelligence has been applied across a range of scenarios, including image generation, inventory optimization, autonomous driving assistance, and route optimization. These applications and the powerful functions they promise to achieve have driven the rapid growth of investment in this field: according to Armstrong [4], the total value of mergers and acquisitions, minority equity, private investments, and public offerings in the past decade reached US$934.2 billion. Perhaps as Kristalina Georgieva mentioned [5], we are on the verge of a technological revolution.

Moreover, existing research shows how contemporary AI can support various types of businesses, especially those in the retail industry, to maintain their momentum [6], accelerate their operations, and promote regional growth [7]. This presents a variety of opportunities, such as enhancing customer interactions to boost consumer satisfaction [8], creating a seamless customer experience to increase appeal [9], and enabling retailers to adopt AI for improving corporate governance while significantly reducing major costs and time inefficiencies [10].

Conversely, a notable gap exists between the potential benefits of AI and its actual implementation in businesses, with many companies surprisingly reluctant to adopt it [11]. In this regard, Marocco et al. observed that the use of AI in human resources is still quite limited [12], with only a few companies, such as Unilever, exploring AI

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8585
© 2025 The Author(s). Published by RTU PRESS
This is an open-access article under the Creative Commons Attribution 4.0 International License.

applications to improve specific management processes like recruitment systems. This gap is further reflected in training programs and human capital development: Eastwood showed that while 94% of executives planned to increase technology investment, only 26% of the investment focused on improving employee skills [13]. Undoubtedly, this gap between the opportunities brought by AI technology and actual adoption reveals the practical challenges of embedding AI into business processes and suggests the existence of potential obstacles.

B. Research Purpose

As mentioned above, a series of factors may hinder or promote the acceptance and application of AI technology by retail companies. Existing research has provided some insights. For example, Kumar et al. mentioned that the most important reason hindering the adoption of AI may be the lack of infrastructure or conservative business culture [14]. Marocco et al. emphasized ethical and privacy issues [12], lack of expertise and insufficient professional training. In addition, Leyer and Schneider focused on some personal characteristics of managers [15], including overconfidence, control, and personality traits. They stifle curiosity and the pursuit of knowledge, further reinforcing the barriers to adopting intelligent systems. Hirvi connected AI adoption to the degree of digitalization within a company [16], suggesting that low digitalization not only signifies a lack of data but also an inability to prepare for AI integration. Rane highlighted knowledge barriers, explaining that the widespread adoption of AI is hindered by the limited understanding and awareness of AI technology among managers [17]. Many business leaders and employees struggle to comprehend how AI works, its capabilities, and the potential advantages it offers. From a more practical standpoint, Bharadiya emphasized that developing and implementing AI systems demands considerable investments in technology, infrastructure, and skilled talent [18].

In summary, in terms of theory, although there is a large amount of literature on human acceptance of artificial intelligence, it is fragmented. This means that the driving and hindering factors are still not fully explored. These research structures have all helped to explain the gap between the opportunities brought by AI technology and actual adoption, but they have not been systematically retrieved and summarized. Conversely, considering AI development trends, retail managers and executives must assess and define their company's technology strategy to effectively navigate the rapid shifts in both internal and external environments, while also investing more in developing the necessary technical skills. For these enterprises, avoiding the risks of adopting new technologies and applying new technologies to cope with competition from peers must be considered simultaneously.

Therefore, it requires a systematic evaluation method that considers a wide range of research. By systematically collecting all studies in this field and critically evaluating previous studies, this method will present a general view of current research and provide a foundation for future research. To fill this research gap, this study aims to conduct a systematic literature review to identify the main factors driving and hindering AI adoption in retail businesses. Not only that, combined with existing theories in the literature, it will also organize these factors into a conceptual framework to help subsequent researchers determine how artificial intelligence can be successfully integrated into the value creation process of enterprises.

C. Key Concept: Artificial Intelligence

Before introducing the methodology used in this study in detail, it is necessary to first define and scope key terms, including the two core concepts of this study, AI technology and retail industry.

It is necessary to first clarify the definition of artificial intelligence (AI) so that researchers can better summarize and explain its application in the express logistics industry. Although it has been widely used, there has been no clear definition of the term "artificial intelligence" [19]; in fact, mainstream research mentions the rich meaning of AI. When discussing the nature of artificial intelligence, researchers generally hold two core views. The first perspective, outlined by Demlehner and Laumer [20], regards artificial intelligence as an effective tool capable of performing tasks that are either too complex or time-consuming for humans. The second perspective views AI as a system that replicates human intelligence and cognitive processes [21]. Although there are some differences, the academic community generally believes that artificial intelligence is to give computers human-like abilities [21], while artificial intelligence is different.

In addition, in terms of the capabilities of artificial intelligence, some researchers believe that artificial intelligence should only refer to those intelligent agents that completely replicate human behavior; while others believe that it can be regarded as a tool that fails to cover all human capabilities [22]. In this article, we adopt Kaplan and Haenlein's definition of AI as a system [23], technology or machine applied to a solution. It is designed as an auxiliary means rather than a substitute for completely imitating human capabilities, aiming to enable the system to recognize, understand, reason and learn from data to achieve specific goals.

Next, for the specific technologies and concepts involved in artificial intelligence, it involves more complex classification issues. As outlined by Toorajipour et al. [24], a review and analysis of existing literature shows that there are about 20 technologies in artificial intelligence. Among them, some technologies are used more than others; the largest part focuses on artificial neural networks (ANN) and genetic algorithms (GA).

Enholm et al. [25] divide these technologies into three categories: machine learning (ML), deep learning (DL), and other AI technologies are key components in this field. Similarly, Verma et al. [26] categorize AI into three fundamental concepts: machine learning, neural networks, and advanced deep learning applications, such as natural language processing and data mining [26]. In this study, it combines the views of Enholm et al. and Verma et al. to take into account AI technologies built on ML, DL, and other technologies [25] [26].

D. Key Concept: Retail

Like AI, retail is a concept that is widely discussed but its meaning and scope are subject to changing trends. It includes all sales to end consumers, from cars to clothing, from restaurant meals to movie tickets: Bangalore Seetharam summarizes its diverse forms, including department stores [27], grocery stores, clothing stores, electronics and consumer goods stores, convenience stores, supermarkets, malls, and some e-commerce platforms. It is widely acknowledged that retail represents the final stage of the distribution channel [28]. Accordingly, this study adopts Vaja's definition to outline the scope of the retail industry [28], encompassing business activities that sell goods and services directly to consumers for personal, family, or household use. It should be emphasized that this activity must be B2C or C2C, that is, sales to consumers, which excludes the so-called B2B form of distribution activities.

It should be emphasized that with the development of e-commerce, social media, and various distribution networks in recent years, online retail has been increasingly mentioned in addition to traditional channels. Among them, traditional retail refers to the general term for retail business forms that sell products and services at fixed locations [29]. Online retail refers to any commercial transaction or business process where parties engage electronically via the internet or mobile phones [30]. Unlike traditional, offline retail, products are delivered to consumers through shipping or express delivery services. As Heins [31] noted, today's consumers expect products to be available around the clock, with the added convenience of digital features and quick online price comparisons. In addition, Chae and Goh also mentioned that traditional retail stores have also been found to incorporate a range of e-commerce payment [32], delivery, or purchase functions, thus achieving a more integrated experience. For this study, it involves all of these retail formats and therefore attempts to provide a comprehensive discussion.

E. Research Structure

The structure of the paper is organized as follows: First, it introduces and explains the key concepts relevant to the study. Then, it outlines the methods used for the systematic literature review (SLR), including the data sources and selection criteria. The paper proceeds to present and discuss the research findings, focusing on the primary drivers and obstacles to AI adoption. Finally, a conceptual framework is proposed, demonstrating how these factors influence the acceptance or rejection of AI technologies within organizations.

II. MATERIALS AND METHODS

This study employs a systematic literature review (SLR) method, which addresses issues like subjectivity and bias commonly found in traditional review approaches [33]. It provides a systematic process for synthesizing and reviewing relevant research, offering valuable insights on recent trends and progress in the research topic or area [34]. Particularly, the process involves a systematic search in reputable databases and securing research samples on significant topics to inform a systematic and comprehensive synthesis. This study adopted the process because there is a wide literature in the field, with numerous research studies on artificial intelligence and on technologies in AI in the retail field. The research in the paper conforms with the PRISMA process in carrying out the search, using three databases: EBSCO, Scopus, and Web of Science, systematically retrieving literature required in the analysis.

In establishing the search criteria, the study used lists of keywords in several current studies in the field of sustainable logistics to get the most appropriate words. The first keyword string contains six terms related to AI and retail: 'retail industry', 'retail enterprises', 'artificial intelligence', 'artificial intelligence technology', 'barriers', and 'driving factors'. The keyword list above was used in coming up with eight combinations and applying them in the EBSCO, Scopus, and Web of Science databases. The final search string used (taking Web of Science as an example) is: TS = (("retail industry" OR "retail enterprises") AND ("artificial intelligence" OR "AI technology") AND ("barriers" OR "driving factors")). Given the important impact of technological progress, this study only collected samples from the past decade (2015-2024). Search results, collected as of February 15, 2025, yielded 332 articles after preliminary searches and deduplication of the three databases.

TABLE I LITERATURE SCREENING CRITERIA

Type	**Inclusion Criteria**
Source Content Standards	The documentation must be completed in English. The papers must be from management, marketing, logistics management, human resources, and other business fields; papers from computer science or algorithms are excluded. The core focus of the literature is on AI applications in the retail industry, including various AI technologies. The article must clearly mention the drivers or barriers to the application of artificial intelligence technology in the retail industry in the main text.

Source Quality Standards	The length of the paper should not be less than 5 pages, excluding reports and short articles under 5 pages. The literature must be available in the database for full text access (full-text paper). The document must include all required information elements, such as an abstract, author details, keywords, and complete references. Journal impact factor >= 1

Next, it is necessary to introduce the criteria for screening literature in this study. When searching for the first time, some seemingly irrelevant articles often appear. Therefore, to ensure that the included literature is relevant to the research topic, manual screening is essential. The above Table 1 shows the screening criteria:

Next, based on the above criteria, the screening process is shown in the Figure 1 above: It reviews the literature based on the framework provided by [35]. The framework finally obtains the sample set through steps such as subtitles, abstracts, and exclusion termination results.

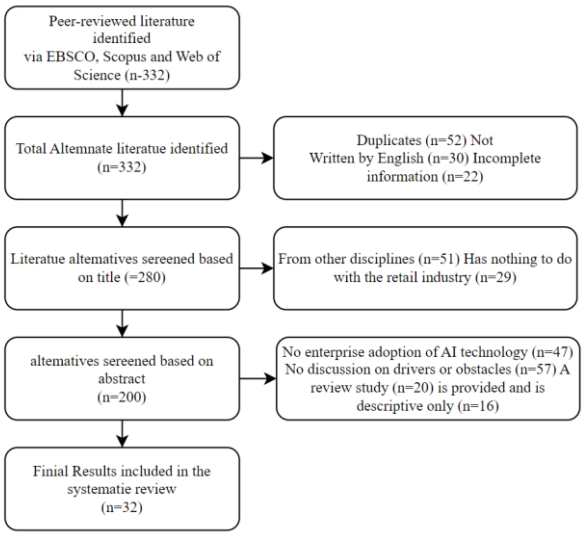


Fig. 1. Literature screening process

By searching keywords in the three databases, a total of 304 documents were obtained. Among them, EBSCO, Scopus, and Web of Science provided 144, 75, and 115 samples; they constituted the initial sample set after excluding duplications. Among them, 30 documents were written in non-English languages, and 22 documents were excluded because of incomplete or unavailable information. Based on the search of article titles and keywords. Among them, 51 people came from other disciplines, including computer science, algorithms, finance, and economics. Next, based on the review of the abstracts, 29 papers were not related to the retail industry. These documents were excluded. Forty-seven papers were excluded for not addressing the adoption of AI technology by enterprises, while fifty-seven papers did not discuss the driving or hindering factors related to AI adoption. In addition, 20 articles provided review studies, while 16 articles were only descriptive. These samples were excluded, and finally 32 samples were included in the study.

III. RESULTS AND DISCUSSION

This section presents the results of the main analyses, focusing on the distribution of papers by journal, country, year, and research field. These analyses aim to provide insights into the development of academic interest in AI in the retail industry and the geographical distribution of research.

A. Distribution by Year, Journal, and Country

The scientific literature on AI is continuously evolving, reflecting the growing interest in these topics within both academia and industry. The 32 selected articles were published over a 10-year period, from 2015 to early 2025. Notably, the number of publications has been rising sharply, with 73% of the articles published in the past five years, highlighting a significant surge in academic interest in AI within the retail sector.

In terms of journals, there are 14 different journals in total. The journals include Decision Support Systems (4), Industrial Marketing Management (4), Sustainability (2), Journal of Retailing and Consumer Services (3), International Journal of Retailing and Distribution, and Retailing Magazine (3), as well as a few others. These figures not only highlight the growing significance of AI in retail but also point to the fragmentation of academic literature across various subfields within retail. Specifically, the papers are published in journals focused on retail, technology, economics, and marketing. Many of these studies include real-world case studies, offering valuable data through the analysis of specific examples.

Mixed method research, qualitative research, exploratory research, quantitative research, case study, and theoretical and conceptual research are the seven types of research coded into categories. Mixed method research is the most common, with a total of 19 articles. Quantitative research and case study are tied for second, with 5 articles each. Additionally, there are 3 qualitative studies, 1 theoretical and conceptual paper, and 2 exploratory studies. Regarding the target regions, it is notable that the largest number of studies come from India (6), the United States (9), and China (13), reflecting these countries' strong economic and cultural investment in emerging technologies, particularly AI.

B. Drivers

The following content shows the driving and obstructive factors based on the induction of sample documents, thereby drawing research conclusions. Based on the data analysis results, five major drivers were identified, including reducing costs, improving service

quality, marketing activities, external factors, and supporting decision-making.

1) Reduce Costs

First, the largest sample (10/35) mentioned the cost and efficiency appeal of retail firms' investment or a complete shift to AI technology. As Polisetty et al. mentioned, artificial intelligence is seen by these as a beneficial tool that can increase productivity, reduce costs and simplify processes [36]. More specifically, this motivation is mainly due to the operational attraction for retailers to drive technology adoption: Artificial intelligence can help retailers simplify inventory management by keeping stocks of popular goods and using clustering technology to predict future consumer demands, thereby saving cost [37][38][39]. Further, by leveraging and deploying artificial intelligence algorithms and automated robots, retailers can optimize logistics transactions such as warehouse facilities, distribution route planning and product supply chains, thereby reducing labor costs [40][41][42]. Another aspect of cost saving comes from AI-driven customer service automation mentioned by Huang & Rust, especially chatbots and virtual assistants based on generative AI [43]. With 24-hour service, it reduces the demand for large customer service teams, making cost reduction highly attractive to retail companies.

2) Improve Service Quality

Next, another widely mentioned driver comes from the prospect of improving service quality (9/35). As Huang and Rust mentioned, when services are relational and high-contact, it feels that artificial intelligence should be used for relationalization, for relationship leadership, and mainly used in the service interaction phase [43]. This is due to the service quality advantages brought by its response speed: the intelligent customer service system uses natural language processing technology to provide 24/7 instant service [45]. Some studies mentioned that an important reason why retailers adopt chatbots is that the "humanized" interactions of AI customer service personnel may reduce burnout, errors and toxic problems caused by human customer service, thereby enhancing trust, perceived risks and satisfaction. , and improve service quality [44][46][47]. In the post-purchase stage, customer service specialists and virtual assistants can automate the return and exchange process after checkout [48][47], thereby avoiding dissatisfaction due to inability to obtain after-sales service in a timely manner. In terms of personalization, using virtual assistants to personalize can reduce consumer service costs and speed up response time to consumer queries [49]. This relies on complex application scenarios of image recognition and speech recognition technology and AI construction.

3) Marketing Activities

Beyond that, another attractive reason for the adoption of AI technology for retailers is its significant marketing significance (5/35). For e-commerce platforms and merchants, it can help e-commerce platforms attract consumers through sorting algorithms to display products that meet consumer expectations or encourage consumers to purchase [50][51]. In fact, everything in the e-commerce platform is presented in image form, image size and better visual product display can create a pleasant shopping experience [52]. Methods such as keyword clustering, image analysis, and computer vision use artificial intelligence to identify relevant areas of action and potentially identify cross-selling activities, thereby helping e-commerce platforms to display products more effectively to customers [52]. This also includes helping to generate marketing content such as advertising images and marketing copywriting [53], and further optimizing marketing campaigns [54]. Malikireddy shows that datasets of AI models can create marketing content that is more engaging and more effective in promoting interaction and advertising revenue [53].

4) Support Decision Making

Companies hope to adopt a data-driven approach in decision-making, using analytics (facts) rather than relying on intuition, are another important driver of their application of AI technology (5/35). As mentioned by Rane et al. artificial intelligence improves decision-making processes, optimizes operations and promotes innovation [55]. Decisions are known to be influenced by psychological and social factors, and machine learning-driven decision support systems can extract actionable insights from customer data to provide undisturbed suggestions [56]. Furthermore, AI can improve data-based revenue models and implement related AI services and solutions [57][58]; this is a significant perceptual usefulness mentioned by many review papers. factors, thus becoming one of the driving factors for adoption.

5) External Factors

In addition, including suppliers or partners (4/35), as well as government or policy encouragement (2/35), are also considered an important reason for promoting retail companies to adopt AI. In detail, supplier partnerships can facilitate businesses to implement AI by providing basic training and addressing data privacy issues [59]. Supportively, Yang et al. argues that vendor participation can significantly affect the adoption and spread of AI solutions among managers [60]. In fact, supply chain digitization generates a large amount of data that is seen as a new type of resource with the potential to create value and enhance competitiveness; suppliers often need a large amount of data to train their AI technology, which often involves consumer information. Therefore, suppliers must work closely with the company to promote AI training during and after implementation [59][61]. In addition, Phuoc research highlights the important role of government participation in adopting AI-based solutions, including setting standards, providing tax incentives, and

providing incubation resources [59]. But in general, there are very few studies referring to government or policy as driving factors.

C. Impediments

Next, based on the data analysis results, seven major impediments were identified, including perceived ease of use, uncertainty of returns, lack of talent, digital environment, investment and cost, data privacy and ethical issues, and organization and culture.

1) Perceived Ease of Use

In previous studies, researchers have very consistently argued that ease of use is the main determinant of technology adoption (14/35). Specifically, when managers believe that adoption of AI technology is difficult, they tend to avoid adopting it [66][67]. For example, Vărzaru proposes a model designed specifically for the adoption of AI technology in a management environment and shows that managers' perceptions of the ease of use of AI technology can affect their use of management and technology resources [62]. When managers view AI solutions as unfriendly and can affect their day-to-day work, they tend to abandon them [63][66]. Similarly, there is evidence that some localized AI models can cause maintenance and operational difficulties [64], which is fatal to many small retail businesses. Further, speed and novelty are determinants of the ease of use of AI technology by managers [62].

2) Uncertainty of Returns

According to Jan et al. (2023), uncertainty regarding the return on the introduction of AI technologies is also a significant hindrance in the introduction of AI solutions. It is also seen from the perspective of numerous researchers (12/35). For the majority of the small and medium-sized firms, the introduction of AI technologies is usually associated with large initial investments [66]. Although certain organizations spend money on AI solutions, they usually encounter the problem of the zero return on this investment [72][71][64]. Uncertainty regarding the return on the investment results in the reluctance of the managers of firms to be accountable for the low returns, which results in hindrances in the introduction of AI technology. In contrast, Paramesha et al. indicated that when the managers of the organization realize the introduction of AI technology is associated with great returns as well as a large return on the investment, they usually make the decision to adopt AI technology [73].

3) Lack of Talent

Kar et al. regarded the lack of AI talent as the greatest obstacle for the introduction of AI technology for retail firms [74]. This view is depicted in many studies (5/35). For example, Wilson, Johnson, and Brown (2024) regard the lack of labor skills as the greatest obstacle for the adoption of artificial intelligence for retail firms. According to the study, since there is no managerial talent with AI capabilities as well as skilled operating talent, certain firms need to invest in training and development [62]. In turn, the need for labor retraining and improving skills cannot be ignored [68][74][57]. Companies must ensure that employees can master the necessary skills to use AI when implementing AI technology. While sufficient training can ensure smooth implementation of the business, the process can put a huge time pressure on the company and thus create organizational confusion. In contrast, hiring relevant talents externally may lead to difficulties in embedding business or organizational environment [58][52].

4) Digital Environment

The implementation of AI technology requires compatibility of digital environments and information systems, which means that enterprises must integrate AI solutions with existing systems. The lack of a digital environment often becomes a barrier to the implementation of AI technology (3/35). As Rane et al. pointed out, embedding AI technology into the company's current business processes means difficulties, which come from hardware compatibility, operating system compatibility, communication protocols, and network matching [55][76]. To implement AI technology, a range of evidence suggests that companies must make large-scale changes to their IT infrastructure, workflows, and data structures [76][71]. This could result in business disruptions and additional costs: concerns about this potential risk make it difficult for managers and technicians to conduct AI technology practices with confidence [54][55].

5) Investment and Cost

The implementation of AI induces high investment and costs, which poses a barrier that cannot be ignored (14/35). According to Barenboim et al. the implementation of AI technology in the retail industry requires substantial investment in different aspects including office facilities, computing equipment, terminals, technology, recruitment of employees, and training existing members [55][64][77]. This is often difficult to afford for small and medium-sized enterprises. In addition to initial investment, the implementation of AI technology also means that companies should continue to pay for data storage, maintenance and updates, which often exacerbates the problem of limited budgets [78][75].

6) Data Privacy and Ethical Issues

It must be considered that the problem of the security of the data as well as the ethical issues of AI systems is a core problem, which garnered wide attention from researchers (7/35). In many fields such as finance, commerce, as well as enterprise management, processing the enterprise's as well as the users' data is important. Leakage as well as abuse of the data have been a barrier

for many firms to embrace the use of AI technology [73][55]. At the same time, the functionality of the AI system is highly correlated with the used data for the system's training, which shows the use of biased data can exaggerate the unfairness as well as the discrimination [73][74]. In enterprise processes, after the AI system is biased, the system can compel firms to discriminate their clients, thereby injuring their image [67].

7) Organization and Culture

Organization and culture have been revealed as the main impediments to the adoption of AI technology (4/35). According to Mahmud et al. aversion toward AI technology is generally produced through factors of the environment, organization, as well as the culture [70]. This is because senior leaders in a company tend to be the biggest drivers of the organization's culture [66]. Where senior managers have the passion toward shaping the organization's culture as being more innovative as well as nonconformist, the adoption of AI technology is more likely to be improved [66][56]. But when the organization's culture is lacking trust as well as the adoption of technology, or is conflicting with the perceived value of AI, the adoption of AI technology will be resisted [70][69]. Because the adoption of AI technology is largely from the top down. But most senior leaders possess low levels of AI competency, which can turn the organization as well as the company's culture into impediments toward the adoption of AI technology.

D. Discussion: Conceptual Framwork

Based on the above discussion, the five drivers include reducing costs, improving service quality, marketing activities, external factors, and supporting decision-making. In addition, seven major barriers were identified, including perceived ease of use, uncertainty in returns, lack of talent, digital environment, investment and cost, data privacy and ethics issues, and organization and culture. For these relatively complex concepts and influencing factors, they clearly exhibit an asymmetric influence: the drivers and hindrances that produce the most important influence do not correspond one by one. Therefore, it is necessary to further establish a conceptual framework to provide a basis.

In this regard, the TAM model proposed by Davis provides a reasonable reference: the intention to use this technology is driven by usefulness and ease of use, which predict actual usage [80]. The model mentions two key factors: PU and PEOU. Among them, the extent to which the user believes that using a specific system can improve his or her work performance is perceived usefulness (PU); perceived ease of use (PEOU) refers to the extent to which the user believes that it is easy to use a specific system. Subsequent research extended the application of the model. For example, Xiao and Kumar conceptualize employee acceptance of robots as a four-dimensional structure [83]. Silva extends the simple TAM model and incorporates external variables (EV), Behavioral Intention to Use (BIU), and attitude towards use (ATU) [82]. Among them, the ATU is directly affected by the PU and PEOU. PEOU directly defines the PU, while both PEOU and PU are affected by external factors. This study uses this relatively complete version to construct a conceptual model.

For the drivers and barriers found in this study, four of the five drivers can be found, including reducing costs, improving service quality, helping to develop marketing activities, and supporting decisions involving the benefits of AI applied by retail enterprises. In other words, they affect the perceived usefulness (PU) of the model. In contrast, perceived ease of use and lack of talent are related to perceived ease of use: they negatively affect PEOU. In addition, the uncertainty of returns and cost of the two factors are mainly effective in the steps of Attitude Toward Use to Behavioral Intention to Use. Ultimately, the digital environment, as well as organizations and cultures, are effective between BIU and AU. This therefore lingers in the following concept map Figure 2 (where drivers and barriers are represented by + or - respectively):

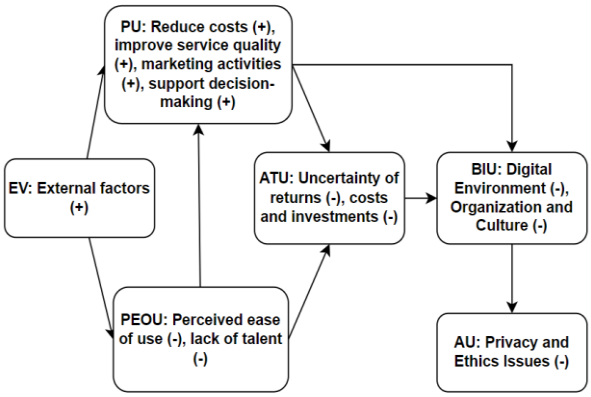


Fig. 2. Concept map.

IV. CONCLUSIONS

A. Conclusion

In summary, this study aims to systematically explore the drivers and barriers to AI adoption in retail enterprises and conduct a systematic literature review of English academic peer review articles published between 2015 and 2025. Ultimately, the results of the study illustrate several drivers, including reducing costs, improving service quality, marketing activities, external factors, and supporting decision-making. In addition, seven major barriers were identified, including perceived ease of use, uncertainty in returns, lack of talent, digital environment, investment and cost, data privacy and ethics issues, and organization and culture. Based on the abstract of these factors, this study also developed a conceptual framework to describe the mechanisms in which driving and impediment factors take effect.

B. Value and Contribution

As research value, in terms of theory, although there is currently a large amount of literature on human acceptance of artificial intelligence, they are fragmented. This study provides a systematic search and summary of these literature, and thus provides a basis for subsequent research. On the other hand, in the face of AI development trends, in practice, managers and executives of retail companies must determine and evaluate the company's technological development strategies, to effectively detect rapid changes in the changing internal and external environment, while investing more in the development of these technical skills. For these businesses, this study helps them revisit their AI adoption plans and effectively eliminate obstacles they face.

C. Limitations and Future Research

This study shows a series of significant contributions, but there are still several limitations and reveals future research directions. First, a systematic literature review (SLR) based on 32 studies may have search limitations, and some related studies may not be included due to the keyword matching mechanism. Due to strict adherence to keyword filtering criteria, literature that may have differentiated title expressions is under-covered. Secondly, the research lacks original data support, and there are shortcomings in revealing the practical details of the artificial intelligence application scenarios in the retail industry and the real experience of organization members. In view of these limitations, further research can be carried out from three dimensions in the future: (1) Deeply explore the specific practices of retailers in artificial intelligence applications through quantitative research methods, and reveal the dynamic relationship between technology adoption and value creation; (2) Application Empirical methods such as field research and case studies to verify the effectiveness of the drivers and obstacle mechanisms identified in this research based on real business scenarios; (3) Expand data collection channels, combine interviews and observations.

V. ACKNOWLEDGMENTS

I sincerely thank all who have contributed to this study. I am particularly grateful to my supervisor, Professor Aldis Bulis, for his expert guidance throughout this research. His regular discussions, constructive feedback, and unwavering encouragement helped me overcome research challenges and refine the academic framework. His innovative suggestions at critical junctures were instrumental in shaping the final conclusions.

Additionally, this study builds upon the foundational work of scholars in related fields, whose theoretical contributions provided essential support. I extend my appreciation to them.

Finally, I offer heartfelt thanks to my family for their enduring support. Their consistent understanding, regardless of my circumstances, has been a vital source of strength in overcoming obstacles. This emotional backing has been crucial to the completion of this research.

I am deeply grateful to all.

VI. REFERENCES

[1] E. M. Alnasser, S. M. Alkhozaim, A. A. Alshiha, and B. S. Al-Romeedy, "The Impact of Artificial Intelligence on the Marketing Performance of Tourism and Hospitality Businesses: The Mediating Role of Marketing Innovation," in *AI Innovations in Service and Tourism Marketing*, IGI Global, 2024, pp. 375-396. https://doi.org/10.4018/979-8-3693-7909-7.ch019

[2] K. Aboalganam, H. Alhanatleh, M. Al-Okaily, M. Alghizzawi, A. Khaddam, and D. Almajali, "Examining antecedents' factors influencing the customer co-creation value using open-sooq app in Jordan," *Uncertain Supply Chain Manag.*, vol. 12, no. 3, pp. 2005-2022, 2024. https://doi.org/10.5267/j.uscm.2024.2.005

[3] N. Kshetri, L. Hughes, E. Louise Slade, A. Jeyaraj, A. Kumar Kar, A. Koohang, ... and R. Wright, "So what if ChatGPT wrote it? Multidisciplinary perspectives on opportunities, challenges and implications of generative conversational AI for research, practice and policy," *Int. J. Inf. Manag.*, vol. 71, p. 102642, 2023. https://doi.org/10.1016/j.ijinfomgt.2023.102642

[4] M. Armstrong and S. Taylor, *Armstrong's Handbook of Human Resource Management Practice: A Guide to the Theory and Practice of People Management*, Kogan Page Publishers, 2023. https://doi.org/10.1108/hrmid.2010.04418dae.001

[5] K. Georgieva, "AI will transform the global economy. Let's make sure it benefits humanity," *IMF Blog*, p. 14, 2024.

[6] F. Omeish, M. Al Khasawneh, and N. Khair, "Investigating the impact of AI on improving customer experience through social media marketing: An analysis of Jordanian Millennials," *Comput. Hum. Behav. Rep.*, vol. 15, p. 100464, 2024. https://doi.org/10.2139/ssrn.4602578

[7] J. Nazir and P. K. Das, "The systematic literature review on business intelligence towards entrepreneurial orientation of ventures," in *Applying Business Intelligence and Innovation to Entrepreneurship*, pp. 1-20, 2024. https://doi.org/10.4018/979-8-3693-1846-1.ch001

[8] C. Heins, "Artificial intelligence in retail–a systematic literature review," *Foresight*, vol. 25, no. 2, pp. 264-286, 2023. https://doi.org/10.1108/fs-10-2021-0210

[9] B. Chae and G. Goh, "Digital entrepreneurs in artificial intelligence and data analytics: Who are they?" *J. Open Innov.: Technol., Mark., Complex.*, vol. 6, no. 3, p. 56, 2020. https://doi.org/10.3390/joitmc6030056

[10] Z. Zhou, X. Chen, E. Li, L. Zeng, K. Luo, and J. Zhang, "Edge intelligence: Paving the last mile of artificial intelligence with edge computing," *Proc. IEEE*, vol. 107, no. 8, pp. 1738-1762, 2019. https://doi.org/10.1109/jproc.2019.2918951

[11] J. Rana, L. Gaur, G. Singh, U. Awan, and M. I. Rasheed, "Reinforcing customer journey through artificial intelligence: a review and research agenda," *Int. J. Emerg. Mark.*, vol. 17, no. 7, pp. 1738-1758, 2022. https://doi.org/10.1108/ijoem-08-2021-1214

[12] S. Marocco, B. Barbieri, and A. Talamo, "Exploring facilitators and barriers to managers' adoption of AI-based systems in decision making: A systematic review," *AI*, vol. 5, no. 4, pp. 2538-2567, 2024. https://doi.org/10.3390/ai5040123

[13] B. Eastwood, "Artificial intelligence pays off when businesses go all in," *MIT Sloan*, Mar. 27, 2023. [Online]. Available: https://mitsloan.mit.edu/ideas-made-to-matter/artificial-intelligence-pays-when-businesses-go-all.

[14] V. Kumar, A. R. Ashraf, and W. Nadeem, "AI-powered marketing: What, where, and how?" *Int. J. Inf. Manag.*, vol. 77, p. 102783, 2024. https://doi.org/10.1016/j.ijinfomgt.2024.102783

[15] M. Leyer and S. Schneider, "Decision augmentation and automation with artificial intelligence: threat or opportunity for managers?" *Bus. Horiz.*, vol. 64, no. 5, pp. 711-724, 2021. https://doi.org/10.1016/j.bushor.2021.02.026

[16] A. Hirvi, *Challenges of adopting AI in Estonian companies in manufacturing and retail fields*, unpublished.

[17] N. Rane, S. P. Choudhary, and J. Rane, "Acceptance of artificial intelligence technologies in business management, finance, and e-commerce: factors, challenges, and strategies," *Stud. Econ. Bus. Relat.*, vol. 5, no. 2, pp. 23-44, 2024. https://doi.org/10.48185/sebr.v5i2.1333

[18] J. P. Bharadiya, "A comparative study of business intelligence and artificial intelligence with big data analytics," *Am. J. Artif. Intell.*, vol. 7, no. 1, pp. 24-30, 2023. https://doi.org/10.11648/j.ajai.20230701.14

[19] A. Di Vaio, R. Palladino, R. Hassan, and O. Escobar, "Artificial intelligence and business models in the sustainable development goals perspective: A systematic literature review," *J. Bus. Res.*, vol. 121, pp. 283-314, 2020. https://doi.org/10.1016/j.jbusres.2020.08.019

[20] Q. Demlehner and S. Laumer, "Shall we use it or not? Explaining the adoption of artificial intelligence for car manufacturing purposes," *unpublished*, 2020. https://doi.org/10.1016/j.ijinfomgt.2021.102317

[21] Mikalef, P., & Gupta, M. (2021). Artificial intelligence capability: Conceptualization, measurement calibration, and empirical study on its impact on organizational creativity and firm performance. *Information & management*, *58*(3), 103434. https://doi.org/10.1016/j.im.2021.103434

[22] S. L. Wamba-Taguimdje, S. F. Wamba, J. R. K. Kamdjoug, and C. E. T. Wanko, "Influence of artificial intelligence (AI) on firm performance: the business value of AI-based transformation projects," *Bus. Process Manag. J.*, vol. 26, no. 7, pp. 1893-1924, 2020. https://doi.org/10.1108/bpmj-10-2019-0411

[23] M. Haenlein, A. Kaplan, C. W. Tan, and P. Zhang, "Artificial intelligence (AI) and management analytics," *J. Manag. Anal.*, vol. 6, no. 4, pp. 341-343, 2019. https://doi.org/10.1080/23270012.2019.1699876

[24] R. Toorajipour, V. Sohrabpour, A. Nazarpour, P. Oghazi, and M. Fischl, "Artificial intelligence in supply chain management: A systematic literature review," *J. Bus. Res.*, vol. 122, pp. 502-517, 2021. https://doi.org/10.1016/j.jbusres.2020.09.009

[25] I. M. Enholm, E. Papagiannidis, P. Mikalef, and J. Krogstie, "Artificial intelligence and business value: A literature review," *Inf. Syst. Front.*, vol. 24, no. 5, pp. 1709-1734, 2022. https://doi.org/10.1007/s10796-021-10186-w

[26] S. Verma, R. Sharma, S. Deb, and D. Maitra, "Artificial intelligence in marketing: Systematic review and future research direction," *Int. J. Inf. Manag. Data Insights*, vol. 1, no. 1, p. 100002, 2021. https://doi.org/10.1016/j.jjimei.2020.100002

[27] S. Bangalore Seetharam, "Developing a digital AI roadmap for retail," unpublished, 2020.

[28] M. B. R. Vaja, "Retail management," *Int. J. Res. Anal. Rev.*, vol. 2, no. 1, pp. 22-28, 2015.

[29] J. Ge, "Traditional retail distribution in megacities," unpublished, 2017.

[30] T. Kollmann, *Digital Marketing: Grundlagen der Absatzpolitik in der Digitalen Wirtschaft*. Stuttgart, Germany: Kohlhammer Verlag, 2019. https://doi.org/10.17433/978-3-17-037003-6

[31] C. Heins, "Artificial intelligence in retail–a systematic literature review," *Foresight*, vol. 25, no. 2, pp. 264-286, 2023. https://doi.org/10.1108/fs-10-2021-0210

[32] B. Chae and G. Goh, "Digital entrepreneurs in artificial intelligence and data analytics: Who are they?" *J. Open Innov.: Technol., Mark., Complex.*, vol. 6, no. 3, p. 56, 2020. https://doi.org/10.3390/joitmc6030056

[33] G. Lame, "Systematic literature reviews: An introduction," in *Proc. Des. Soc. Int. Conf. Eng. Des.*, vol. 1, no. 1, pp. 1633-1642, Jul. 2019, Cambridge University Press. https://doi.org/10.1017/dsi.2019.169

[34] M. Pradana, H. P. Elisa, and S. Syarifuddin, "Discussing ChatGPT in education: A literature review and bibliometric analysis," *Cogent Educ.*, vol. 10, no. 2, p. 2243134, 2023. https://doi.org/10.1080/2331186x.2023.2243134

[35] H. Arksey and L. O'Malley, "Scoping studies: towards a methodological framework," *Int. J. Soc. Res. Methodol.*, vol. 8, no. 1, pp. 19-32, 2005. https://doi.org/10.1080/1364557032000119616

[36] A. Polisetty, D. Chakraborty, A. K. Kar, and S. Pahari, "What determines AI adoption in companies? Mixed-method evidence," *J. Comput. Inf. Syst.*, vol. 64, no. 3, pp. 370-387, 2024. https://doi.org/10.1080/08874417.2023.2219668

[37] J. Bughin, E. Hazan, S. Ramaswamy, M. Chui, T. Allas, P. Dahlstrom, N. Henke, and M. Trench, "Artificial intelligence: the next digital frontier?", *McKinsey & Company*, 2017. [Online]. Available: www.mckinsey.com/~/media/mckinsey/industries/advanced%20electronics/our%20insights/how%20artificial%20intelligence%20can%20deliver%20real%20value%20to%20companies/mgi-artificial-intelligence-discussion-paper.ashx

[38] F. Petropoulos, N. Kourentzes, K. Nikolopoulos, and E. Siemsen, "Judgmental selection of forecasting models," *J. Oper. Manag.*, vol. 60, no. 1, pp. 34-46, 2018. https://doi.org/10.1016/j.jom.2018.05.005

[39] K. Oosthuizen, E. Botha, J. Robertson, and M. Montecchi, "Artificial intelligence in retail: the AI-enabled value chain," *Australas. Mark. J.*, vol. 29, no. 3, pp. 264-273, 2021. https://doi.org/10.1016/j.ausmj.2020.07.007

[40] R. Dubey, D. J. Bryde, C. Blome, D. Roubaud, and M. Giannakis, "Facilitating artificial intelligence powered supply chain analytics through alliance management during the pandemic crises in the B2B context," *Ind. Mark. Manag.*, vol. 96, pp. 135-146, 2021. https://doi.org/10.1016/j.indmarman.2021.05.003

[41] D. Loske and M. Klumpp, "Human-AI collaboration in route planning: an empirical efficiency based analysis in retail logistics," *Int. J. Prod. Econ.*, vol. 241, p. 108236, 2021. https://doi.org/10.1016/j.ijpe.2021.108236

[42] D. Loske and M. Klumpp, "Intelligent and efficient? An empirical analysis of human–AI collaboration for truck drivers in retail logistics," *Int. J. Logist. Manag.*, vol. 32, no. 4, pp. 1356-1383, 2021. https://doi.org/10.1108/ijlm-03-2020-0149

[43] M. H. Huang and R. T. Rust, "Engaged to a robot? The role of AI in service," *J. Serv. Res.*, vol. 24, no. 1, pp. 30-41, 2021. https://doi.org/10.1177/1094670520902266

[44] N. Rane, S. P. Choudhary, and J. Rane, "Acceptance of artificial intelligence technologies in business management, finance, and e-commerce: factors, challenges, and strategies," *Stud. Econ. Bus. Relat.*, vol. 5, no. 2, pp. 23-44, 2024. https://doi.org/10.48185/sebr.v5i2.1333

[45] K. Jiang, M. Qin, and S. Li, "Chatbots in retail: How do they affect the continued use and purchase intentions of Chinese consumers?" *J. Consum. Behav.*, vol. 21, no. 4, pp. 756-772, 2022. https://doi.org/10.1002/cb.2034

[46] S. Schanke, G. Burtch, and G. Ray, "Estimating the impact of 'humanizing' customer service chatbots," *Inf. Syst. Res.*, vol. 32, no. 3, pp. 736-751, 2021. https://doi.org/10.1287/isre.2021.1015

[47] H. P. Lu, H. L. Cheng, J. C. Tzou, and C. S. Chen, "Technology roadmap of AI applications in the retail industry," *Technol. Forecast. Soc. Change*, vol. 195, p. 122778, 2023. https://doi.org/10.1016/j.techfore.2023.122778

[48] L. Cui, S. Huang, F. Wei, C. Tan, C. Duan, and M. Zhou, "Superagent: A customer service chatbot for e-commerce

websites," in *Proc. ACL 2017, System Demonstrations*, pp. 97-102, 2017. https://doi.org/10.18653/v1/p17-4017

[49] C. H. Leung and W. T. Yan Chan, "Retail chatbots: The challenges and opportunities of conversational commerce," *J. Digit. Soc. Media Mark.*, vol. 8, no. 1, pp. 68-84, 2020. https://doi.org/10.69554/apsb6546

[50] A. Giri, S. Chatterjee, P. Paul, and S. Chakraborty, "Determining the impact of artificial intelligence on 'developing marketing strategies' in organized retail sector of West Bengal, India," *Int. J. Eng. Adv. Technol.*, vol. 8, no. 6, pp. 3031-3036, 2019. https://doi.org/10.35940/ijeat.f9030.088619

[51] T. K. Vashishth, K. K. Sharma, B. Kumar, S. Chaudhary, and R. Panwar, "Enhancing customer experience through AI-enabled content personalization in e-commerce marketing," in *Advances in Digital Marketing in the Era of Artificial Intelligence*, pp. 7-32, 2025. https://doi.org/10.1201/9781003450443-2

[52] M. Geru, A. E. Micu, A. Capatina, and A. Micu, "Using artificial intelligence on social media's user generated content for disruptive marketing strategies in eCommerce," *Econ. Appl. Informatics*, vol. 24, no. 3, pp. 5-11, 2018.

[53] S. K. R. Malikireddy, "Generative AI for retail marketing: Automated campaign creation and optimization," *World J. Adv. Eng. Technol. Sci.*, vol. 13, no. 1, pp. 1058-1068, 2024. https://doi.org/10.30574/wjaets.2024.13.1.0487

[54] L. Cao, "Artificial intelligence in retail: applications and value creation logics," *Int. J. Retail Distrib. Manag.*, vol. 49, no. 7, pp. 958-976, 2021. https://doi.org/10.1108/ijrdm-09-2020-0350

[55] N. Rane, S. P. Choudhary, and J. Rane, "Acceptance of artificial intelligence technologies in business management, finance, and e-commerce: factors, challenges, and strategies," *Stud. Econ. Bus. Relat.*, vol. 5, no. 2, pp. 23-44, 2024.

[56] V. Chattaraman, W. S. Kwon, K. Ross, J. Sung, K. Alikhademi, B. Richardson, and J. E. Gilbert, "'Smart'Choice? Evaluating AI-Based mobile decision bots for in-store decision-making," *J. Bus. Res.*, vol. 183, p. 114801, 2024. https://doi.org/10.1016/j.jbusres.2024.114801

[57] I. Anica-Popa, L. Anica-Popa, C. Rădulescu, and M. Vrîncianu, "The integration of artificial intelligence in retail: benefits, challenges and a dedicated conceptual framework," *Amfiteatru Econ.*, vol. 23, no. 56, pp. 120-136, 2021. https://doi.org/10.24818/ea/2021/56/120

[58] S. Sajja, N. Aggarwal, S. Mukherjee, K. Manglik, S. Dwivedi, and V. Raykar, "Explainable AI based interventions for pre-season decision making in fashion retail," in *Proc. 3rd ACM India Joint Int. Conf. Data Sci. Manag. Data*, pp. 281-289, Jan. 2021. https://doi.org/10.1145/3430984.3430995

[59] N. V. Phuoc, "The critical factors impacting artificial intelligence applications adoption in Vietnam: a structural equation modeling analysis," *Economies*, vol. 10, no. 6, p. 129, 2022. https://doi.org/10.3390/economies10060129

[60] M. Yang, M. Fu, and Z. Zhang, "The adoption of digital technologies in supply chains: Drivers, process and impact," *Technol. Forecast. Soc. Change*, vol. 169, p. 120795, 2021. https://doi.org/10.1016/j.techfore.2021.120795

[61] D. De Silva and D. Alahakoon, "An artificial intelligence life cycle: From conception to production," *Patterns*, vol. 3, no. 6, 2022. https://doi.org/10.1016/j.patter.2022.100489

[62] A. A. Vărzaru, "Assessing artificial intelligence technology acceptance in managerial accounting," *Electronics*, vol. 11, no. 14, p. 2256, 2022. https://doi.org/10.3390/electronics11142256

[63] S. Marocco, B. Barbieri, and A. Talamo, "Exploring facilitators and barriers to managers' adoption of AI-based systems in decision making: A systematic review," *AI*, vol. 5, no. 4, pp. 2538-2567, 2024. https://doi.org/10.3390/ai5040123

[64] G. Cao, Y. Duan, J. S. Edwards, and Y. K. Dwivedi, "Understanding managers' attitudes and behavioral intentions towards using artificial intelligence for organizational decision-making," *Technovation*, vol. 106, p. 102312, 2021. https://doi.org/10.1016/j.technovation.2021.102312

[65] Z. Jan, F. Ahamed, W. Mayer, N. Patel, G. Grossmann, M. Stumptner, and A. Kuusk, "Artificial intelligence for industry 4.0: Systematic review of applications, challenges, and opportunities," *Expert Syst. Appl.*, vol. 216, p. 119456, 2023. https://doi.org/10.1016/j.eswa.2022.119456

[66] A. Hirvi, "Challenges of adopting AI in Estonian companies in manufacturing and retail fields," unpublished.

[67] N. Rane, S. P. Choudhary, and J. Rane, "Acceptance of artificial intelligence technologies in business management, finance, and e-commerce: factors, challenges, and strategies," *Stud. Econ. Bus. Relat.*, vol. 5, no. 2, pp. 23-44, 2024. https://doi.org/10.48185/sebr.v5i2.1333

[68] G. Wilson, O. Johnson, and W. Brown, "Exploring the integration of artificial intelligence in retail operations," unpublished, 2024. https://doi.org/10.20944/preprints202408.0012.v1

[69] R. Urbani, C. Ferreira, and J. Lam, "Managerial framework for evaluating AI chatbot integration: Bridging organizational readiness and technological challenges," *Bus. Horiz.*, vol. 67, no. 5, pp. 595-606, 2024. https://doi.org/10.1016/j.bushor.2024.05.004

[70] H. Mahmud, A. N. Islam, S. I. Ahmed, and K. Smolander, "What influences algorithmic decision-making? A systematic literature review on algorithm aversion," *Technol. Forecast. Soc. Change*, vol. 175, p. 121390, 2022. https://doi.org/10.1016/j.techfore.2021.121390

[71] I. U. Jan, S. Ji, and C. Kim, "What (de) motivates customers to use AI-powered conversational agents for shopping? The extended behavioral reasoning perspective," *J. Retail. Consum. Serv.*, vol. 75, p. 103440, 2023. https://doi.org/10.1016/j.jretconser.2023.103440

[72] T. Davenport and K. Malone, "Deployment as a critical business data science discipline," *Harvard Data Sci. Rev.*, vol. 3, no. 1, 2021. https://doi.org/10.1162/99608f92.90814c32

[73] M. Paramesha, N. Rane, and J. Rane, "Enhancing resilience through generative artificial intelligence such as ChatGPT," SSRN, 2024. [Online]. Available: SSRN 4832533 https://doi.org/10.2139/ssrn.4832533

[74] S. Kar, A. K. Kar, and M. P. Gupta, "Modeling drivers and barriers of artificial intelligence adoption: Insights from a strategic management perspective," *Intell. Syst. Account. Finance Manag.*, vol. 28, no. 4, pp. 217-238, 2021. https://doi.org/10.1002/isaf.1503

[75] M. Boyd and N. Wilson, "Rapid developments in artificial intelligence: how might the New Zealand government respond?" *Policy Quart.*, vol. 13, no. 4, 2017. https://doi.org/10.26686/pq.v13i4.4619

[76] A. Micu, A. E. Micu, M. Geru, A. Căpăţînă, and M. C. Muntean, "The impact of artificial intelligence use on e-commerce in Romania," *Amfiteatru Econ.*, vol. 23, no. 56, pp. 137-154, 2021. https://doi.org/10.24818/ea/2021/56/137

[77] G. Barenboim, J. Hirn, and V. Sanz, "Symmetry meets AI," *SciPost Phys.*, vol. 11, no. 1, p. 014, 2021. https://doi.org/10.21468/scipostphys.11.1.014

[78] S. Kumar, W. M. Lim, U. Sivarajah, and J. Kaur, "Artificial intelligence and blockchain integration in business: trends from a bibliometric-content analysis," *Inf. Syst. Frontiers*, vol. 25, no. 2, pp. 871-896, 2023. https://doi.org/10.1007/s10796-022-10279-0

[79] V. R. Palanivelu and B. Vasanthi, "Role of artificial intelligence in business transformation," *Int. J. Adv. Sci. Technol.*, vol. 29, no. 4, pp. 392-400, 2020.

[80] T. Fernandes and E. Oliveira, "Understanding consumers' acceptance of automated technologies in service encounters: Drivers of digital voice assistants' adoption," *J. Bus. Res.*, vol. 122, pp. 180-191, 2021. https://doi.org/10.1016/j.jbusres.2020.08.058

[81] F. D. Davis, "Technology acceptance model: TAM," in *Inf. Seeking Behavior and Technology Adoption*, M. N. Al-Suqri and A. S. Al-Aufi, Eds., pp. 205-219, 1989. https://doi.org/10.4018/978-1-4666-8156-9.ch013

[82] P. Silva, "Davis' technology acceptance model (TAM) (1989)," in *Information Seeking Behavior and Technology Adoption: Theories and Trends*, pp. 205-219, 2015. https://doi.org/10.4018/978-1-4666-8156-9.ch013

[83] L. Xiao and V. Kumar, "Robotics for customer service: a useful complement or an ultimate substitute?" *J. Serv. Res.*, vol. 24, no. 1, pp. 9-29, 2021. https://doi.org/10.1177/1094670519878881

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 77-82

Evaluation of the Diagnostic Accuracy of Two AI Models for Analyzing Mammographic Images

Bora Dogan
Medical University of Varna „Prof. Dr. Paraskev Stoyanov“
Varna, Bulgaria
bdogan008@gmail.com

Yanka Baneva
Medical University of Varna „Prof. Dr. Paraskev Stoyanov“
Varna, Bulgaria
yanysh@abv.bg

Yordanka Eneva
Medical University of Varna „Prof. Dr. Paraskev Stoyanov“
Varna, Bulgaria
stemivada@abv.bg

Elena Ivanova
Medical Imaging Clinic
University Hospital St. Marina
Varna, Bulgaria
ed.ivanova@abv.bg

***Abstract*—Early diagnosis of breast cancer is crucial for improving prognosis and reducing mortality. Mammographic screening is a standard method for detecting malignant lesions, but its effectiveness depends on accurate interpretation and clear communication with patients. In recent years, artificial intelligence (AI) has shown promising results in medical diagnostics, yet its ability to analyze mammographic images and provide reliable patient guidance remains insufficiently studied. This pilot study evaluates the diagnostic accuracy and informational quality of two AI models—ChatGPT and X-Ray Insight. To assess their performance, we use a standardized database of mammographic images, including benign and malignant findings. Additionally, patient inquiry scenarios are used to evaluate the AI-generated explanations, recommendations, and overall clarity in response to common patient concerns. The results are compared against expert radiologist assessments. The AI models are evaluated based on diagnostic accuracy, clarity and correctness of explanations, usefulness of recommendations, and potential risks. Both models performed equally in determining the BI-RADS category, Differential Diagnosis, and Next Clinical Steps. The study underscores the challenges of integrating generative AI models into medical diagnostics, revealing both accurate insights and notable inaccuracies compared to expert interpretations. These discrepancies highlight the need for further training and refinement to improve the reliability and applicability of AI in clinical settings.**

***Keywords*—artificial intelligence, ChatGPT, mammography, X-Ray Insight.**

I. INTRODUCTION

Breast cancer remains one of the most prevalent and life-threatening diseases affecting women worldwide, accounting for approximately 460,000 deaths annually [1]. Despite advances in early detection and treatment, it continues to pose a significant public health challenge. The development of breast cancer is influenced by a combination of genetic, hormonal, and lifestyle factors. Several key risk factors are identified that increase a woman's likelihood of developing the disease: genetic and family history, personal medical history – women who have previously been diagnosed with breast cancer face a greater risk of recurrence or developing cancer in the other breast, breast tissue density, hormonal and reproductive factors, such as early onset of menstruation and late menopause, result in prolonged exposure to estrogen and progesterone, increasing breast cancer risk. While breast cancer is a significant health concern, early detection through regular screening plays a crucial role in improving survival rates. Mammograms, clinical breast exams, and self-examinations help identify cancer at an early stage when treatment is most effective. Tumor size, proliferative activity, and lymph node metastasis are fundamental in defining treatment plans and patient prognosis [2], [3]. Mammography is the gold standard for breast cancer screening, used extensively to detect early signs of breast cancer, often before clinical symptoms appear [4]. Despite its efficacy, mammography interpretation is a challenging task. False positives and false negatives can occur, leading to unnecessary biopsies or missed diagnoses. Interpretation of mammograms is inherently subjective, influenced by factors like the radiologist's experience, the quality of the mammogram, and the complexity of the tissue being examined. Studies have shown that even experienced

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8572
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

radiologists can miss certain abnormalities, especially in dense breast tissue [5].

Artificial intelligence (AI) has the potential to transform medical diagnostics by enhancing the accuracy and efficiency of diagnostic processes [6], [7]. AI models can be trained on vast datasets of mammograms and learn to identify complex patterns in images, enabling them to detect even subtle abnormalities that might be overlooked by human eyes. AI can assist radiologists by providing a second opinion, reducing the risk of errors, and enhancing productivity [8]. Additionally, AI systems can help prioritize cases, flagging high-risk images for immediate attention, thus improving workflow efficiency. AI models can analyze mammogram images with great detail, examining microcalcifications, masses, and architectural distortions that indicate potential tumors or abnormalities [9]. This is especially important in cases of dense breast tissue, where traditional mammograms might struggle to identify lesions.

II. Materials and Methods

This pilot study is a comparative evaluation of the diagnostic accuracy of two AI models, ChatGPT-4o and X-Ray Insight, in analyzing mammographic images.

The goal was to assess their ability to detect, classify, and provide differential diagnoses for breast abnormalities compared to ground truth diagnoses and expert radiologist interpretations.

Mammographic images were sourced from Radiopaedia [10] – [30], a trusted repository of medical imaging cases. To identify and select images relevant to this study, specific filters were applied within the "Cases" section: the system was set to "breast," and the study modality was restricted to "mammography." The search results were then sorted by case completion percentage, and only cases with a high diagnostic certainty were chosen. A total of 20 clinical cases comprising mammographic images were selected. These cases represented a broad spectrum of breast pathologies, ensuring a diverse and comprehensive dataset for analysis (Table 1).

Table 1 Summary of clinical case characteristics

Category	Details
Pathology Type	Malignant: 14 (70%), Benign: 6 (30%)
Patient Gender	Female: 18 (90%), Male: 2 (10%)
Age Range	40 to 80 years
Imaging View	CC: 17 (85%), MLO: 3 (15%)

Of the 20 cases, 70% (14/20) represented malignant pathologies, while 30% (6/20) were benign. The cases included 90% (18/20) female patients and 10% (2/20) male patients, with an age range of 40 to 80 years. In terms of imaging views, 85% (17/20) were craniocaudal (CC) views, and 15% (3/20) were mediolateral oblique (MLO) views. All of them were 2D mammograms.

Next, the following study prompt was carefully crafted to be entered into the AI models:

"This is a [2D/3D] mammogram in the [CC/MLO view] of a [age]-year-old [gender] patient, presenting with [clinical presentation, e.g., screening, palpable lump, nipple discharge]. Please describe the findings in the image, including masses (size, shape, margins, density), calcifications (morphology, distribution), architectural distortions, asymmetries, or other abnormalities. Provide a differential diagnosis, listing the most likely diagnosis first, and justify your reasoning. Assess the ACR breast density (Category A, B, C, or D) and assign a BI-RADS category (0-6), explaining your rationale. Estimate the likelihood of malignancy (low, intermediate, high) and recommend next steps for the physician, such as additional imaging, biopsy, or follow-up intervals."

The prompt's design was critical, as it needed to reflect real-world clinical workflows to ensure practical applicability. It incorporated key elements essential for mammogram interpretation, including ACR density and BI-RADS classification. Structured to guide the AI through a systematic analysis, the prompt segmented the task into specific components: findings, differential diagnosis, ACR density, BI-RADS assessment, next steps, and malignancy likelihood. This approach ensured that AI models provided comprehensive and methodical responses. Additionally, the prompt encouraged AI to justify its assessments with rationales and supporting evidence, a crucial factor in evaluating the model's reasoning capabilities. To maintain consistency and facilitate fair comparisons across AI models and datasets, the prompt was standardized.

The final step involved inputting the prompt, along with a single mammographic image from each case, into a new chat session within the AI models. This method was essential for several reasons. First, it ensured that AI evaluated each image independently, free from influence or bias from prior cases—mirroring real-world clinical practice, where radiologists assess each case on its own merits. Second, starting a new session prevented the AI from retaining context from previous interactions, which could otherwise skew results and compromise evaluation fairness. Finally, this approach maintained consistency throughout the study, enabling accurate comparisons of AI performance across different cases and models. By isolating each case, the study upheld scientific rigor and ensured the reliability of its findings.

The AI-generated responses, which were recorded in a shared document, and the relevant portions were organized into a table to facilitate comparison and evaluation. The radiologist's remarks for each case were also included in the comparison to ensure a balanced assessment. Discrepancies between AI models, radiologist, and ground truth diagnoses were analyzed to assess AI diagnostic accuracy, sensitivity, specificity, and clinical reliability.

In this study, we use ChatGPT-4o of OpenAI and X-Ray Insight, developed by AiWebTools.Ai (Table 2). It

is a custom version of ChatGPT that is specifically designed to assist in interpreting medical images and supporting doctors in diagnosis. ChatGPT-4o is an AI model based on natural language processing (NLP). It is not trained for direct analysis of mammographic images and uses a pre-trained medical knowledge base to provide insights into mammography reports. On the other hand, X-Ray Insight is an image-based deep learning model that specializes in analyzing x-ray images, i.e. mammographic images. It can classify findings based on the BI-RADS categories, identify suspicious lesions, and suggest next steps.

TABLE 2 COMPARISON OF THE TWO AI MODELS

Feature	ChatGPT-4o	X-Ray Insight
Input Type	Text, images, and files	Text, images, and files
Processing Method	NLP (Natural Language Processing)	Designed to interpret x-ray images
Can Identify Tumors?	Yes	Yes
Provides BI-RADS Classification?	Yes	Yes
Suggests Clinical Management?	Yes (biopsy, MRI, follow-up)	Yes (based on detected abnormalities)
Main Limitation	Not specifically designed for interpreting x-ray images	Lacks full clinical context, potential overdiagnosis
Best Use Case	Assisting with report analysis and decision support	Detecting abnormalities in screening mammograms

III. RESULTS AND DISCUSSION

To assess AI model performance, we compared their outputs against ground truth diagnoses and radiologist interpretations using the following metrics: diagnostic accuracy, sensitivity, specificity , BI-RADS classification agreement with ground truth, false positives, false negatives, agreement with radiologist's assessments (%). A board-certified radiologist independently reviewed AI outputs and rated the accuracy, relevance, and clinical usability of the AI-generated findings. AI results were compared to pathology-confirmed diagnoses. Discrepancies were analyzed to identify common misclassification trends. 20 cases were reported, and Fig.1 includes:

1. **Findings Description:** AI-generated mammographic interpretation from ChatGPT-4o, AI-generated mammographic interpretation from X-Ray Insight, Ground truth diagnosis based on pathology-confirmed findings.
2. **Radiologist's Assessment of AI Interpretations:** The radiologist reviewed and scored the accuracy of the findings provided by both AI models, errors were noted, including missed abnormalities, incorrect lesion descriptions, and misclassified BI-RADS categories.
3. **BI-RADS Classification Comparison:** AI-assigned BI-RADS categories, Ground truth BI-RADS classification for each case, the radiologist's assessment of whether AI overestimated, underestimated, or correctly assigned BI-RADS levels.
4. **Malignancy Likelihood Estimation:** AI models provided malignancy probability estimates based on findings. The radiologist assessed whether AI was overestimated, underestimated, or correctly estimated malignancy risk compared to pathology.
5. **Recommended Next Steps:** AI models suggested clinical management plans, Ground truth clinical recommendations were included for comparison, and the radiologist evaluated whether AI recommendations were appropriate or unnecessary.

Both ChatGPT-4o and X-Ray Insight often provided similar interpretations (table 3). However, errors occurred in identifying key findings such as: Missing architectural distortion (a crucial early malignancy sign), Incorrectly classifying breast density (ACR categories), Differences in malignancy likelihood estimations (e.g., ChatGPT often reported ≥50%, while X-Ray Insight went for ≥95%). Doctor's interpretations of AI outputs varied, some cases showed consensus with AI findings, while others had significant discrepancies, where AI misclassified benign vs. malignant lesions. For the BI-RADS classification consistency, BI-RADS 4 and 5 cases (high suspicion for malignancy) were more consistently identified while BI-RADS 2 and 3 cases (benign or probably benign findings) had more misinterpretations

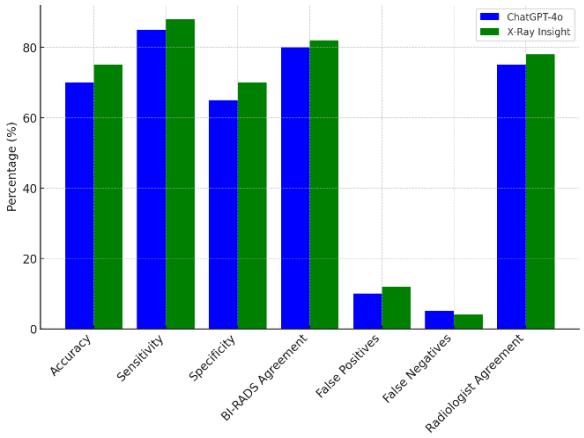


Fig. 1. Evaluation metrics comparison of AI models.

AI models misidentified normal post-surgical scars as potential malignancies. Some benign conditions (e.g., gynecomastia, hamartomas) were flagged as potentially malignant.

Among the 20 cases analyzed, the most common errors were: missed architectural distortion in 3 cases, overestimated malignancy in 4 cases, incorrect BI-RADS classification in 5 cases, missed lymph node involvement in 2 cases.

ChatGPT-4o and X-Ray Insight had an accuracy of ~5-6% when compared strictly to the Ground truth.

Doctors agreed with AI models in ~64% of cases but had disagreements in specific borderline cases.

TABLE 3 THE COMPARISON BETWEEN CHATGPT-4O AND X-RAY INSIGHT BASED ON THEIR PERFORMANCE ACROSS TWENTY CASES

Metric	ChatGPT-4o	X-Ray Insight
Overall Accuracy (%)	65%	70%
BI-RADS 4-5 Accuracy (%)	85%	87%
BI-RADS 1-3 Accuracy (%)	50%	55%
False Positives (Overestimated Risk)	4 cases	5 cases
False Negatives (Missed Malignancies)	2 cases	1 case
Doctor Agreement (%)	64%	66%
Correct Next Step Recommendation (%)	85%	88%

ChatGPT-4o and X-Ray Insight had an accuracy of ~5-6% when compared strictly to the Ground truth. Doctors agreed with AI models in ~64% of cases but had disagreements in specific borderline cases.

For the Findings Description, AI models detected abnormalities correctly in ~60% of cases. They accurately described tumor shape, density, and calcifications, while missing key features in ~40% of cases.

AI models have a high ability to identify the correct pathology. Almost ~75% of the cases were correctly listed by the models. Difficulty appeared when distinguishing rare conditions and post-surgical changes from malignancy. For the AI models' performance in categorizing breast tissue, the agreement with the Ground truth is ~80%. For the malignancy likelihood estimation, AI risk estimation was more aligned with human experts in high-suspicion cases but overcalled risk in borderline lesions.

Both AI models generally provided the correct Next steps for the treatment recommendations but sometimes failed in triaging lower-risk cases.

Additionally, the AI model's responses for each clinical case were analyzed across six components: Findings Description, Differential Diagnosis, ACR Density, BI-RADS, Malignancy Likelihood, and Next Steps. The radiologist evaluated each component across all cases, assigning scores on a scale from 2 to 6, with 2 representing the lowest grade and 6 the highest.

Fig. 2 illustrates the percentage distribution of individual scores assigned to ChatGPT-4o and X-Ray Insight across all components of the clinical cases. The score distribution indicates that X-Ray Insight received a higher proportion of top scores (6) at 57.50%, compared to 50.83% for ChatGPT-4o, suggesting a stronger overall performance. Lower scores (3 and 2) were relatively infrequent for both models, though ChatGPT-4o had a higher percentage of the lowest score (2) at 13.33% compared to 7.50% for X-Ray Insight, suggesting occasional inconsistencies.

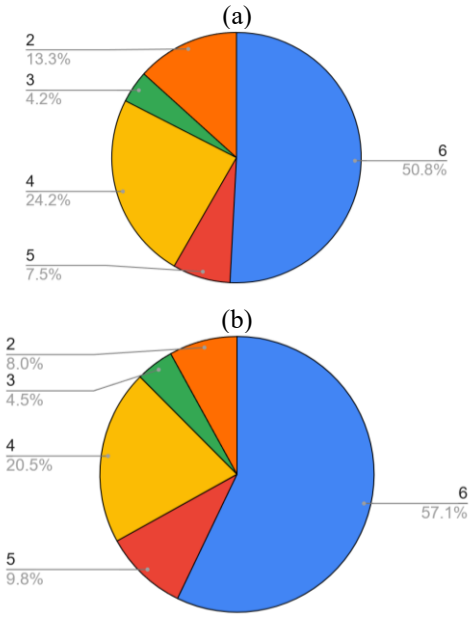


Fig. 2. Percentage distribution of scores assigned to ChatGPT-4o (a) and X-Ray Insight (b)

Fig. 3 presents the average scores assigned to AI models by the radiologist for each clinical case. X-Ray Insight generally scored higher in malignancy-related cases such as Invasive Ductal Carcinoma (IDC), Multifocal Breast Cancer, and Plasma Cell Mastitis, aligning with its strength in Findings Description and Malignancy Likelihood. ChatGPT-4o performed better in Ductal Carcinoma in Situ (DCIS), Invasive Solid Papillary Breast Carcinoma, and Axillary Tail Breast Cancer, suggesting potential advantages in interpretative aspects of ACR Density. Some cases, including Fibroadenoma, Fibrocystic Disease, and Invasive Breast Carcinoma, showed equal performance, indicating areas where AI models provide comparable insights.

IV. CONCLUSIONS

AI models perform well in high-suspicion cancer cases (BI-RADS 4-5) but struggle with low-risk or benign cases. AI is useful as a second opinion tool but cannot yet replace radiologists. Training AI on more diverse mammography datasets could improve its accuracy, especially for borderline cases.

ChatGPT-4o is best for interpreting mammography reports and helping doctors make decisions based on text-based data. X-Ray Insight is ideal for image-based detection, helping radiologists spot potential cancers directly from mammograms. Combining the two AI models could create a hybrid system, where text-based insights and image-based detections work together for more accurate diagnoses.

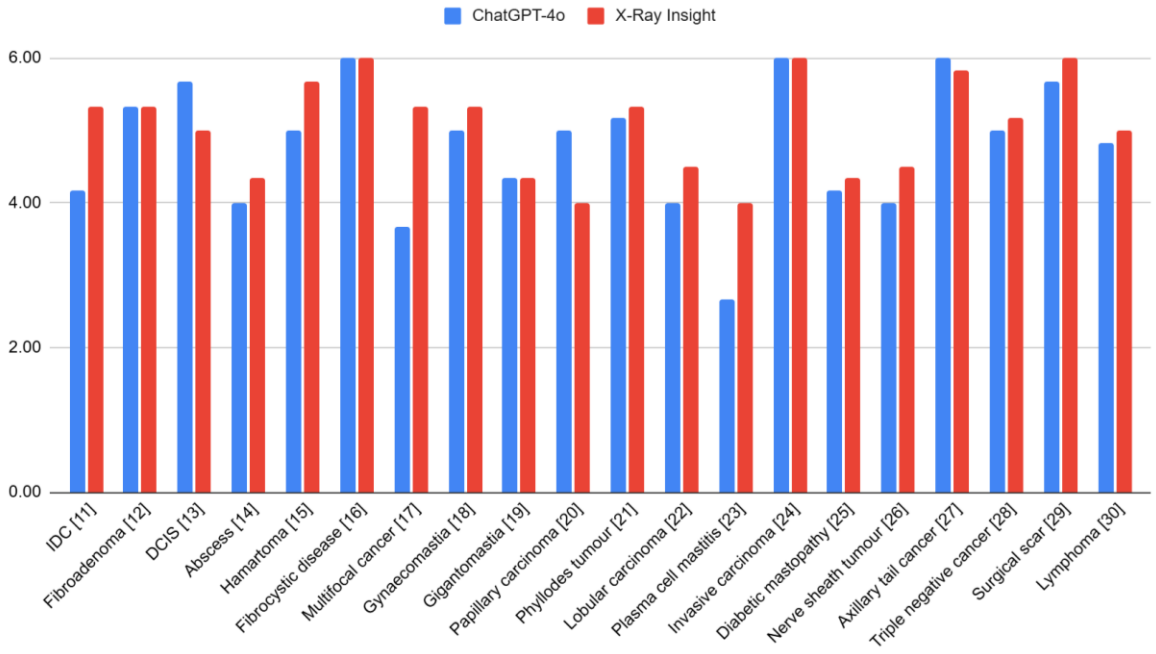


Fig. 3. Radiologist-assigned average scores, ranging from 2 to 6, for ChatGPT-4o and X-Ray Insight for each clinical case.

The integration of AI into mammography is a game-changer for breast cancer detection, improving accuracy, efficiency, and early detection rates. By automating routine analysis, providing a second opinion, reducing human error, and supporting radiologists in decision-making, AI is enhancing the ability to detect breast cancer earlier, which is key to improving patient outcomes. As AI technology continues to evolve, its integration with multi-modal imaging, its ability to learn from diverse data, and its potential to reduce health disparities will only continue to make mammography a more effective tool in the fight against breast cancer.

X-Ray Insight provides results without sufficient justification, limiting its use for learning while with ChatGPT-4o medical students can input case descriptions and get step-by-step diagnostic reasoning, and may receive an explanation of why a case falls into a certain BI-RADS category.

V. REFERENCES

[1] G. Dimitrov, I. Gavrilov, and T. Sedloev, Eds., *Breast Cancer*. Paradigm, 2014.

[2] V. Parvanova, *Breast Cancer - Early Detection and Modern Treatment*, Sofia: Tip - Top Press, 2006.

[3] T. Deliyski and D. Damyanov, *Recommendations for Complex Treatment of Breast Cancer*, Pleven: University Hospital-Pleven EAD, 2005.

[4] N. Day and R. Warren, "Mammographic screening and mammographic patterns," *Breast Cancer Res.*, vol. 2, no. 4, pp. 247-251, 2000, doi: 10.1186/bcr64.

[5] E. U. Ekpo, M. Alakhras, and P. Brennan, "Errors in Mammography Cannot be Solved Through Technology Alone," *Asian Pac. J. Cancer Prev.*, vol. 19, no. 2, pp. 291-301, 2018, doi: 10.22034/APJCP.2018.19.2.291.

[6] Y. Eneva and B. Dogan, "A Qualitative Assessment of Medical Diagnosis Capabilities of Three Artificial Intelligence Models: ChatGPT-4o, CodyMD, and Dr. Gupta," *J. Biosci. Med.*, vol. 12, pp. 243-254, 2024, doi: 10.4236/jbm.2024.1211021.

[7] Y. Eneva and B. Dogan, "Evaluation of Medical Diagnosis Capabilities of Three Artificial Intelligence Models – ChatGPT-3.5, Google Gemini, Microsoft Copilot: Sustainable Development Goals (SDGs)," *J. Lifestyle and SDGs Review*, vol. 5, no. 2, e03545, 2025, doi: 10.47172/2965-730X.SDGsReview.v5.n02.pe03545.

[8] D. Killock, "AI outperforms radiologists in mammographic screening," *Nat. Rev. Clin. Oncol.*, vol. 17, no. 3, p. 134, 2020, doi: 10.1038/s41571-020-0329-7.

[9] S. Al Muhaisen, O. Safi, A. Ulayan, et al., "Artificial Intelligence-Powered Mammography: Navigating the Landscape of Deep Learning for Breast Cancer Detection," *Cureus*, Mar. 2024, doi: 10.7759/cureus.56945.

[10] Radiopaedia.org, "The peer-reviewed collaborative Radiology Resource," [Online]. Available: https://radiopaedia.org/. [Accessed: Mar. 1, 2025].

[11] H. Al Ja'afreh, "Invasive ductal carcinoma," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-174470. [Accessed: Feb. 3, 2025].

[12] A. Ashraf, "Giant fibroadenoma," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-90946. [Accessed: Feb. 3, 2025].

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8572
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

[13] W. Lee, "Ductal carcinoma in situ," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-160609. [Accessed: Feb. 3, 2025].

[14] A. Ruiz Gaviria, "Breast abscess - male," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-163546. [Accessed: Feb. 3, 2025].

[15] V. Pai, "Hamartoma of the breast," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-27023. [Accessed: Feb. 7, 2025].

[16] M. Altintakan, "Multiple fibroadenomas and fibrocystic disease," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-75028. [Accessed: Feb. 7, 2025].

[17] M. Niknejad, "Multifocal breast cancer - 2D mammography and tomosynthesis," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-156732. [Accessed: Feb. 7, 2025].

[18] A. Abougazia, "Gynaecomastia," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-23657. [Accessed: Feb. 7, 2025].

[19] A. Ashraf, "Gigantomastia," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-150940. [Accessed: Feb. 7, 2025].

[20] W. Lee, "Invasive solid papillary carcinoma of the breast," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-161313. [Accessed: Feb. 7, 2025].

[21] A. Ashraf, "Malignant phyllodes tumour," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-89374. [Accessed: Feb. 7, 2025].

[22] S. Sorrentino, "Invasive lobular carcinoma," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-34821. [Accessed: Feb. 8, 2025].

[23] A. Ranchod, "Plasma cell mastitis," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-175533. [Accessed: Feb. 8, 2025].

[24] I. Khatatbeh, "Invasive breast carcinoma," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-190669. [Accessed: Feb. 8, 2025].

[25] N. Abidin, "Diabetic mastopathy," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-58607. [Accessed: Feb. 8, 2025].

[26] G. Kruger, "Nerve sheath tumour - breast," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-18778. [Accessed: Feb. 8, 2025].

[27] H. Knipe, "Axillary tail breast cancer," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-43262. [Accessed: Feb. 9, 2025].

[28] A. Abdelrahman, "Triple negative breast cancer," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-78448. [Accessed: Feb. 9, 2025].

[29] G. Kruger, "Surgical scar of the breast," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-22389. [Accessed: Feb. 9, 2025].

[30] G. Baratelli, "Non-Hodgkin lymphoma arising from an intramammary lymph node," *Case study, Radiopaedia.org*, [Online]. Available: https://doi.org/10.53347/rID-42463. [Accessed: Feb. 9, 2025].

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 83-92

Comparative Analysis of the Capabilities of Two Artificial Intelligence Models for Chest X-Ray Image Interpretation

Bora Dogan
Faculty of Medicine
Medical University of Varna „Prof. Dr. Paraskev Stoyanov“
Varna, Bulgaria
bdogan008@gmail.com

Yordanka Eneva
Department of Physics and Biophysics, Faculty of Pharmacy
Medical University of Varna „Prof. Dr. Paraskev Stoyanov“
Varna, Bulgaria
stemivada@abv.bg

Yanka Baneva
Department of Physics and Biophysics, Faculty of Pharmacy
Medical University of Varna „Prof. Dr. Paraskev Stoyanov“
Varna, Bulgaria
yanysh@abv.bg

Elena Ivanova
Medical Imaging Clinic
University Hospital St. Marina
Varna, Bulgaria
ed.ivanova@abv.bg

***Abstract*—The automated interpretation of chest X-rays with the help of artificial intelligence (AI) is gaining increasing importance in medical diagnostics. Technologies based on machine learning and deep neural networks demonstrate the potential to assist radiologists by accelerating the diagnostic process and reducing subjective errors. However, the effectiveness of different AI models varies depending on the algorithms, training data used, and methods of analysis. This pilot study conducts a comparative analysis between two AI models – ChatGPT and X-Ray Insight, a GPT model specifically developed to assist in the interpretation of medical images and support doctors in diagnostics. Their ability to interpret chest X-rays is evaluated, along with an examination of their strengths and limitations in real clinical scenarios. A standardized database of radiographs is used, including normal findings, pneumonia, pulmonary infiltrates, and other pathological conditions. The evaluation of the models includes diagnostic accuracy, clarity and correctness of interpretations, the usefulness of the provided explanations, and recommendations for further examinations. The obtained results are compared with expert radiological assessments. A paired t-test revealed no significant differences in Findings Description and Differential Diagnosis, but X-Ray Insight performed significantly better in recommending the Next Steps, suggesting stronger recommendations for further management. The study highlights the challenges and potential of generative and image-based AI models in radiographic diagnostics. Further adaptation and training of the models are necessary to achieve clinical reliability and effectiveness.**

Keywords*— *artificial intelligence, ChatGPT, chest X-rays, X-Ray Insight.

I. INTRODUCTION

The use of artificial intelligence (AI) in medicine has the potential to revolutionize medical imaging diagnostics. Deep learning algorithms have demonstrated exceptional efficiency in analyzing X-ray images [1]. AI-driven models have demonstrated the potential to assist radiologists in interpreting complex imaging studies, thereby improving diagnostic accuracy and workflow efficiency. The integration of AI into medical imaging has the potential to address challenges such as high workload, diagnostic variability among radiologists, and the need for rapid and accurate assessments [2]. However, despite the growing interest in AI applications, concerns regarding the reliability, clinical applicability, and interpretability of AI-generated analyses remain critical areas of study.

Chest X-ray interpretation is one of the most fundamental tasks in radiology, serving as a primary imaging modality for detecting thoracic diseases [3], including infectious conditions, cardiovascular abnormalities, and malignancies. Traditional diagnostic approaches [4] rely on the expertise of radiologists, who assess imaging findings in conjunction with clinical information to reach an accurate diagnosis and formulate

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8573
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

an appropriate treatment plan. In recent years, AI-based models have been developed to automate and enhance the analysis of chest X-rays, offering promising results in disease detection, differential diagnosis formulation, and clinical decision support [5]. However, a crucial factor in X-ray interpretation is image quality, which directly impacts diagnostic accuracy. Research on computational phantoms and simulation studies, particularly in mammography [6], [7], has demonstrated their ability to enhance image quality and refine key imaging parameters. Integrating these advancements into AI-driven chest X-ray analysis could help minimize interpretation errors and improve overall diagnostic performance.

This study aims to evaluate and compare the performance of two AI models, ChatGPT-4o and X-Ray Insight, in interpreting chest X-ray images. The study specifically assesses their capabilities across three key criteria: Findings Description, Differential Diagnosis [8], [9], and Next Steps. By analyzing the effectiveness of these models, we seek to determine their potential role in assisting radiologists and enhancing patient care. Furthermore, this research explores whether AI-generated recommendations align with those of human experts and whether they can be effectively integrated into clinical workflows. Understanding the strengths and limitations of these AI systems is essential for optimizing their use in practice and ensuring that they complement rather than replace human expertise.

II. MATERIALS AND METHODS

This pilot study is a comparative evaluation of the diagnostic accuracy of two AI models, ChatGPT-4o of OpenAI and X-Ray Insight, developed by AiWebTools.Ai, in analyzing chest X-rays.

The goal was to assess their ability to detect, classify, and provide differential diagnoses for chest abnormalities compared to ground truth diagnoses and expert radiologist interpretations.

TABLE 1 SUMMARY OF CLINICAL CASE CHARACTERISTICS

Category	Details
Imaging View	PA: 16 (80%), AP: 4 (20%)
Patient Gender	Male: 12 (60%), Female: 8 (40%)
Age Range	9 to 90 years
Pathology Type	Infectious: 6 (30%), Cardiovascular: 4 (20%), Neoplastic: 5 (25%), Other: 5 (25%)

Chest X-ray images were obtained from Radiopaedia, a reputable platform for medical imaging cases. [10 – 29] To identify and select images relevant to this study, specific filters were applied within the "Cases" section: the system was set to "chest," and the study modality was restricted to "X-ray." The search results were sorted by case completion percentage, and only cases with a high diagnostic certainty were included. A total of 20 clinical cases, comprising chest X-ray images, were selected. These cases encompassed a wide range of thoracic pathologies, ensuring a diverse and representative dataset for analysis (Table 1).

Of the 20 cases, 80% (16/20) were posterior-anterior (PA) views, while 20% (4/20) were anterior-posterior (AP) views. The cases included 60% (12/20) male patients and 40% (8/20) female patients, with an age range of 9 to 90 years. The pathologies represented infectious diseases (e.g., pneumonia, tuberculosis), cardiovascular conditions (e.g., aortic valve stenosis, pericardial effusion), neoplastic processes (e.g., adenocarcinoma, thymoma), and other thoracic abnormalities (e.g., hiatal hernia, Chilaiditi sign).

Next, the following study prompt was carefully crafted to be entered into the AI models:

"This is a chest X-ray in the [PA/AP/lateral view] of a [age]-year-old [gender] patient, presenting with [clinical presentation, e.g., cough, shortness of breath, chest pain, fever, hemoptysis, or routine screening]. Please describe the findings in the image, including abnormalities in the lungs (e.g., opacities, nodules, pneumothorax, pleural effusion), mediastinum (e.g., widening, masses, lymphadenopathy), cardiac silhouette (e.g., size, shape, chamber enlargement), bony structures (e.g., fractures, lesions), and any other findings (e.g., diaphragmatic elevation, free air). Provide a differential diagnosis, listing the most likely diagnosis first, and justify your reasoning with a confidence level (low, intermediate, high) for each. Recommend next steps for the physician, such as additional imaging (e.g., CT scan, ultrasound), laboratory tests, biopsy, follow-up intervals, or urgent interventions (e.g., thoracentesis, chest tube placement) if life-threatening conditions are suspected."

The prompt was designed to guide the AI through a systematic and detailed analysis of the chest X-ray, ensuring comprehensive and structured responses. It also encouraged the AI to provide rationales and evidence for its assessments, which was critical for evaluating the model's reasoning capabilities. To maintain consistency and enable fair comparisons across different AI models and datasets, the prompt was standardized.

The final step involved inputting the prompt, along with a single chest X-ray image from each case, into a new chat session within the AI models. This approach was essential for several reasons. First, it ensured that the AI evaluated each image independently, without influence or bias from previous cases, closely mimicking real-world clinical practice where radiologists assess each case on its own merits. Second, starting a new session prevented the AI from retaining context or information from prior interactions, which could distort results and compromise the fairness of the evaluation. Finally, this method maintained consistency across the study, enabling a more accurate comparison of the AI's performance across different cases and models. By isolating each case, the study upheld scientific rigor and ensured the reliability of its findings.

The responses generated by the AI were recorded in a shared document, and the relevant portions were organized into a table to facilitate comparison and evaluation. The radiologist's remarks for each case were also included in the comparison to ensure a balanced assessment.

The paired t-test was conducted, using R software (version 4.3.2; 2023 The R Foundation for Statistical Computing) to compare the performance of ChatGPT-4o and X-Ray Insight in interpreting chest X-ray images across three criteria: Findings Description, Differential Diagnosis, and Next Steps. The paired t-test was chosen because both models evaluated each case, allowing for a direct comparison of their performance. This method is ideal for detecting statistically significant differences in means while accounting for the paired nature of the data.

III. RESULTS AND DISCUSSION

A board-certified radiologist analyzed the AI models' responses for each clinical case across three components: Findings Description, Differential Diagnosis, and Next Steps. The radiologist evaluated each component across all cases, assigning scores on a scale from 2 to 6, with 2 representing the lowest grade and 6 the highest. The table with AI-generated answers to the relative clinical cases together with scores from the radiologist are given in Appendix.

Fig. 1 illustrates the percentage distribution of individual scores assigned to ChatGPT-4o and X-Ray Insight across all components of the clinical cases. The score distribution indicates that X-Ray Insight received a higher proportion of top scores (6) at 41.67%, compared to 33.33% for ChatGPT-4o, suggesting stronger overall performance. Mid-range scores (4 and 5) were more evenly distributed between the two models, though ChatGPT-4o had a slightly higher percentage of scores in the 4 range (23.33% vs. 16.67%). Lower scores (3 and 2) were relatively uncommon for both models, with ChatGPT-4o receiving slightly lower scores than X-Ray Insight.

Fig. 2 presents the average scores assigned to AI models by the radiologist for each clinical case. X-Ray Insight generally performed slightly better in key diagnostic cases. It received higher scores in conditions such as Aortic Valve Stenosis, Giant Hiatal Hernia, and Bronchial Carcinoid. Both models performed equally in cases like Chilaiditi Sign, Oesophageal-Pleural Fistula, Sarcoidosis, Right Lobe Consolidation, Mitral Valve Regurgitation, Adenocarcinoma, Pulmonary Metastases, and COVID-19 Pneumonia, indicating comparable diagnostic accuracy. ChatGPT-4o demonstrated a slight advantage in Phrenic Nerve Palsy but received lower scores for Pneumothorax and Thymoma.

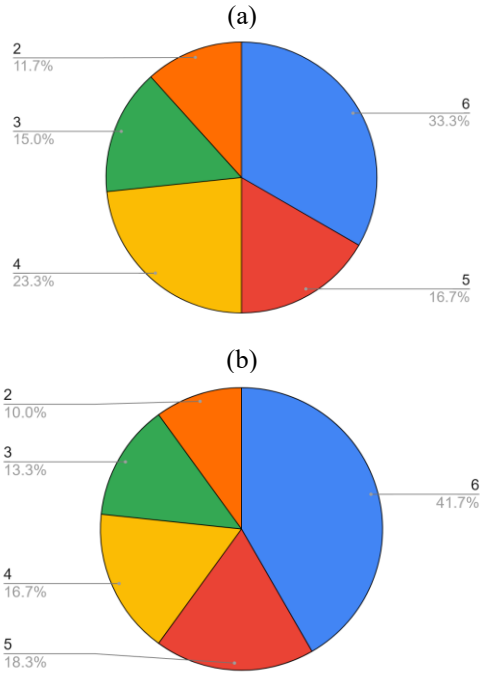


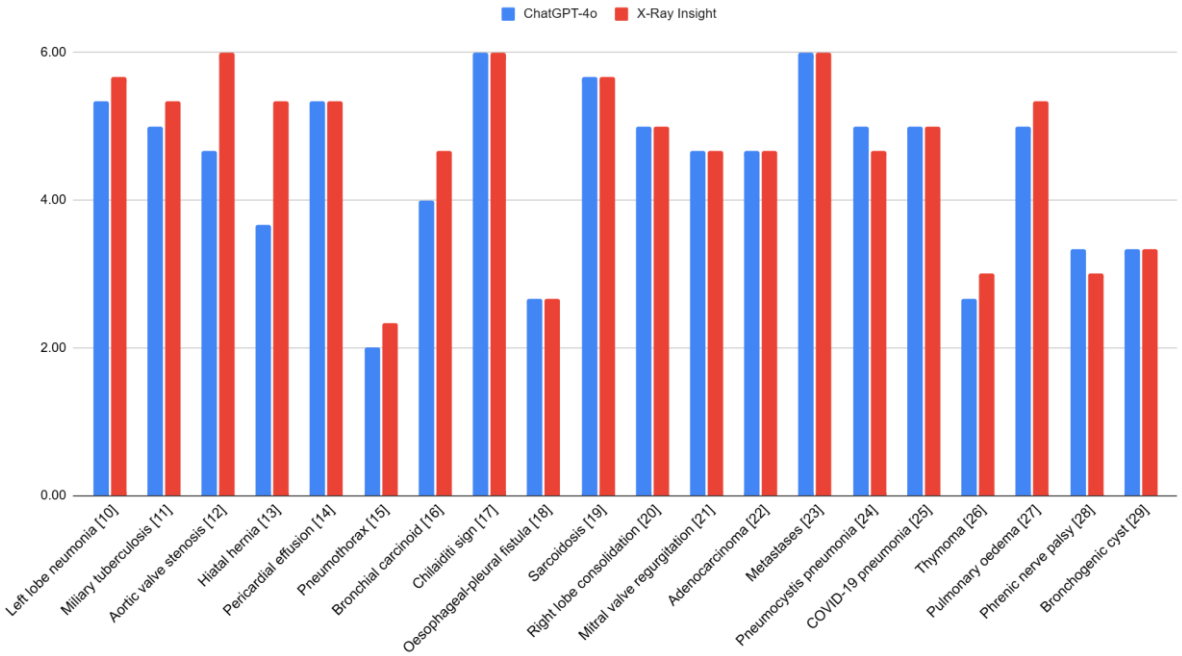
Fig. 1. Percentage distribution of scores assigned to ChatGPT-4o (a) and X-Ray Insight (b).

Table 2 presents the results of the paired t-test, including the mean difference (MD), standard deviation of differences (SD), t-value, degrees of freedom (df), and p-value.

TABLE 2 THE RESULTS OF THE PAIRED T-TEST

Criteria	**MD**	**SD**	**t-value**	**df**	**p-value**
Findings Description	-0.2	0.894	-1	19	0.33
Differential Diagnosis	-0.1	0.852	-0.525	19	0.606
Next Steps	-0.35	0.671	-2.33	19	0.031

The statistical analysis revealed that both AI models performed similarly in Findings Description and Differential Diagnosis, with no significant differences observed ($p = 0.330$ and $p = 0.606$, respectively). These results indicate that ChatGPT-4o and X-Ray Insight possess comparable abilities in identifying radiographic abnormalities and generating differential diagnoses. This suggests that both models could serve as valuable tools in supporting radiologists by providing initial impressions of chest X-ray findings.



Radiologist-assigned average scores, ranging from 2 to 6, for ChatGPT-4o and X-Ray Insight for each clinical case.

However, a notable discrepancy was observed in the Next Steps category, where X-Ray Insight outperformed ChatGPT-4o ($p = 0.031$). This indicates that X-Ray Insight is more effective at recommending appropriate clinical actions based on the interpreted findings. The superior performance in this category may stem from differences in training data, algorithmic design, or model optimization strategies. This finding is particularly relevant in clinical settings, as appropriate follow-up actions are crucial for patient management and treatment planning.

Despite these findings, it is essential to consider the study's limitations. The dataset consisted of only 20 clinical cases, which may not fully represent the broad spectrum of thoracic pathologies encountered in real-world practice. Additionally, while efforts were made to standardize prompts and minimize biases, AI models inherently rely on training data that may introduce certain limitations. Future research should explore larger datasets and incorporate diverse imaging conditions to further validate these results.

IV. Conclusions

This study provides valuable insights into the capabilities of AI models in chest X-ray interpretation. The findings suggest that ChatGPT-4o and X-Ray Insight perform comparably in describing radiographic findings and formulating differential diagnoses. However, X-Ray Insight demonstrates superior performance in recommending the next steps, highlighting its potential as a more clinically actionable tool. While AI-assisted radiology holds promise, further research is necessary to refine these models, expand their training datasets, and ensure their safe and effective integration into clinical workflows. Ultimately, AI should be viewed as a complementary tool to human expertise, enhancing diagnostic accuracy and patient care rather than replacing radiologists.

V. References

[1] M. A. Mazurowski, M. Buda, A. Saha, and M. R. Bashir, "Deep learning in radiology: An overview of the concepts and a survey of the state of the art with a focus on MRI," J. Magn. Reson. Imaging, vol. 49, no. 4, pp. 939–954, 2019, doi: 10.1002/jmri.26534.

[2] J. G. Lee, S. Jun, Y. W. Cho, et al., "Deep learning in medical imaging: general overview," Korean J. Radiol., vol. 18, pp. 570–584, 2017, doi: 10.3348/kjr.2017.18.4.570.

[3] G. Litjens, T. Kooi, B. E. Bejnordi, et al., "A survey on deep learning in medical image analysis," Med. Image Anal., vol. 42, pp. 60–88, 2017, doi: 10.1016/j.media.2017.07.005.

[4] S. Waite, A. Grigorian, R. G. Alexander, S. L. Macknik, M. Carrasco, D. J. Heeger, and S. Martinez-Conde, "Analysis of perceptual expertise in radiology - current knowledge and a new perspective," Front. Hum. Neurosci., vol. 13, p. 213, Jun. 2019, doi: 10.3389/fnhum.2019.00213. Erratum in: Front. Hum. Neurosci., vol. 13, p. 272, Aug. 2019, doi: 10.3389/fnhum.2019.00272.

[5] S. Nazir, D. M. Dickson, and M. U. Akram, "Survey of explainable artificial intelligence techniques for biomedical imaging with deep neural networks," Comput. Biol. Med., vol. 156, p. 106668, 2023, doi: 10.1016/j.compbiomed.2023.106668.

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8573
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

[6] Y. Baneva, T. Georgiev, and K. Bliznakova, "Design and use of computational models for contrast-enhanced spectral mammography," Scripta Scientifica Medica, vol. 54, no. 3, pp. 27-33, 2022, doi: 10.14748/ssm.v54i2.8361.

[7] Y. Baneva and K. Bliznakova, "Influence of incident mammography spectra and breast phantom characteristics on mammography features," in Contemporary Methods in Bioinformatics and Biomedicine and Their Applications, S. S. Sotirov, T. Pencheva, J. Kacprzyk, K. T. Atanassov, E. Sotirova, and G. Staneva, Eds., BioInfoMed 2020, Lecture Notes in Networks and Systems, vol. 374, Springer, Cham, 2022, pp. 573-581, doi: 10.1007/978-3-030-96638-6_41.

[8] Y. Eneva and B. Dogan, "A Qualitative Assessment of Medical Diagnosis Capabilities of Three Artificial Intelligence Models: ChatGPT-4o, CodyMD, and Dr. Gupta," J. Biosci. Med., vol. 12, pp. 243–254, 2024, doi: 10.4236/jbm.2024.1211021.

[9] Y. Eneva and B. Dogan, "Evaluation of Medical Diagnosis Capabilities of Three Artificial Intelligence Models – ChatGPT-3.5, Google Gemini, Microsoft Copilot: Sustainable Development Goals (SDGs)," J. Lifestyle and SDGs Review, vol. 5, no. 2, e03545, 2025, doi: 10.47172/2965-730X.SDGsReview.v5.n02.pe03545.

[10] R. Kulkarni, "Left upper lobe pneumonia," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-27378. [Accessed: Feb. 12, 2025].

[11] M. Holland, "Miliary tuberculosis," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-20025. [Accessed: Feb. 12, 2025].

[12] F. Gaillard, "Aortic valve stenosis," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-15391. [Accessed: Feb. 12, 2025].

[13] K. Drežewski, "Giant hiatal hernia," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-95741. [Accessed: Feb. 24, 2025].

[14] H. Knipe, "Pericardial effusion," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-42975. [Accessed: Feb. 12, 2025].

[15] M. Mohammed, "Traumatic pneumothorax," Case study, Radiopaedia.org, [Online]. Available: https://radiopaedia.org/cases/204575. [Accessed: Feb. 13, 2025].

[16] L. Silverstone, "Bronchial carcinoid," Case study, Radiopaedia.org, [Online]. Available: https://radiopaedia.org/cases/202984. [Accessed: Feb. 13, 2025].

[17] A. Shetty, "Chilaiditi sign," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-26874. [Accessed: Feb. 14, 2025].

[18] L. Hartley, "Oesophageal-pleural fistula (spontaneous)," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-52346. [Accessed: Feb. 14, 2025].

[19] M. Hall, "Sarcoidosis," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-44870. [Accessed: Feb. 14, 2025].

[20] M. Mohammed, "Right lower lobe consolidation," Case study, Radiopaedia.org, [Online]. Available: https://radiopaedia.org/cases/205135. [Accessed: Feb. 15, 2025].

[21] M. Holland, "Mitral valve regurgitation," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-18796. [Accessed: Feb. 15, 2025].

[22] J. Ren, "Adenocarcinoma of lung," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-24509. [Accessed: Feb. 15, 2025].

[23] A. Shetty, "Pulmonary metastases - cannonball," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-27024. [Accessed: Feb. 15, 2025].

[24] A. Dixon, "Pneumocystis pneumonia," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-9613. [Accessed: Feb. 15, 2025].

[25] M. Al-Tibi, "COVID-19 pneumonia," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-75305. [Accessed: Feb. 15, 2025].

[26] A. Alomari, "Thymoma," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-181667. [Accessed: Feb. 15, 2025].

[27] A. Alhelali, "Pulmonary oedema," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-51448. [Accessed: Feb. 15, 2025].

[28] D. Smith, "Left phrenic nerve palsy," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-37404. [Accessed: Feb. 15, 2025].

[29] A. Johnstone, "Bronchogenic cyst," Case study, Radiopaedia.org, [Online]. Available: https://doi.org/10.53347/rID-77801. [Accessed: Feb. 15, 2025].

APPENDIX

TABLE. AI-GENERATED ANSWERS TO THE RELATIVE CLINICAL CASES TOGETHER WITH SCORES FROM THE RADIOLOGIST

To visually highlight the performance of the AI models relative to the correct answers, colors to the cells in the table were assigned based on the closeness of the answers to the ground truth.	
Green	The AI model's answer is correct or very close to the correct answer
Yellow	The AI model's answer is partially correct or has minor inaccuracies
Red	The AI model's answer is incorrect or significantly deviates from the correct answer

Case	Criteria	ChatGPT-4o	X-Ray Insight	Ground Truth	Specialist
1	**Findings Description**	Left upper lobe consolidation noted, but air bronchograms not clearly visible. No pleural effusion or pneumothorax.	Left upper lobe consolidation with air bronchogram sign noted. No pleural effusion or pneumothorax	Left upper zone consolidation with air bronchograms typical of pneumonia. No pleural effusion, pneumothorax, or other abnormalities	5; 6
	Differential Diagnosis	Left upper lobe pneumonia (most likely), but includes less likely diagnoses like lung abscess and	Community-acquired pneumonia (most likely), with appropriate consideration of TB and pulmonary	Left upper lobe pneumonia	5; 6

		malignancy without strong justification	embolism. Less emphasis on unlikely diagnoses like malignancy		
	Next Steps	Recommends antibiotics, CT scan, sputum analysis, and blood cultures. Suggests follow-up in 6 weeks, which is less urgent than needed	Recommends immediate antibiotics, CT scan, sputum analysis, blood cultures, and repeat X-ray in 48-72 hours. Considers hospitalization if severe, aligning well with clinical urgency	Immediate antibiotics, follow-up imaging, sputum analysis, and blood cultures. Consider hospitalization if severe	6; 5
2	**Findings Description**	Multiple small, diffuse nodular opacities throughout both lung fields. No pleural effusion, pneumothorax, or lymphadenopathy	Diffuse micronodular opacities throughout both lung fields. No pleural effusion, pneumothorax, or obvious lymphadenopathy	Widespread, randomly distributed innumerable tiny nodules in both lungs. No consolidation, pleural fluid, or lymphadenopathy	4; 4
	Differential Diagnosis	Miliary TB (most likely), disseminated fungal infection, metastatic disease, sarcoidosis, pneumoconiosis	Miliary TB (most likely), disseminated fungal infection, metastatic disease, pneumoconiosis, sarcoidosis	Miliary TB (most likely), miliary metastases, atypical infections, hypersensitivity, pneumoconioses (if history fits)	6; 6
	Next Steps	Recommends HRCT, sputum AFB, GeneXpert, blood cultures, and HIV testing. Suggests bronchoscopy if sputum is negative, but lacks emphasis on urgency of anti-TB therapy	Recommends immediate sputum AFB, GeneXpert, HRCT, HIV testing, and urgent anti-TB therapy. Highlights need for hospitalization if worsening	Immediate TB confirmation (sputum AFB, GeneXpert), HRCT chest, HIV testing, and urgent anti-TB therapy	5; 6
3	**Findings Description**	Mild aortic valve calcification noted, but misses the prominent ascending aorta. Correctly identifies no lung/pleural abnormalities	Prominent aortic arch and widened mediastinum noted, consistent with ascending aorta enlargement. Correctly identifies no lung/pleural abnormalities	Prominent right mediastinal border (ascending aorta), normal descending aorta, normal heart size, no lung/pleural abnormalities	4; 6
	Differential Diagnosis	Aortic valve stenosis (most likely), left ventricular hypertrophy, early heart failure, coronary artery disease (less likely)	Aortic valve stenosis (most likely), hypertensive heart disease, aortic aneurysm (less likely), mild pulmonary congestion	Aortic valve stenosis (most likely), hypertensive heart disease, aortic aneurysm (less likely)	6; 6
	Next Steps	Recommends echocardiography, CT chest, BNP, and cardiology referral. Lacks emphasis on urgency if severe aortic stenosis is confirmed	Recommends echocardiography, CT angiography, BNP, ECG, and cardiology referral. Highlights urgency if severe aortic stenosis is confirmed	Echocardiography (TTE) to confirm aortic stenosis, CT angiography if aortic aneurysm suspected, BNP, ECG, cardiology referral	4; 6
4	**Findings Description**	Correctly identifies pacemaker placement and no pneumothorax. Misses the large air-fluid level but notes elevated left hemidiaphragm and abnormal gastric position	Correctly identifies pacemaker placement, no pneumothorax, and notes a large retrocardiac radiolucency (giant hiatal hernia). Also notes elevated diaphragm	Pacemaker leads correctly placed. Single large air-fluid level (giant hiatal hernia). No pneumothorax or pleural effusion	4; 6
	Differential Diagnosis	Giant hiatal hernia (most likely), congestive heart failure, COPD, aortic aneurysm. Misses retrocardiac lung abscess and pneumopericardium	Giant hiatal hernia (most likely), congestive heart failure, COPD. Focuses on the correct primary diagnosis and provides relevant alternatives	Giant hiatal hernia (most likely), retrocardiac lung abscess, pneumopericardium	2; 4
	Next Steps	Recommends CT chest/abdomen, echocardiogram, BNP, and barium swallow study. Lacks emphasis on surgical consultation for symptomatic hiatal hernia	Recommends CT chest, barium swallow study, echocardiogram, BNP, and surgical consultation for symptomatic hiatal hernia. Aligns well with clinical urgency	CT scan to confirm hiatal hernia, barium swallow study, echocardiogram, BNP, and surgical consultation if symptomatic	5; 6
5	**Findings Description**	Correctly identifies enlarged cardiac silhouette and bilateral pleural effusions but misses the small left pleural effusion specifically	Correctly identifies enlarged cardiac silhouette, bilateral pleural effusions, and notes the globular shape suggestive of pericardial effusion	Enlarged cardiac silhouette, small left pleural effusion, no focal consolidation	4; 4
	Differential Diagnosis	Pericardial effusion (most likely), congestive heart failure, pneumonia, malignancy, constrictive pericarditis	Pericardial effusion (most likely), congestive heart failure, pneumonia, malignancy	Pericardial effusion (most likely), cardiomegaly, pericardial effusion, cardiac tumors (rare)	6; 6
	Next Steps	Recommends echocardiogram (STAT), ECG, CT scan, BNP, cardiac enzymes, and pericardiocentesis if tamponade is present	Recommends echocardiogram (STAT), CT scan, BNP, cardiac enzymes, and pericardiocentesis if tamponade is present. Also suggests	Echocardiogram (STAT), CT scan, BNP, cardiac enzymes, pericardiocentesis if tamponade suspected	6; 6

			thoracic ultrasound for pleural effusion		
6	**Findings Description**	Misses pneumothorax entirely. Incorrectly suggests a possible rib fracture	Misses pneumothorax but correctly notes no rib fractures or mediastinal shift. Suggests mild interstitial changes, which could be reactive	Left visceral pleural edge with no lung markings (pneumothorax). No rib fracture, no mediastinal shift, no soft tissue emphysema	2; 2
	Differential Diagnosis	Misses pneumothorax entirely. Suggests rib fracture (incorrect) and pulmonary contusion	Misses pneumothorax but suggests pulmonary contusion (most likely), rib microfracture, and occult pneumothorax	Traumatic pneumothorax (most likely), pulmonary contusion, rib fracture (if present)	2; 2
	Next Steps	Misses pneumothorax entirely. Recommends CT scan and follow-up X-ray but does not address pneumothorax management	Misses pneumothorax but recommends CT scan if symptoms worsen and suggests chest tube placement if pneumothorax develops	Immediate chest tube placement if pneumothorax is large or symptomatic. Follow-up imaging if needed	2; 3
7	**Findings Description**	Identifies increased opacity in the right lung and possible pleural effusion but misses hypertransradiancy and indistinct right heart border	Identifies increased opacity in the right lower lung field and blunted costophrenic angle (effusion). Misses hypertransradiancy but notes elevated right hemidiaphragm	Patchy consolidation in the right lower zone, indistinct right heart border, hypertransradiancy of the right upper/mid zones, no effusions	4; 5
	Differential Diagnosis	Suggests bronchial carcinoid tumor (most likely), pneumonia, pulmonary embolism, and malignancy	Suggests pulmonary carcinoid tumor (most likely), atypical pneumonia, pleural effusion, and lung mass. Focuses on carcinoid as the primary diagnosis	Atypical bronchial carcinoid tumor (most likely), pneumonia, pulmonary embolism, malignancy	4; 4
	Next Steps	Recommends CT chest, ultrasound, thoracentesis, and bronchoscopy with biopsy. Misses tumor markers and surgical referral	Recommends CT chest, ultrasound, thoracentesis, bronchoscopy with biopsy, and tumor markers. Emphasizes referral to pulmonology and oncology, aligning with surgical referral	CT chest with contrast, bronchoscopy with biopsy, thoracentesis if effusion present, tumor markers, and surgical referral	4; 5
8	**Findings Description**	Correctly identifies bowel gas interposition (Chilaiditi sign) and rules out pneumoperitoneum. No other abnormalities noted	Correctly identifies bowel gas interposition (Chilaiditi sign) and rules out pneumoperitoneum. No other abnormalities noted	Interposition of bowel loop (hepatic flexure of colon) between the right hemidiaphragm and liver. No other abnormalities	6 6
	Differential Diagnosis	Chilaiditi sign (most likely), pneumoperitoneum (less likely), right hemidiaphragmatic paralysis (less likely)	Chilaiditi sign (most likely), Chilaiditi syndrome, pneumoperitoneum (less likely)	Chilaiditi sign (most likely), pneumoperitoneum (less likely)	6 6
	Next Steps	Recommends no further intervention if asymptomatic. Suggests abdominal X-ray or CT scan if perforation is suspected	Recommends no further intervention if asymptomatic. Suggests abdominal X-ray, CT scan, or ultrasound if perforation or obstruction is suspected	No further intervention if asymptomatic. CT scan if perforation is suspected	6 6
9	**Findings Description**	Identifies mediastinal shift but misunderstnads large left-sided pleural effusion for right-sided and misses the gas-containing collection and air-fluid level	Identifies left-sided pleural effusion but misses the gas-containing collection, air-fluid level, and mediastinal shift	Large gas-containing collection in the left hemithorax with air-fluid level, loss of left heart and diaphragm silhouette, mediastinal shift to the right, and overlying atelectasis	2 2
	Differential Diagnosis	Suggests malignant pleural effusion, parapneumonic effusion, TB, CHF, and esophageal-pleural fistula. Misses hiatus hernia and pyopneumothorax	Suggests malignant pleural effusion, parapneumonic effusion, CHF, and esophageal-pleural fistula. Misses hiatus hernia and pyopneumothorax	Esophageal-pleural fistula (most likely), hiatus hernia, intrapulmonary cavitating lesion, hydro- or pyopneumothorax	3 3
	Next Steps	Recommends thoracentesis, CT chest, pleural fluid analysis, and oncology referral. Misses water-soluble contrast swallow and intercostal drain placement	Recommends thoracentesis, CT chest, pleural fluid analysis, and esophagogram. Misses intercostal drain placement and surgical referral	CT chest, water-soluble contrast swallow, pleural fluid analysis, intercostal drain placement, and surgical referral	3 3
10	**Findings Description**	Correctly identifies bilateral reticulonodular opacities and hilar	Correctly identifies bilateral reticulonodular opacities and hilar	Widespread reticulonodular pattern, bilateral hilar and paratracheal	5 5

		lymphadenopathy. Misses paratracheal lymphadenopathy and sparing of lung bases	lymphadenopathy. Misses paratracheal lymphadenopathy and sparing of lung bases	lymphadenopathy, relative sparing of lung bases	
	Differential Diagnosis	Sarcoidosis (most likely), tuberculosis, lymphoma, hypersensitivity pneumonitis, pneumoconiosis	Sarcoidosis (most likely), tuberculosis, lymphoma, hypersensitivity pneumonitis	Sarcoidosis (most likely), tuberculosis, lymphoma, hypersensitivity pneumonitis, pneumoconiosis	6 6
	Next Steps	Recommends CT chest, serum ACE, TB workup, bronchoscopy with biopsy, calcium levels, and referral to pulmonology	Recommends CT chest, serum ACE, TB workup, bronchoscopy with biopsy, calcium levels, and referral to pulmonology	CT chest, serum ACE, TB workup, bronchoscopy with biopsy, calcium levels, and referral to pulmonology	6 6
11	**Findings Description**	Correctly identifies right lower lobe consolidation and silhouetting of the right hemidiaphragm. Misses air bronchograms and loss of lucency over the lower thoracic spine	Correctly identifies right lower lobe consolidation and silhouetting of the right hemidiaphragm. Misses air bronchograms and loss of lucency over the lower thoracic spine	Homogeneous opacification of the right lower lung zone with air bronchograms, silhouetting of the right hemidiaphragm, and loss of lucency over the lower thoracic spine	4 4
	Differential Diagnosis	Bacterial pneumonia (most likely), atypical pneumonia, tuberculosis, aspiration pneumonia, lung abscess/empyema	Bacterial pneumonia (most likely), atypical pneumonia, tuberculosis, aspiration pneumonia	Bacterial pneumonia (most likely), atypical pneumonia, tuberculosis, aspiration pneumonia, lung abscess/empyema	5 5
	Next Steps	Recommends empiric antibiotics, sputum culture, chest X-ray follow-up, CT scan if no improvement, and TB workup if indicated	Recommends empiric antibiotics, sputum culture, chest X-ray follow-up, CT scan if no improvement, and TB workup if indicated	Empiric antibiotics, sputum culture, chest X-ray follow-up, CT scan if no improvement, and TB workup if indicated	6 6
12	**Findings Description**	Correctly identifies cardiomegaly, left atrial enlargement, and pulmonary venous congestion. Misses specific features like double contour and splayed carina	Correctly identifies cardiomegaly, left atrial enlargement, and pulmonary venous congestion. Misses specific features like double contour and splayed carina	Cardiomegaly, left atrial enlargement (double contour, splayed carina, enlarged left atrial auricle), pulmonary venous congestion	4 4
	Differential Diagnosis	Mitral valve disease (most likely), congestive heart failure, hypertensive heart disease, pericardial effusion	Mitral regurgitation (most likely), congestive heart failure, hypertensive heart disease, pericardial effusion	Mitral regurgitation (most likely), congestive heart failure, hypertensive heart disease, pericardial effusion	5 5
	Next Steps	Recommends echocardiography, BNP, ECG, cardiology referral, and consideration of valve repair/replacement	Recommends echocardiography, BNP, ECG, cardiology referral, and consideration of valve repair/replacement	Echocardiography (urgent), BNP, ECG, cardiology referral, and consideration of valve repair/replacement	5 5
13	**Findings Description**	Identifies increased opacity in the central/lower lung zones but misses the specific right lower lobe lesion and hilum overlay sign	Identifies an ill-defined opacity in the left mid-lung field (incorrect side) and misses the right lower lobe lesion and hilum overlay sign	Round opacity lesion in the right lower lobe (hilum overlay sign), no pneumothorax or pleural effusion	2 2
	Differential Diagnosis	Primary lung malignancy, pulmonary metastasis, post-radiotherapy fibrosis, infectious process	Primary lung adenocarcinoma, pulmonary metastasis, post-radiotherapy fibrosis, infectious process	Primary lung adenocarcinoma (most likely), pulmonary metastasis, post-radiotherapy fibrosis, infectious process	6 6
	Next Steps	Recommends CT chest, PET-CT, biopsy, tumor markers, and follow-up imaging	Recommends CT chest, PET-CT, biopsy, tumor markers, and follow-up imaging	CT chest, PET-CT, biopsy, tumor markers, and follow-up imaging	6 6
14	**Findings Description**	Correctly identifies multiple well-defined nodules, no pleural effusion, no pneumothorax, and normal bony structures	Correctly identifies multiple well-defined nodules, no pleural effusion, no pneumothorax, and normal bony structures	Multiple well-defined nodules in both lungs, no pleural effusion, no pneumothorax, normal bony structures	6; 6
	Differential Diagnosis	Pulmonary metastases (most likely), septic emboli, granulomatous diseases (e.g., sarcoidosis, fungal infections)	Pulmonary metastases (most likely), septic emboli, granulomatous diseases (e.g., TB, fungal infections)	Pulmonary metastases (most likely), septic emboli, granulomatous diseases (e.g., TB, fungal infections)	6 6
	Next Steps	Recommends CT chest, PET-CT, tumor markers, biopsy if needed, oncology consultation, and follow-up imaging	Recommends CT chest, PET-CT, tumor markers, biopsy if needed, oncology consultation, and follow-up imaging	CT chest, PET-CT, tumor markers, biopsy if needed, oncology consultation, and follow-up imaging	6 6

15	**Findings Description**	Correctly identifies diffuse, bilateral, hazy opacities with a ground-glass appearance. Misses pneumatocoeles	Identifies diffuse bilateral reticulonodular opacities but misses hazy perihilar opacification and pneumatocoeles	Hazy perihilar mid and upper zone opacification, interstitial prominence, pneumatocoeles, no pleural effusion or nodal enlargement	4 5
	Differential Diagnosis	Pneumocystis pneumonia (most likely), atypical pneumonia, miliary TB, pulmonary edema	Pulmonary TB (most likely), Pneumocystis pneumonia, fungal infection, lymphoma	Pneumocystis pneumonia (most likely), TB, fungal infection, viral pneumonia	5 5
	Next Steps	Recommends CT chest, sputum/BAL PCR, LDH, beta-D-glucan, empiric TMP-SMX, corticosteroids if hypoxic	Recommends CT chest, sputum AFB smear/culture, GeneXpert, beta-D-glucan, and empiric anti-TB therapy. Misses empiric TMP-SMX for Pneumocystis pneumonia	CT chest, sputum/BAL PCR for Pneumocystis, LDH, beta-D-glucan, empiric TMP-SMX, corticosteroids if hypoxic	6 4
16	**Findings Description**	Identifies bilateral diffuse patchy opacities but misses specific consolidations and air bronchograms	Identifies bilateral diffuse opacities but misses specific consolidations and air bronchograms	Bilateral peripheral consolidations with air bronchograms, right upper lobe pneumonia, left lower lobe pneumonia, support lines in situ	3 3
	Differential Diagnosis	Severe COVID-19 pneumonia (most likely), bacterial pneumonia, ARDS, cardiogenic pulmonary edema	Severe COVID-19 pneumonia (most likely), bacterial pneumonia, ARDS, cardiogenic pulmonary edema	Severe COVID-19 pneumonia, bacterial pneumonia, ARDS, cardiogenic pulmonary edema	6 6
	Next Steps	Recommends CT chest, COVID-19 PCR, blood cultures, ABG, broad-spectrum antibiotics, corticosteroids, and ventilatory support	Recommends CT chest, blood cultures, ABG, broad-spectrum antibiotics, corticosteroids, and ventilatory support. Misses COVID-19 PCR	CT chest, COVID-19 PCR, blood cultures, ABG, broad-spectrum antibiotics, corticosteroids, and ventilatory support	6 6
17	**Findings Description**	Identifies increased opacification in the right lower lung field but misses the specific lesion and hilum overlay sign	Identifies increased opacity in the right middle/lower lung zones but misses the specific lesion and hilum overlay sign	Well-defined, smoothly marginated opaque lesion in the right cardiophrenic angle, hilum overlay sign, no pleural effusion or pneumothorax	3 3
	Differential Diagnosis	Pulmonary fibrosis, lung malignancy, atypical pneumonia, aortic aneurysm. Misses thymoma and other mediastinal masses	Pulmonary malignancy, pneumonia, tuberculosis, sarcoidosis. Misses thymoma and other mediastinal masses	Thymoma (most likely), lymphoma, teratoma, pericardial cyst	2 2
	Next Steps	Recommends CT chest, sputum culture, bronchoscopy, and oncology referral. Misses biopsy and tumor markers	Recommends CT chest, CBC, tumor markers, and biopsy. Misses referral to thoracic surgery	CT chest, biopsy, tumor markers, and referral to oncology or thoracic surgery	3 4
18	**Findings Description**	Correctly identifies bilateral interstitial and alveolar opacities, cardiomegaly, and pacemaker in situ. Misses upper lobe pulmonary venous diversion and Kerley B lines	Correctly identifies bilateral interstitial and alveolar opacities, cardiomegaly, and pacemaker in situ. Misses upper lobe pulmonary venous diversion and Kerley B lines	Bilateral lung congestion, upper lobe pulmonary venous diversion, Kerley B lines, cardiomegaly, pacemaker in situ	4 5
	Differential Diagnosis	Congestive heart failure (most likely), volume overload, pneumonitis, pulmonary venous hypertension	Congestive heart failure (most likely), pneumonia, interstitial lung disease	Cardiogenic pulmonary edema (most likely), pneumonia, interstitial lung disease	5 5
	Next Steps	Recommends echocardiogram, BNP, diuretics, oxygen therapy, and cardiology referra	Recommends chest CT, BNP, diuretics, oxygen therapy, and pacemaker evaluation. Misses echocardiogram and cardiology referral	Echocardiogram, BNP, diuretics, oxygen therapy, and cardiology referral	6 6
19	**Findings Description**	Identifies elevated left hemidiaphragm and possible left lower lung opacity but misses surgical clips and specific findings like no consolidation or atelectasis	Identifies elevated left hemidiaphragm and left lower lung opacity but misses surgical clips and specific findings like no consolidation or atelectasis	Elevated left hemidiaphragm, surgical clips at base of left neck, no consolidation, atelectasis, or pneumothorax	4 4
	Differential Diagnosis	Post-surgical changes, postoperative pneumonia, atelectasis, pleural effusion. Misses phrenic nerve palsy as the primary diagnosis	Post-operative atelectasis, pleural effusion, pulmonary edema, aspiration pneumonia. Misses phrenic nerve palsy as the primary diagnosis	Phrenic nerve palsy (most likely), atelectasis, pleural effusion, aspiration pneumonia	3 2

	Next Steps	Recommends CT chest, ultrasound, sputum culture, CBC, and follow-up imaging. Misses specific focus on phrenic nerve palsy	Recommends repeat chest X-ray, ultrasound, CBC, sputum culture, and supportive management. Misses CT chest and specific focus on phrenic nerve palsy	CT chest, ultrasound, sputum culture, CBC, and follow-up imaging	3 3
20	**Findings Description**	Identifies bilateral diffuse airspace opacities but misses splaying of the carina, subcarinal mass, and retrocardiac opacification	Identifies bilateral diffuse interstitial and alveolar opacities but misses splaying of the carina, subcarinal mass, and retrocardiac opacification	Splaying of the carina, large subcarinal mass, prominent pulmonary vasculature, retrocardiac opacification, bilateral lung opacities	3 3
	Differential Diagnosis	ARDS, peripartum cardiomyopathy, sepsis, atypical pneumonia, pulmonary embolism. Misses bronchogenic cyst	Severe pneumonia, ARDS, peripartum cardiomyopathy, pulmonary embolism. Misses bronchogenic cyst	Bronchogenic cyst (most likely), pneumonia, ARDS, pulmonary embolism	3 3
	Next Steps	Recommends CT chest, echocardiography, ABG, blood cultures, and antibiotics. Misses urgent surgical consultation	Recommends CT chest, ABG, blood cultures, and antibiotics. Misses echocardiography and urgent surgical consultation	CT chest, echocardiography, ABG, blood cultures, and urgent surgical consultation	4 4

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 93-98

Methodological Aspects and Limitations for Ensuring Safety in Transport Management Using Artificial Intelligence

Dimitar Dimitrov
Faculty of Transport Management
University of Transport
Sofia, Bulgaria
ddimitrov@vtu.bg

Todor Balabanov
Faculty of Telecommunications and Electrical Equipment in Transport
University of Transport
Sofia, Bulgaria
todor.balabanov@vtu.bg

***Abstract*—Recently, there has been rapid technological progress in transportation, which is expressed in the field of telematics, the Internet of Things, the Internet of Vehicles, Big Data Analysis, etc. The use of information technology by drivers, including so-called smart devices, technological advances in sensor devices, autonomous vehicles, vessel telematics, cameras, etc., provides new potential for driver/operator behaviour monitoring, vehicle communication, surveillance, and incident detection in all modes of transport. The adoption of these technological advances is widespread, and the emanation of their use is the introduction of A.I. into the decision-making process. All this opens up the important topic of taking responsibility for decisions, detecting and eliminating errors in decisions and actions, and hazardous traffic management and safety processes. This article aims to examine and summarize these problems, especially when using A.I. in transport, from the point of view of ensuring safety. Methodological formulations and a general concept for a limit of admissibility in ensuring the necessary safety in transport are also proposed.**

Keywords*— *Artificial Intelligence, Internet of Vehicles, Telematics, Transport.

I. Introduction

The application of Artificial Intelligence (AI) in transport has evolved from academic theoretical concepts to real-world practical applications [1]-[6]. In the beginning, efforts focused on automating essential functions, such as signalling infrastructure management and traffic light management, as well as route planning algorithms, which laid the groundwork for the use of more advanced applications [7]-[9].

Gradually, the application of AI in transportation has increased, driven by advances in machine learning, computer vision, and sensor technologies. The most significant developments have focused on autonomous vehicles (AV) [10]-[12]. AVs using artificial intelligence have already begun to interpret the data received from their sensors, allowing them to understand and navigate the environment without human intervention [13]-[15].

AI applications have also been developed for public transport, from predictive maintenance for rolling stock to route optimization and intelligent systems for reservations, ticketing, etc. These innovations aim to improve interoperability and passenger service. AI also plays an important role in logistics and freight transport, optimizing routes and increasing supply chain efficiency [16]. Advanced AI algorithms help with predictive analysis for maintenance, load optimization, and real-time load tracking. Today's traffic management systems, as well as AI-driven autonomous vehicles, have fundamentally changed the way transportation functions.

In this regard, the primary purpose of this article is to consider and summarize these problems, especially when using artificial intelligence in transport from the point of view of ensuring safety in transport [17], [18]. Methodological formulations and a general concept for a limit of admissibility in ensuring the necessary safety in transport are also proposed.

II. Materials and Methods

The integration of AI into transportation, especially in the form of AV, presents a new set of ethical challenges. While AVs offer many benefits, they also raise critical questions related to safety, decision-making algorithms, and, of course, public trust.

Regarding safety concerns, the determination of liability for AV accidents becomes complicated. When the

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8580
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

AV is at fault, this fault can fall on the manufacturer, software developer, or even the passenger. In this regard, the risk of malfunctions increases. AVs rely heavily on software and sensors. This makes them susceptible to malfunctions, and due to software bugs and/or hacking, it also leads to safety risks [19].

In terms of decision-making algorithms, AVs must make ethical decisions in unavoidable catastrophe scenarios, which is a great challenge. In fact, the debate is around whether an AV should prioritize the safety of its occupants or pedestrians, for example. AIs are guaranteed to be free from biases leading to discriminatory navigation or pedestrian recognition practices.

Regarding public trust and acceptance, transparency is required in how AVs work and make decisions, which is challenging given the complexity of AI algorithms. From a legal point of view, establishing comprehensive legal frameworks governing AV use and safety standards is essential to gaining public trust.

AI applications in transportation are limited in their decision-making abilities, which creates serious challenges in complex situations requiring human judgment and intuition. AI systems excel at processing large amounts of data and making decisions based on predefined rules and patterns; they try to adapt to unique or unpredictable scenarios.

AI cannot make ethical judgments, raising concerns about the potential consequences of its decisions on human life and public well-being.

The implementation of AI in transportation has a social and economic impact that can lead to the loss of human jobs, especially for roles that can be automated.

The development and implementation of AI technologies in transportation also face regulatory challenges; existing laws may not adequately respond to AI decision-making.

The topic of AI limitations and strategies to overcome them is certainly both complex and fascinating. Common limitations in using AI are related to data quality, training bias, outdated infrastructure, and integration with other systems. Overcoming these limitations can help unlock the full potential of AI, making it a powerful tool for innovation and efficiency.

Overcoming these limitations and training requirements for AI systems must be carefully considered. AI algorithms need to be trained on vast amounts of data to improve their decision-making capabilities in complex situations. Additionally, ongoing research and development are needed to improve AI's decision-making abilities and overcome the ethical implications and regulatory barriers associated with its use in transportation.

III. Results and discussion

A. Cybersecurity risks

T The cybersecurity risks of using AI technologies in transport require robust safeguards to protect against potential threats [20], [21]. These AI applications increase the risk of cyber threats, including breaches, manipulation, data loss, hacking vulnerabilities, and privacy concerns. To protect itself from cyberattacks, the transportation industry must address these risks by implementing strong security measures, software updates, and hardware upgrades. The disruption of operations and the potential for hackers to steal sensitive information are the main concerns.

Table 1 Cybersecurity Measures Description

Cybersecurity Measures	Description
Encryption	Encrypting data to protect it from unauthorized access
Intrusion Detection Systems	Installing systems to detect and prevent unauthorized access
Regular System Updates	Keeping software and hardware up to date with the latest security patches
User Authentication	Implementing strong authentication protocols to ensure only authorized users have access
Employee Training	Providing training to employees on cybersecurity best practices
Incident Response Plan	Developing a plan to respond to and mitigate cyber threats

Protecting AI technology from cyber threats is crucial for maintaining the integrity and security of transportation operations. As shown in Table 1, the following security measures should be implemented to mitigate these risks.

B. Integration challenges

The application of AI technologies in transport is a complex task requiring their integration with existing systems and processes [22]. Successful integration is associated with several challenges, such as:

Compatibility issues - AI systems may not be compatible with existing infrastructure and software used in the transportation industry. This can lead to difficulties in data sharing, communication, and interoperability between different systems.

System integration - Integrating AI technology requires seamless integration with existing transportation systems and processes. This involves connecting AI algorithms to existing hardware, software, and databases, which can also be complex.

Implementation barriers - Organizations may resist implementing AI in transportation due to factors such as cost, lack of experience, and concerns about job losses. Overcoming these barriers requires careful planning, proper training, and addressing stakeholder concerns.

Addressing these integration challenges is critical to fully leveraging AI's potential benefits in transportation.

Collaboration between providers of these new technologies, industry stakeholders, and policymakers is also required. This is necessary to develop effective solutions and ensure a smooth transition to intelligent transport systems. Successfully integrating AI technology into the transportation industry also requires addressing the challenge of not having a skilled workforce capable of effectively using and managing AI systems.

C. Intelligent transportation

In recent years, various innovative applications related to transport and technology have been built. The developers of these applications focus on a process-oriented system approach, and the main goal is to create a feedback mechanism and measure the results of decisions related to transport management.

Transportation management systems (TMS) coordinate the overall transport process and the performance of individual transport operations. These systems aim to create efficient route planning, load optimization, and improved flexibility and transparency using the data in them. The data generated by users and vehicles is used to build efficient Intelligent Transportation Systems (ITS). The integration of these ITS into transport systems has provided increased productivity thanks to the collection, exchange, and integration of information between vehicles, urban infrastructure, and a range of other related activities.

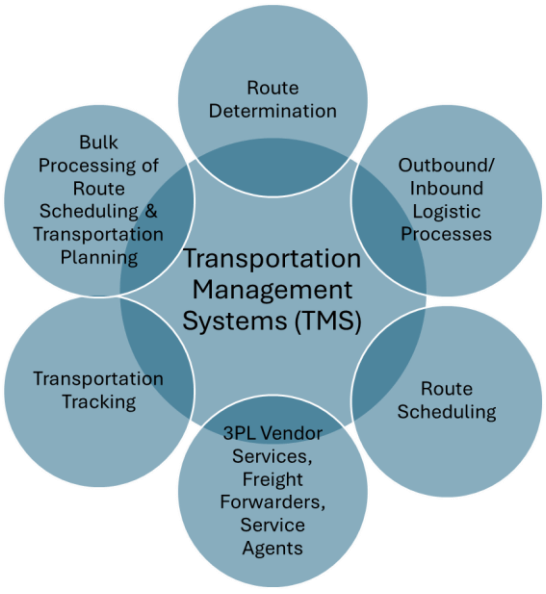


Fig. 1. Functions of TMS.

The main functions of TMS shown in Figure 1 include route definition, entry-exit logistics processes, route planning, services for Third-party logistics (3PL) suppliers, freight forwarders, service agents, transport tracking, mass processing, route planning, and comprehensive transport planning [23]. TMS-related functions relate to the transportation of goods. TMS integrates multiple transport applications into one package for better ease of use.

With the development of new technologies and cloud computing, there has also been talk of Cloud TMS, shown in Figure 2 [24].

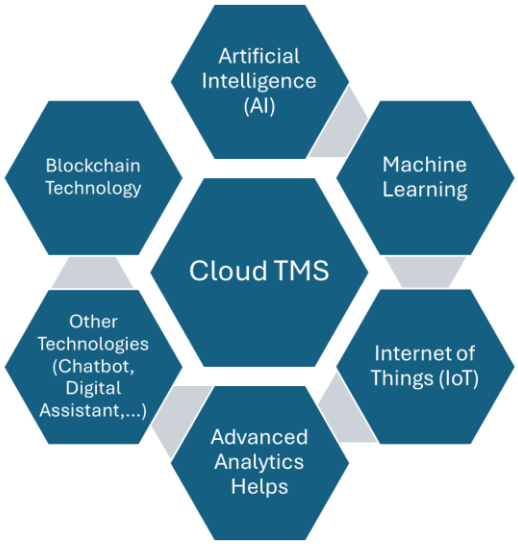


Fig. 2. Cloud TMS.

Cloud technologies make TMS systems much more accessible, which allows new capabilities and flexibility of the software used – MercuryGate, Transplace, SAP Transportation Management, Kuebix, Manhattan TMS, etc. (Source: https://www.selecthub.com/transportation-and-logistics-management/cloud-tms/).

AI brings several innovations. It handles time-consuming, routine tasks throughout the process and provides the benefits of time and cost savings.

Machine learning (ML) can quickly make accurate predictions based on massive data sets [25]. ML can help businesses manage the important trade-offs between cost savings and on-time delivery, taking into account the geographical factors of delivery in real-time, as well as direct and indirect delivery.

IoT, Internet of Vehicles (IoV). Sensors collect invaluable information that can be used to identify equipment that needs to be maintained [26]-[28]. The more equipment along the entire supply chain is equipped with sensors, the more efficient the process becomes [29].

Advanced analytics help optimize routes and delivery methods, improve delivery times, increase fuel economy, efficiency, and profitability, and adapt to changes in transport demand. As more data is generated, the role of analytics becomes even more important.

Other technologies can also make TMS systems more efficient. Chatbots or digital assistants can reduce administrative costs by handling routine customer inquiries. Blockchain technologies also provide transparency for tracking throughout the supply chain.

D. Limitation of AI Techniques

In the field of transportation, there are various criticisms of AI methods [30], with one of the main

limitations of AI being the view of Artificial Neural Networks (ANN) as a "black box." [31]. ANNs are generalized in cases where some information is missing in the data. However, this limitation is overcome by combining the neural network with other traditional AI techniques and tools, such as a hybrid solution [32]-[34]. This hybridization requirement to improve performance, especially in multiple scenarios, is a common weakness [8].

Developing an efficient transport system based on artificial intelligence is very complex due to the creation of mechanical intelligence and the correct understanding of information [35]. Because of this, AI applications in transport are limited to specific applications of ITS, such as data analysis and predictions of future mobility; i.e., they are not yet able to handle the full scope of the process [36]. In order to work as stand-alone systems, it is necessary to realize the full potential of AI to develop sufficiently practical applications. It is important to introduce AI knowledge into traffic analysis, data collection and storage, and modelling and optimization decision-making [37]. AI techniques are based on data collected using loop detectors, sensors, actuators, etc., and accuracy and timely predictions are still unreliable.

Mathematical methods provide an understanding of the problem's internal structure and the nature of the solution, in contrast to the so-called - AI raster algorithms. However, in complex optimization problems, where it is impossible to use traditional mathematical techniques, the quick analysis results generated by these algorithms are better than the lack of solutions, although these algorithms arrive at a good solution in most cases, i.e., the parameters and assumptions must be adjusted and repeated many times in order to achieve the best solutions and have more insight into the problem. Another limitation has to do with the bias introduced in the training data. In most cases, this is checked by people who can introduce errors and biases into the labelling of the data.

The ability to predict short-term and long-term traffic is essential for transport, with the challenge being to predict unexpected events and adverse weather conditions, which existing artificial intelligence techniques are not yet able to address [38]. In this regard, developing incident response algorithms and forecasting schemes is important for high accuracy. In developing these algorithms, AI should increase its efficiency in online computing and improve the standardization of requirements regarding space-time coverage of data [39]. Most AI approaches, such as neural networks in time-series transport applications, rarely involve testing the properties of the error. Because of this, the model specification is considered a limitation. AI statistics should have an interdependent relationship for improvement in the development of the underlying model and suitability, as well as the ability for effective and accurate Big Data analysis [39], [40]. AI also has other common limitations, such as the high cost of development and maintenance due to its complexity, lack of customer privacy, and transparency of AI-driven technologies. Another major limitation is the computational complexity of AI algorithms. These problems require a lot of computing power to solve the complexity of increasing data density.

In general, the main task in transport includes problems such as vehicle routing and optimal planning for drivers and road users [41]. In a simple algorithm scenario, the number of input data increases, and the number of operations grows constantly. However, in real life, challenging scenarios apply, i.e., for the algorithm, the number of operations and calculations is explained in polynomial time (X^2), exponential time (2^X) and factorial time (X!). The theoretical explanation for the complexity of the algorithm is expressed in the Polynomial (P) Problem and the Nondeterministic Polynomial (NP) Problem [42]. These problems require a lot of computing power to solve the complexity problem of increasing data density. The complexity of the calculations limits the AI techniques; most algorithms are classified as NP problems and NP-complete problems. In DL, many hidden layers are built into the network architecture, and the complexity relies on the fact that Big Data contains noise and distortion from which characteristics are challenging to extract [43]. Transport data is collected from road sensors, connected devices, tolls, GPS applications, cloud applications, and other transport features [44]. These functions include traffic, speed, traffic occupancy, and the behaviour of drivers and passengers, which further complicates the computational process when solving a specific problem.

E. Alalysis

The analysis of this study's work can be classified into two aspects to ensure transport safety when using AI: transport problems when using AI and Techniques related to solving these problems.

a) Transport Issues

Population and transport traffic is constantly increasing, raising topical issues such as traffic control, air pollution, disaster and accident management, and congestion control through appropriate AI navigation systems.

Various issues focused on the literature review are summarized. Based on the study, it can be concluded that the main challenges in most of TMS's work are traffic and congestion control, as well as disaster and accident management. Air pollution, efficient traffic management, and resources are also important, and the focus on these issues is taking on new dimensions in the context of the use of AI in the transport sector. letters.

b) Techniques Involved in Solving These Issues

The specificity of the transport process is that various problems must be solved in real-time based on the dynamic information received to solve them. Technological solutions are diverse, often technologies of different generations, which must reliably and securely communicate with each other. As an example, various video surveillance cameras and sensors can be used to provide real-time information. GPS technology combines

various image processing techniques for more advanced navigation systems.

Advanced AI technologies, cloud computing, and agent-based computing are being introduced to make the transportation system more efficient and intelligent. So far, the sensors and vehicle cloud computing techniques used are agent-based. Now, this is the best solution; improvements due to technological progress are expected in the future, and the use of increasingly intelligent infrastructure will support the overall process of secure and safe management of transport processes based on AI.

IV. CONCLUSIONS

The explosive growth in traffic and population density has raised various technical and environmental issues, such as air pollution, increased traffic, congestion, and accidents, which have increased interest in researching the issue.

Implementing AI in transportation is a critical issue as it solves several problems related to the transportation system [45]. The design of TMS, including AI, is essential for security and safety, and on the other hand, it improves the system of road infrastructure and traffic management [46]. Therefore, AI can be used to address these transportation-related issues. TMS with AI combine various technologies such as data collection, communication, machine learning, and data mining to provide transportation and related services. These services include intelligent traffic control, intelligent navigation and driver assistance systems, as well as fault detection systems. In addition to this, AI also makes decisions about transportation, related to issues such as disaster management, congestion control, and air pollution. Further improvement of TMS includes the addition of new techniques such as IoV, cloud computing for vehicles, and agent-based computing, which include the introduction of AI into transportation systems. By combining these techniques, TMS with AI can be more effective in solving transportation-related problems.

A systematic study of existing TMS looks at them from different perspectives, considering the pros and cons of various issues related to security and design challenges. Many review articles have been published in the context of TMS, but none of them address all aspects related to TMS with AI. The open research questions in this TMS with AI study include identifying important metrics that affect TMS performance. This should be done in the field of providing solutions for the reliability and security aspects of TMS with AI, not only in a technical context, but also in a regulatory and moral context.

REFERENCES

[1] L. Chan, L. Hogaboam and R. Cao, "Artificial Intelligence in Transportation," in Applied Artificial Intelligence in Business: Concepts and Cases, Cham, Springer International Publishing, 2022, p. 231–247.

[2] J. Bharadiya, "Artificial Intelligence in Transportation Systems A Critical Review," American Journal of Computing and Engineering, vol. 6, pp. 34-45, June 2023.

[3] A. Azimian, "Design of an Intelligent Traffic Management System," University of Dayton, 2011.

[4] A. S. P. K. &. S. Y. Zear, "Intelligent Transport System: A Progressive Review," Indian Journal of Science and Technology, vol. 9, no. 32, pp. 1-8, 2016.

[5] S. Ahmed, M. Hossain, M. S. Kaiser, M. Noor, M. Mahmud and C. Chakraborty, "Artificial Intelligence and Machine Learning for Ensuring Security in Smart Cities," 2021, pp. 23-47.

[6] Dimitrov D., Petrova I., „Use of artificial intelligence in transport project management," Mechanics Transport Communications, том 21, № 3, 2023.

[7] T. Garg and G. Kaur, "A Systematic Review on Intelligent Transport Systems," Journal of Computational and Cognitive Engineering, vol. 2, June 2022.

[8] P. Harcourt, Route Optimization Techniques: An Overview., 2016.

[9] Petrova I., "Challenges to improve road safety solved with the help of artificial intelligence," Proceedings of University of Ruse, vol. 62, no. 4.1, pp. 34-39, 2023.

[10] J. Park and D. Kang, "Artificial Intelligence and Smart Technologies in Safety Management: A Comprehensive Analysis Across Multiple Industries," Applied Sciences, vol. 14, 2024.

[11] S. Sharma and B. Kaushik, "A survey on internet of vehicles: Applications, security issues & solutions," Vehicular Communications, vol. 20, p. 100182, 2019.

[12] Z. Mahmood, "Connected Vehicles in the IoV: Concepts, Technologies and Architectures," in Connected Vehicles in the Internet of Things: Concepts, Technologies and Frameworks for the IoV, Z. Mahmood, Ed., Cham, Springer International Publishing, 2020, p. 3–18.

[13] I. Vourgidis, L. Maglaras, A. Alfakeeh, A. Al-Bayatti and M. A. Ferrag, "Use Of Smartphones for Ensuring Vulnerable Road User Safety through Path Prediction and Early Warning: An In-Depth Review of Capabilities, Limitations and Their Applications in Cooperative Intelligent Transport Systems," Sensors, vol. 20, February 2020.

[14] S. Olugbade, S. Ojo, A. Imoize, J. Isabona and M. Alaba, "A Review of Artificial Intelligence and Machine Learning for Incident Detectors in Road Transport Systems," Mathematical and Computational Applications, vol. 27, p. 77, September 2022.

[15] T. Yuan, W. Da Rocha Neto, C. E. Rothenberg, K. Obraczka, C. Barakat and T. Turletti, "Machine learning for next-generation intelligent transportation systems: A survey," Transactions on Emerging Telecommunications Technologies, vol. 33, p. e4427, 2022.

[16] A. Maimaris and G. Papageorgiou, "A review of Intelligent Transportation Systems from a communications technology perspective," in 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), 2016.

[17] W. Du, A. Dash, J. Li, H. Wei and G. Wang, "Safety in Traffic Management Systems: A Comprehensive Survey," Designs, vol. 7, p. 100, August 2023.

[18] A. Lamssaggad, N. Benamar, A. S. Hafid and M. Msahli, "A Survey on the Current Security Landscape of Intelligent Transportation Systems," IEEE Access, vol. 9, pp. 9180-9208, 2021.

[19] J. Kukulski, K. Lewczuk, I. Góra and M. Wasiak, "Methodological aspects of risk mapping in multimode transport systems," Eksploatacja i Niezawodnosc - Maintenance and Reliability, vol. 25, February 2023.

[20] M. F. Ansari, B. Dash, P. Sharma and N. Yathiraju, "The Impact and Limitations of Artificial Intelligence in Cybersecurity: A Literature Review," IJARCCE, vol. 11, pp. 81-90, October 2022.

[21] J. Kołodziej, C. Hopmann, G. Coppa, D. Grzonka and A. Widłak, "Intelligent Transportation Systems – Models, Challenges, Security Aspects," in Cybersecurity of Digital Service Chains: Challenges, Methodologies, and Tools, J. Kołodziej, M. Repetto

and A. Duzha, Eds., Cham, Springer International Publishing, 2022, p. 56–82.

[22] M. Tonhauser and J. Ristvej, "Implementation of New Technologies to Improve Safety of Road Transport," Transportation Research Procedia, vol. 55, pp. 1599-1604, 2021.

[23] L. S. Iyer, "AI enabled applications towards intelligent transportation," Transportation Engineering, vol. 5, p. 100083, 2021.

[24] K. Ashokkumar, B. Sam, R. Arshadprabhu and Britto, "Cloud Based Intelligent Transport System," Procedia Computer Science, vol. 50, pp. 58-63, 2015.

[25] D. I. Tselentis, E. Papadimitriou and P. van Gelder, "The usefulness of artificial intelligence for safety assessment of different transport modes," Accident Analysis & Prevention, vol. 186, p. 107034, 2023.

[26] D. F. Murad, Meyliana, A. N. Hidayanto and HarjantoPrabowo, "IoT for Development of Smart Public Transportation System: A Systematic Literature Review," 2018.

[27] D. Ushakov, E. Dudukalov, E. Kozlova and K. Shatila, "The Internet of Things impact on smart public transportation," Transportation Research Procedia, vol. 63, pp. 2392-2400, June 2022.

[28] F. Yang, J. Li, T. Lei and S. Wang, "Architecture and key technologies for Internet of Vehicles: a survey," Journal of Communications and Information Networks, vol. 2, p. 1–17, 2017.

[29] V. V. Okrepilov, B. B. Kovalenko, G. V. Getmanova and M. S. Turovskaj, "Modern Trends in Artificial Intelligence in the Transport System," Transportation Research Procedia, vol. 61, pp. 229-233, 2022.

[30] R. Abduljabbar, H. Dia, S. Liyanage and S. A. Bagloee, "Applications of Artificial Intelligence in Transport: An Overview," Sustainability, vol. 11, 2019.

[31] J. D. Olden and D. A. Jackson, "Illuminating the “black box”: a randomization approach for understanding variable contributions in artificial neural networks," Ecological Modelling, vol. 154, pp. 135-150, 2002.

[32] J. E. Dayhoff and J. M. DeLeo, "Artificial neural networks: opening the black box," Cancer: Interdisciplinary International Journal of the American Cancer Society, vol. 91, p. 1615–1635, 2001.

[33] D. P. Kanungo, M. K. Arora, S. Sarkar and R. P. Gupta, "A comparative study of conventional, ANN black box, fuzzy and combined neural and fuzzy weighting procedures for landslide susceptibility zonation in Darjeeling Himalayas," Engineering Geology, vol. 85, pp. 347-366, 2006.

[34] R. Setiono, W.-K. Leow and J. Thong, "Opening the neural network black box: an algorithm for extracting rules from function approximating artificial neural networks," ICIS 2000 Proceedings, p. 17, 2000.

[35] D. L. Waltz, "Artificial Intelligence: realizing the ultimate promises of computing," AI magazine, vol. 18, p. 49–49, 1997.

[36] A. Musa, S. Malami, F. Alanazi, W. Ounaies, M. Alshammari and S. Haruna, "Sustainable Traffic Management for Smart Cities Using Internet-of-Things-Oriented Intelligent Transportation Systems (ITS): Challenges and Recommendations," Sustainability, vol. 15, pp. 1-16, June 2023.

[37] D. Mirindi, "A Review of the Advances in Artificial Intelligence in Transportation System Development," Journal of Civil, Construction and Environmental Engineering, vol. 9, pp. 72-83, 2024.

[38] S. Sobczuk and A. Borucka, "Recent Advances for the Development of Sustainable Transport and Their Importance in Case of Global Crises: A Literature Review," Applied Sciences, vol. 14, 2024.

[39] E. I. Vlahogianni, M. G. Karlaftis and J. C. Golias, "Short-term traffic forecasting: Where we are and where we’re going," Transportation Research Part C: Emerging Technologies, vol. 43, p. 3–19, 2014.

[40] H. Nguyen, P. Nguyen and V. Bui, "Applications of Big Data Analytics in Traffic Management in Intelligent Transportation Systems," JOIV : International Journal on Informatics Visualization, vol. 6, p. 177, May 2022.

[41] M. Shahraz, "Intelligent Transportation Systems: An Overview of Current Trends and Limitations," INTERANTIONAL JOURNAL OF SCIENTIFIC RESEARCH IN ENGINEERING AND MANAGEMENT, vol. 06, December 2022.

[42] L. Fortnow, "The status of the P versus NP problem," Communications of the ACM, vol. 52, p. 78–86, 2009.

[43] R. Cheong, J. Lim and R. Parthiban, "Missing Traffic Data Imputation for Artificial Intelligence in Intelligent Transportation Systems: Review of Methods, Limitations, and Challenges," IEEE Access, vol. PP, pp. 1-1, January 2023.

[44] M. G. K. R. Prabha, "Overview of Data Collection Methods for Intelligent Transportation Systems," The International Journal of Engineering and Science, vol. 5, pp. 16-20, March 2016.

[45] L. Janušová and S. Čičmancová, "Improving Safety of Transportation by Using Intelligent Transport Systems," Procedia Engineering, vol. 134, pp. 14-22, 2016.

[46] R. Eswaraprasad and L. Raja, "Improved intelligent transport system for reliable traffic control management by adapting internet of things," in 2017 International Conference on Infocom Technologies and Unmanned Systems (Trends and Future Directions) (ICTUS), 2017.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 99-106

The Risk of Personal Smart Devices in the Operational Security for Military Bases, Personnel and Missions

Dimitar S. Dimitrov
IT Department
Nikola Vaptsarov Naval Academy
Varna, Bulgaria
dimitar@nvna.bg

Iliyan Y. Iliev
IT Department
Nikola Vaptsarov Naval Academy
Varna, Bulgaria
i.y.iliev@naval-acad.bg

***Abstract* – The increasing integration of personal smart devices into military operations has significantly expanded the attack surface, introducing critical security vulnerabilities. This paper explores how smart devices can compromise operational security (OPSEC) through unauthorized data leaks, cyber exploitation, and geolocation tracking. It examines real-world incidents, including security breaches during the Russian-Ukrainian conflict and the exposure of military bases via fitness tracking applications. Additionally, the study analyses adversarial tactics that leverage AI-driven OSINT and behavioural analytics to exploit smart device vulnerabilities. Finally, mitigation strategies, including policy recommendations and technical countermeasures, are discussed to enhance the cybersecurity posture of military personnel and operations.**

Keywords – AI, Cyber Threats, Smart Device, OPSEC.

I. INTRODUCTION

The widespread adoption of personal smart devices in the military has reshaped the security landscape, expanding the attack surface and exacerbating OPSEC vulnerabilities in modern warfare. These devices ranging from smartphones and tablets to fitness trackers, smartwatches, and even augmented reality headsets offer unprecedented connectivity, convenience, and mobility. Yet, their presence in both professional and personal military environments has unintentionally created numerous security risks [1]. By relying on these devices for communication, navigation, health monitoring, and data synchronization, military units are exposed to potential adversarial exploitation [2], [3]. The convergence of consumer grade technology with military operations has not only complicated cybersecurity defences but also challenged the reliability of secure communication systems, thereby making these devices prime targets for sophisticated cyber threats.

In modern military operations, smart devices have seamlessly integrated into critical mission activities, serving as tools for navigation, real time communication, health surveillance, and operational coordination. However, their extensive usage has broadened the attack vectors, making them more vulnerable to exploitation by state-sponsored cyber adversaries, organized hacking groups, and even low-level cybercriminals.

Smart devices inherently rely on wireless communication protocols such as Bluetooth, Wi-Fi, and GPS, which remain susceptible to interception, spoofing, and manipulation.

Such vulnerabilities enable adversaries to gather intelligence, conduct cyber espionage, and physically track military personnel, ultimately compromising mission integrity and safety.

Moreover, the continuous synchronization of these devices with cloud servers and social media platforms inadvertently exposes sensitive operational data, increasing the risk of unauthorized access, data exfiltration, and geolocation tracking.

The 2018 Strava heat map incident, for example, revealed secret U.S. and allied military installations, as well as Russian military bases, through aggregated fitness tracking data [4], [5].

The public accessibility of these heat maps provided adversaries with actionable intelligence on troop movements, operational schedules, and even internal base layouts.

In another case, the geolocation data from personal fitness trackers enabled the targeted assassination of Stanislav Rzhitsky, a high-ranking Russian naval commander. By analysing his jogging patterns recorded on a fitness tracking application, adversaries were able to predict his routine and carry out a precision strike with lethal efficiency [6].

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8616
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

These cases highlight the evolving cyber threat landscape in military operations, demonstrating how adversaries exploit digital footprints left by seemingly harmless personal devices. Addressing these risks requires robust cybersecurity measures, stricter device usage policies, and heightened awareness among military personnel to mitigate potential threats.

The rapid evolution of cyber warfare has further exacerbated these risks, as state sponsored hacking groups and advanced persistent threats increasingly leverage artificial intelligence and machine learning algorithms to automate and optimize their attacks.

AI-driven cyber operations can process vast amounts of data from compromised smart devices to predict military movements, analyse behavioural patterns, and profile personnel vulnerabilities. By correlating this data with open-source intelligence (OSINT), adversaries can create predictive models of troop deployments, mission schedules, and strategic decision-making processes. The integration of AI into cyber espionage tactics enables adversaries to execute highly targeted phishing campaigns, deploy adaptive malware that evolves in real-time, and even generate deepfake communications for social engineering attacks. These capabilities allow adversaries to infiltrate military networks, manipulate operational data, and disrupt critical infrastructure with unprecedented speed and precision.

The growing dependence on personal smart devices has inadvertently created an asymmetric warfare advantage for adversaries, particularly those backed by nation-states with significant cyber capabilities. The lack of standardized regulations governing the use of personal smart devices in military environments further compounds the risk, making them an unintentional weak link in military cybersecurity. Unlike military-grade communication systems, commercial smart devices are not designed to meet stringent security standards, often lacking end-to-end encryption, robust authentication mechanisms, and secure software update protocols. Additionally, the widespread usage of third-party applications many of which request excessive permissions introduces a new layer of vulnerability that adversaries can exploit for surveillance, data exfiltration, and network infiltration. The ease of integrating these applications into personal devices makes it difficult to establish secure perimeters within military bases, thereby compromising OPSEC.

The aim of this research is to assess the vulnerabilities linked to personal smart devices, investigate real-life incidents that demonstrate these risks, and propose actionable solutions at both the policy and operational levels. By gaining a deeper understanding of various attack vectors and their outcomes, military organizations can implement robust cybersecurity protocols to prevent unauthorized access and mitigate the threats these devices present. This study contributes to the ongoing dialogue on cybersecurity within military operations by providing recommendations for securing personal smart devices without compromising the operational capabilities of military personnel. In the subsequent sections, the paper will examine the core vulnerabilities inherent in smart devices, analyse the attack methods adversaries use to exploit these weaknesses, and present case studies that highlight their real-world impact. Additionally, it will explore mitigation strategies aimed at strengthening OPSEC and reinforcing military cybersecurity measures.

II. Materials and Methods

The reliance on interconnected smart devices and technologies creates multiple points of entry for cyber threats, making military personnel and operations more susceptible to intelligence gathering, cyber espionage, and network infiltration.

Since the connection is not completely secured, the primary concerns associated with smart devices is unintentional data leakage. Many applications and built-in functionalities continuously collect and transmit user data, often without explicit consent. Location services, Bluetooth connections, and automatic cloud synchronization expose military personnel to unauthorized tracking. Even when military personnel disable location-sharing settings, metadata embedded in messages, photos, and social media activity can still provide adversaries with crucial intelligence. This kind of passive surveillance allows adversaries to map operational areas, identify personnel movement patterns, and assess the presence of classified facilities [7].

The growing sophistication of state-sponsored cyber operations has further amplified the risks associated with smart devices. APT groups often linked to national intelligence agencies actively exploit smart device vulnerabilities to gather intelligence on foreign military activities. These groups employ a range of tactics, including malware injection, phishing campaigns, and network intrusion techniques, to compromise military networks through personal devices. [8], [9].

Given the widespread usage of consumer-grade smart devices in military settings, adversaries can leverage these vulnerabilities to conduct targeted attacks, gather intelligence, or even manipulate information to disrupt military operations. Beyond cyber threats, supply chain vulnerabilities present another significant risk [10]. Many smart devices are manufactured using global supply chains, making them susceptible to firmware manipulation or pre-installed malware before they even reach the end user. Hardware backdoors embedded in commercially produced devices can enable adversaries to conduct long-term intelligence gathering and system infiltration. Unlike military-grade communication equipment, which undergoes extensive security testing, consumer smart devices do not always meet stringent security standards, leaving them exposed to potential exploitation at multiple stages of production and distribution. The convergence of smart devices with military operations has created a hybrid security challenge, where traditional OPSEC measures are insufficient to counteract the evolving cyber threat landscape.

A. Types of Weakness in Smart Devices

Smart devices contain several inherent weaknesses that make them highly vulnerable to exploitation by

adversaries, presenting significant risks to military operational security. A key issue lies in ***the protocols used*** for data exchange, such as Bluetooth, Wi-Fi, and cellular networks, which are particularly prone to interception, spoofing, and man-in-the-middle attacks. These communication protocols are often poorly secured, allowing adversaries to intercept sensitive military data, manipulate transmissions, and track personnel movements. The absence of robust end-to-end encryption in many commercial smart devices intensifies this vulnerability, enabling unauthorized data extraction and heightening the potential for cyber espionage.

Another critical vulnerability is found in ***the default data-sharing configurations*** embedded in many smart devices and applications. Fitness tracking applications, social media platforms, and cloud-based services frequently collect and store user data without explicit consent. Without careful configuration for privacy, these applications continuously track user activities and locations, creating extensive datasets that can be exploited by adversaries. When aggregated across multiple personnel, this data can unintentionally expose movement patterns, deployment sites, and the positioning of key military assets, posing serious risks to operational security (OPSEC).

Smart devices are particularly vulnerable to cyberattacks due to ***outdated or insecure firmware***. Many consumer-grade devices operate on outdated firmware versions, lacking adequate encryption protocols and essential security patches, making them easy targets for malicious actors. Firmware manipulation, zero-day vulnerabilities, and supply chain attacks provide opportunities for adversaries to compromise devices even before they are deployed in military environments. The military's dependence on off-the-shelf consumer technology amplifies this risk, as these devices do not adhere to the rigorous cybersecurity standards required for military operations.

Supply chain vulnerabilities further compound the cybersecurity risks associated with smart devices [9]. Most smart devices are produced through complex global supply chains, making them susceptible to firmware manipulation or pre-installed malware before they even reach the end user. Embedded hardware backdoors during production allow adversaries to conduct long-term intelligence gathering, data exfiltration, and remote sabotage. In contrast to military-grade communication systems, which undergo extensive security testing, consumer smart devices often fail to meet the stringent cybersecurity standards necessary to safeguard against exploitation throughout production and distribution.

The ***continuous synchronization*** of smart devices with cloud services significantly increases the risk of unauthorized data exposure. Many personal smart devices automatically sync their data with cloud storage platforms, making sensitive military information vulnerable to external breaches. Cyber adversaries can infiltrate these cloud environments, gain access to classified data, and use it to disrupt and compromise military operations.

The ***integration of smart devices with commercial networks***, often lacking military-grade security measures, introduces another layer of risk, allowing adversaries to exploit these unsecured channels for intelligence gathering and system infiltration.

The growing complexity of smart device ecosystems, combined with the absence of standardized security protocols, creates a multi-faceted threat landscape that traditional military OPSEC measures struggle to address. As the military continues to adopt smart devices in its operations, the challenge of protecting sensitive data and communications from cyber threats becomes increasingly daunting.

B. Fitness Tracking Devices

Fitness tracking devices pose a unique security risk due to their continuous monitoring of user activities and locations. These devices, which include brands such as Fitbit, Garmin, and Apple Watch, collect extensive biometric data such as heart rate, sleep patterns, and movement habits. While these features are beneficial for personal health tracking, they also provide adversaries with valuable intelligence on military personnel. In recent years, these devices have been implicated in significant security breaches, where adversaries have exploited publicly available fitness data to track military movements and base locations. One of the most notorious security breaches involving fitness tracking devices was the Strava heat map incident, where aggregated GPS data from users inadvertently exposed sensitive military locations worldwide. The heat map, intended to display global exercise activity, highlighted heavily frequented routes in isolated regions many of which corresponded to secret U.S. military bases and intelligence outposts. The revelation of these locations posed a severe OPSEC threat, as adversaries could analyse movement patterns, shift schedules, and personnel routines. The exposure demonstrated how seemingly harmless fitness applications could compromise national security.

In late 2024, the exposure of Israeli military bases through Strava data further underscored the security risks associated with fitness tracking devices. In this instance, military personnel inadvertently shared their running routes on a publicly accessible platform, enabling adversaries to analyse and map military training facilities, patrol patterns, and operational movements. The intelligence derived from this data allowed hostile actors to estimate troop deployments, operational readiness, and high-value target locations. A report by Haaretz [11], an Israeli newspaper, first revealed a critical security vulnerability within the Strava fitness application that could be exploited by an unidentified actor, potentially a foreign intelligence operative. By creating a fraudulent account, the individual systematically uploaded falsified geolocation data, simulating jogging routes through highly sensitive military installations, including Israeli Air Force bases, intelligence facilities, naval stations, and a U.S. military facility. This deceptive tactic inadvertently exposed the identities of active military personnel, compromising their operational

locations, residential addresses, and movement patterns, thereby posing a significant national security risk.

C. The Importance of Data in the Age of Artificial Intelligence

The advent of artificial intelligence (AI) has profoundly reshaped the realm of cyber warfare and intelligence gathering, intensifying the risks related to personal smart devices in military settings. AI-driven systems possess the capability to analyse massive volumes of data in real time, allowing adversaries to detect and manipulate patterns in military movements, personnel actions, and logistical operations. This convergence of AI with cyber espionage has ushered in a new era where state-sponsored hacker groups can automate and expand their attacks, rendering traditional cybersecurity defences insufficient and inadequate in safeguarding sensitive military assets.

One of the most alarming aspects of AI in cyber warfare is its ability to predict and manipulate human behaviour based on collected data. By analysing geolocation metadata, biometric readings, and device usage patterns, AI-driven systems can generate predictive models of military operations. These models enable adversaries to forecast troop deployments, mission schedules, and logistical weaknesses with a high degree of accuracy. Machine learning algorithms can also aggregate information from publicly available sources, such as social media posts and fitness tracking applications, to refine intelligence assessments and enhance targeting precision. AI enhances the effectiveness of automated phishing and social engineering attacks. Deep learning models can generate highly convincing phishing emails and messages tailored to specific military personnel by mimicking writing styles, tone, and organizational jargon. AI-generated deepfake videos and voice recordings further complicate cybersecurity efforts by making it increasingly difficult to differentiate between legitimate and fraudulent communications. This technology has been used to impersonate senior military officials, tricking personnel into divulging classified information or granting access to secure systems.

AI-driven cyber operations also play a crucial role in automated malware deployment and adaptive cyberattacks. Traditional malware detection systems rely on known attack signatures, but AI-powered malware continuously evolves, modifying its structure and behaviour to evade detection. Self-learning malware can autonomously assess a target's defence, identify vulnerabilities, and optimize its attack strategy in real time. Such adaptive threats pose significant challenges to military cybersecurity teams, requiring continuous monitoring and rapid-response capabilities to mitigate potential breaches.

The ability of AI to conduct real-time data exploitation has further intensified the risks posed by personal smart devices in military settings. AI algorithms can sift through massive datasets collected from compromised smart devices, identifying sensitive information and classifying it for strategic use [12]. This automated intelligence processing allows adversaries to extract mission-critical details with minimal human intervention, significantly reducing the time required to act on intercepted data. The speed and efficiency of AI-driven intelligence gathering enable adversaries to conduct cyber operations at an unprecedented scale, heightening the need for robust cybersecurity frameworks.

D. The Role of Smart Devices in AI-Driven Cyber Espionage

Smart devices play a crucial role in enabling AI-driven cyber espionage. Many military personnel unknowingly carry AI-assisted surveillance tools in the form of fitness trackers, smartphones, and wearable devices that continuously collect and transmit personal data. Adversaries can exploit this data to create detailed behavioural profiles of military personnel, identifying their routines, stress levels, and potential vulnerabilities. These insights can be used to develop targeted cyberattacks that exploit psychological and operational weaknesses.

For example, AI can analyse sleep patterns and biometric data from fitness trackers to determine when personnel are most fatigued or vulnerable to social engineering attacks. If an adversary identifies that a particular soldier regularly experiences sleep deprivation, they can time their cyberattacks to coincide with periods of reduced alertness.

Similarly, AI-driven sentiment analysis of private messages and emails can detect dissatisfaction or stress among military personnel, enabling adversaries to exploit morale issues through psychological manipulation. The growing interconnectivity of smart devices within military environments has also increased the risk of coordinated AI-powered surveillance campaigns. By compromising multiple personal devices, adversaries can establish a network of real-time intelligence sources within military bases and operational zones. AI algorithms can correlate data from different compromised devices to reconstruct tactical movements and strategic planning. This level of intelligence gathering far exceeds traditional reconnaissance methods, making smart device security a top priority for military cybersecurity teams. The risk of AI-assisted malware attacks targeting smart devices has also escalated in recent years. Malicious AI can craft highly personalized phishing messages, manipulate voice recognition systems, and even mimic biometric authentication processes to gain access to classified networks. These attacks can be further enhanced by deepfake technology, which allows adversaries to impersonate military personnel with near-perfect accuracy. The combination of smart devices and AI-driven deception tactics poses a formidable challenge for cybersecurity professionals.

III. RESULTS AMD DISCUSSION

The real-world implications of smart device vulnerabilities in military environments have been demonstrated through several major security breaches. These incidents highlight how adversaries exploit personal technology to compromise military bases, personnel, and operations. The following case studies provide in-depth analyses of how fitness tracking applications, social media

activity, and geolocation data have been used to undermine OPSEC, leading to strategic exposure and, in some instances, lethal consequences.

A. 2018 - Strava's Heat Map Revealing Taiwan's Secrets and Secret US Military Bases

In 2018, Strava, a fitness tracking application, published a global heat map (Fig. 1) that visualized user activity by aggregating GPS data from millions of users worldwide.

While this data was intended for civilian fitness tracking, it inadvertently exposed numerous secret military installations, particularly in Africa (Fig. 2 and Fig. 3), the Middle East, Afghanistan, and Taiwan (Fig. 4). Distinct movement patterns recorded in remote and strategically sensitive areas revealed U.S. and allied military bases.

Fig. 2 shows Camp Lemonnier (top right) and a suspected CIA base (bottom left) in Djibouti, both clearly distinguishable by their illumination. Fig. 3 depicts the U.S. base at Al-Tanf, Syria, near the Iraqi border, appearing as a distinct elongated light signature. Similarly, forward operating bases in Helmand, Afghanistan, are illuminated, indicating significant activity. These examples demonstrate how light emissions and activity patterns can inadvertently reveal the locations of sensitive military installations.

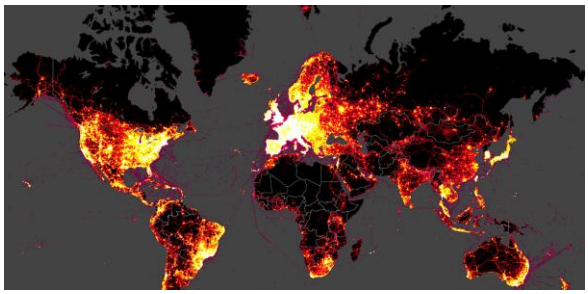


Fig. 1. Stava worldwide heatmap (2018) [13].

The heat map highlighted high-activity exercise routes in isolated regions, which adversaries used alongside satellite imagery and intelligence databases to pinpoint covert military sites. Military analysts noted that the data not only delineated base perimeters but also revealed patrol routes, shift rotations, and internal facility layouts. These insights enabled hostile actors to infer troop deployments, high-value target locations, and logistical vulnerabilities.



Fig. 2. US military and CIA presence in Djibouti [14].

Another significant incident involved the inadvertent disclosure of Taiwan's Missile Command Center (shown in Fig. 4), a facility of high strategic importance. This center oversees Taiwan's long-range missile operations, including cruise missiles capable of reaching mainland China. The exposure occurred when analysts examined Strava's heat map data, which revealed unexpected fitness activity in a restricted area.

OSINT specialists and military analysts detected concentrated movement patterns – primarily from jogging – within a zone off-limits to civilians. These patterns aligned with typical routines of military personnel at secure sites. By cross-referencing the coordinates with satellite imagery and existing maps, analysts pinpointed the activity within a known military installation in Taiwan. Further examination of Taiwan's military infrastructure confirmed that this was not just any base, but the headquarters of Taiwan's missile command.



Fig. 3. US outpost at Al-Tanf, Syria [15].

Reports and prior intelligence assessments indicated the presence of long-range cruise missiles in the area, intended to counter threats from mainland China. Despite efforts to camouflage missile transporter vehicles, analysts observed personnel movements around structures resembling missile launch facilities. The correlation between Strava data and known military logistics strongly suggested a link to Taiwan's missile operations.



Fig. 4. Heatmap of Strava showing activity around and in Taiwan's missile command [16].

OSINT experts and defence analysts corroborated their findings by matching movement patterns with previously leaked information about Taiwan's missile strategy. They

also identified additional concealment measures, such as structures designed to shield vehicles from satellite surveillance. Nonetheless, consistent jogging patterns around the facility provided clear evidence of military activity. The integration of heat map data, satellite imagery, and intelligence reports led to the definitive identification of the site as Taiwan's Missile Command Center, highlighting a significant operational security lapse.

B. The Assassination of Stanislav Rzhitsky through Strava Data Tracking

In 2023, Russian naval officer Stanislav Rzhitsky, a former submarine commander, was assassinated while jogging in Krasnodar. Investigations revealed that his fitness tracking data on Strava had been used by adversaries to monitor and predict his routine (Fig. 5), ultimately facilitating his targeted elimination. Using AI-driven behavioural analytics and OSINT aggregation, adversaries developed a predictive model of Rzhitsky's daily jogging routes. By cross-referencing his social media activity, fitness tracker data, and time-stamped geolocation points, attackers identified the optimal time to strike when security presence was minimal. The precise timing and execution of the assassination suggested the use of AI-enhanced surveillance techniques to anticipate Rzhitsky's movements in real time.

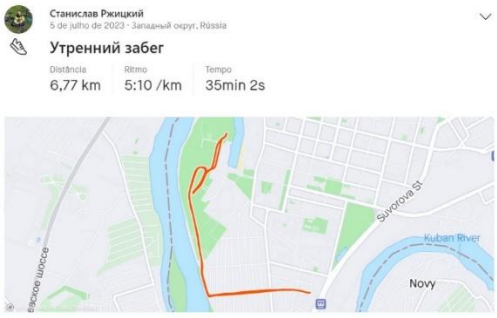


Fig. 5. The route that Stanislav Rzhitsky regularly ran, posted publicly on his Strava account [6].

The assassination served as a stark demonstration of the lethal risks posed by unsecured (unregulated) digital footprints, particularly among high-value military personnel. Following this incident, Russian intelligence agencies imposed strict bans on fitness tracking applications within military ranks, strengthening cybersecurity measures against adversarial intelligence efforts. The case highlighted how AI-driven OSINT can be exploited to execute precision strikes on high-profile targets.



Fig. 6. Russian Airbase in Khmeimim, Syria. [5].

A recurring example of data consolidation from mobile applications and intelligence is the disclosure of the Russian Airbase in Khmeimim, Syria (Fig. 6).

C. 2025 - Military Personnel on a French Nuclear Submarine Reveal Sensitive Information Through Strava

In early 2025, a major security breach within the French Navy's nuclear submarine fleet [17] was exposed when Strava's heat map revealed the operational routes and patrol cycles of ballistic missile submarines (SSBNs). The leak, which was investigated by French intelligence and cybersecurity agencies, showed that crew members stationed at the Ile Longue naval base in Brest had inadvertently shared sensitive operational data through their personal fitness trackers.

This breach allowed adversaries to reconstruct submarine deployment schedules, docking routines, and patrol routes, critically undermining France's nuclear deterrence strategy. More alarmingly, several personnel had used real names on public Strava profiles, making it possible to identify individual crew members and track their activities. The compromised data could potentially enable adversaries to pre-position surveillance assets, track SSBN departures and predict deterrence readiness cycles.

French defence officials implemented emergency countermeasures, including the mandatory deactivation of fitness tracking applications, OPSEC retraining for naval personnel, and real-time cybersecurity monitoring of unauthorized data transmission. However, this incident demonstrated the inherent risks of unsecured digital footprints in the context of strategic military operations, highlighting the urgent need for comprehensive cybersecurity protocols in nuclear deterrence efforts.

IV. CONCLUSION

The findings of this study underscore the significant security risks posed by personal smart devices in military environments. As demonstrated by the documented cases, adversaries have successfully exploited geolocation tracking, metadata exposure, and AI-driven OSINT techniques to compromise operational security. The ability to reconstruct troop movements, predict deployment schedules, and even execute targeted assassinations highlights the severity of the threat landscape.

To mitigate these risks, military organizations must adopt a multi-layered cybersecurity approach. This

includes enforcing strict device usage policies, mandatory OPSEC training, and real-time monitoring of unauthorized data transmissions. Additionally, AI-driven anomaly detection systems should be deployed to identify and neutralize potential cyber threats in real time. The adoption of military-issued, security-hardened devices and strict geofencing of sensitive locations can further reduce vulnerabilities.

The increasing sophistication of cyber adversaries necessitates continuous adaptation in cybersecurity practices. As AI-powered cyber warfare capabilities evolve, military forces must proactively update their defensive strategies to counter emerging threats. Future research should focus on the development of secure-by-design military-grade smart devices and the implementation of AI-assisted counter-surveillance techniques to neutralize adversarial intelligence efforts.

By addressing these challenges, military organizations can strengthen their cybersecurity posture and ensure the integrity of critical missions in an era of digital warfare.

A. Mitigation

To prevent similar security breaches, military organizations must enforce strict digital hygiene policies. Key mitigation strategies include:

- Refining OPSEC Policies**:** Commanders should tailor security measures based on adversary capabilities, balancing operational efficiency with risk mitigation when using smart devices.
- Enhanced Training & Awareness: Utilize subject matter experts to educate personnel on digital footprints, adversarial electronic warfare, and the risks of smart devices, ensuring regular OPSEC training.
- Restricting Location-Based Features**:** Mandatory disabling of fitness tracking apps and location-sharing features to minimize exposure.
- Geofencing & Network Controls**:** Blocking access to social media and tracking apps in sensitive areas to prevent data leaks.
- AI-Driven Security**:** Leveraging AI for real-time anomaly detection and unauthorized data transmission monitoring.
- Strict Device Policies**:** Enforcing the use of military-issued, security-controlled devices to limit risks.
- Tech Industry Collaboration: Partnering with private sector firms to develop secure communication applications for military use.
- Cybersecurity Taxonomy Implementation: Standardizing threat identification and AI-based defenses to strengthen OPSEC policies.
- Specialized Cybersecurity Recruitment**:** Rigorous selection and training of cybersecurity personnel to improve threat response and resilience [18].

ACKNOWLEDGEMENT

This research paper has received funding from Ministry of Education and Science of the Republic of Bulgaria under the National Science Program "SECURITY AND DEFENCE", in implementation of the Decision of the Council of Ministers of the Republic of Bulgaria No: 731/21.10.2021 and according to Agreement No: D01-74/19.05.2022.

REFERENCES

[1] J. K. Kirschbaum et. al., "Internet Of Things: Enhanced Assessments and Guidance Are Needed to Address Security Risks in DOD," United States Government Accountability Office, Washington, USA, Report to Congressional Committees GAO-17-668, 2017.

[2] M. Koller, "Recommendations for Safety-Conscious Smart Device Use by Military Professionals", AARMS., Vol. 21, № 2, pp. 5-14, 2022, https://doi.org/10.32565/aarms.2022.2.1.

[3] K. Dhondt et al., A Run a DayWon't Keep the Hacker Away: Inference Attacks on Endpoint Privacy Zones in Fitness Tracking Social Networks, Conference on Computer and Communication (CCS '22), November 7-11, 2022, Los Angeles, CA, USA. New York, NY, USA, 16 pages, 2022, https://doi.org/10.1145/3548606.3560616.

[4] A. Nocks, The Geointelligence Revolution: Real-Time Reconnaissance and Its Dangers, PIPS, Institute for the Theory and Practice of International Relations, Williamsburg, Virginia, USA, 2018.

[5] Data and Defense: The Case of Strava, Feb. 2, 2018. [Online]. Available: https://medium.com/dfrlab/data-and-defense-the-case-of-strava-6b56ee3b1a2. [Accessed: Feb. 22, 2025].

[6] Russian commander who posted running routine on app is murdered while exercising, July 11, 2023 [Online]. Available: https://g1.globo.com/mundo/noticia/2023/07/11/comandante-russo-que-publicava-rotina-de-corrida-em-aplicativo-e-assassinado-quando-se-exercitava.ghtml [Accessed: Feb. 22, 2025]

[7] S. Szymoniak and K. Foks, "Open Source Intelligence Opportunities and Challenges – A review", Advances in Science and Technology Research Journal, Vol 18, № 3, pp 123-139, 2024, https://doi.org/10.12913/22998624/186036.

[8] S. Grooby, T. Dargahi and A. Dehghantanha. Protecting IoT and ICS platforms against advanced persistent threat actors: Analysis of APT1, in In Handbook of Big Data and IoT Security, Springer, Cham, 2019, pp. 225-255.

[9] D. Dimitrov and D. Nikolov, Current Cybersecurity Issues in the Industrial Control System of Nuclear Power Plants, Vol. 2, Conference on Radiation Safety in the Modern World, November 16-18, 2022, Veliko Tarnovo, Bulgaria, 8 pages, 2022, https://doi.org/10.34660/INF.2023.43.56.040. (In Bulgarian).

[10] N. Takpah and V. Oriakhi, "Cybersecurity Challenges and Technological Intergration in Military Supply Chain 4.0", Journal of Information Security, Vol. 16, № , pp. 131-148, 2025, https://doi.org/10.4236/jis.2025.161007.

[11] Haaretz Investigation: Intelligence Operation Collected Information on Sensitive Israeli Bases, Soldiers, Oct. 29, 2024. [Online]. Available: https://www.haaretz.com/israel-news/security-aviation/2024-10-29/ty-article-magazine/.premium/intelligence-operation-collected-information-on-sensitive-israeli-bases-soldiers/00000192-d7bb-df2b-a5db-d7bf8d440000 [Accessed: Feb. 22, 2025].

[12] V. Atanasov and Y. Sivkov, Evaluating Yolov5 Models on Thermal Imagery for Aerial Drone Applications, Conference 23rd International Symposium on Electrical Apparatus and Technologies (SIELA), June 12-15, 2024, Bourgas, Bulgaria, 4 pages, 2024, https://doi.org/10.1109/SIELA61056.2024.10637871.

[13] Strava oficial site. [Online]. Available: https://www.strava.com/maps/global-heatmap?sport=All&style=dark&terrain=false&labels=true&poi=true&cPhotos=true&gColor=blue&gOpacity=100#1.5/31.1/12.5 [Accessed: Feb. 22, 2025].

[14] Fitness Tracker Data Highlights Sprawling U.S. Military Footprint in Africa, Jan. 29, 2018. [Online]. Available: https://theintercept.com/2018/01/29/strava-heat-map-fitness-tracker-us-military-base/ [Accessed: Feb. 22, 2025].

[15] D. Brown, "Here are some of the biggest reveals from a fitness-tracker data map that may have compromised top-secret US military bases around the world", Jan. 29, 2018. [Online]. Available: https://www.businessinsider.com/strava-heatmap-most-revealing-images-2018-1 [Accessed: Feb. 22, 2025].

[16] An American fitness app leaked global military bases. Do we still dare to publish our running records?, Jan. 30, 2018 [Online]. Available: https://kknews.cc/world/l2ba32g.html#google_vignette [Accessed: Feb. 22, 2025].

[17] French submarine crew accidentally leak sensitive information through Strava app, Jan. 15, 2025. [Online]. Available:https://www.euronews.com/2025/01/15/french-submarine-crew-accidentally-leak-sensitive-information-through-strava-app [Accessed: Feb. 22, 2025].

[18] M. Maroun and A. Ivanova, Ontology-based approach for cybersecurity recruitment, Applications of Mathematics in Engineering and Economics (AMEE '20), June 7-13, 2020, Sofia, Bulgaria, 11 pages, 2021, https://doi.org/10.1063/5.0042320.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 107-113

Leveraging YARA and Sigma Rules to Detect Chinese State-Sponsored Hacking Groups of the "Typhoon" Type

Dimitar Dimitrov
IT Department
Nikola Vaptsarov Naval Academy
Varna, Bulgaria
dimitar@nvna.bg

Dimitar Nikolov
IT Department
Nikola Vaptsarov Naval Academy
Varna, Bulgaria
d.nikolov@naval-acad.bg

Abstract – This study addresses the escalating cyber threat posed by Chinese state-sponsored hacking groups, particularly the "Typhoon" class (Salt Typhoon and Volt Typhoon) which target critical infrastructure through stealthy and persistent techniques. The research aims to enhance detection capabilities against these advanced persistent threats by analysing their tactics, techniques, and procedures and by developing YARA and Sigma rules. The methodology involves mapping observed TTPs to MITRE ATT&CK and designing detection rules that identify key indicators of compromise in both system files and event logs. The main contribution of the study is the implementation of rule-based detection mechanisms that proactively uncover malicious activities often missed by traditional signature-based tools.

Keywords – China, Cyberspace, Salt Typhoon, Sigma rules, Volt Typhoon, YARA rules

I. INTRODUCTION

Cyber threats have become an undeniable reality in the modern digital landscape, with state-sponsored groups playing a critical role in cyber-espionage, sabotage and information warfare. Among the most concerning threats are those originating from Chinese state-sponsored advanced persistent threat groups, which have been implicated in large-scale cyber operations targeting government agencies, critical infrastructure, military entities and private sector organizations across the globe. These groups operate with significant resources, advanced technical capabilities and a strategic focus on long-term objectives, allowing them to execute sophisticated and persistent cyber campaigns. Chinese advanced persistent threat (APT) groups employ a wide range of tactics, techniques and procedures that include credential theft, supply chain compromises, data exfiltration and stealthy network intrusions that remain undetected for extended periods. Their operations align with China's broader geopolitical, economic and military ambitions, making them a persistent and evolving cyber threat.

Within this landscape, the "Typhoon" class of Chinese APTs, particularly Volt Typhoon and Salt Typhoon, has emerged as a significant concern. These groups are distinguished by their emphasis on stealth, persistence and operational security, leveraging advanced techniques to maintain access to victim networks while avoiding detection. Volt Typhoon, for example, has been observed targeting critical infrastructure, including communications networks, energy providers and transportation systems. Rather than relying on traditional malware, this group primarily uses "living off the land" techniques, meaning it exploits built-in system tools and legitimate network functionalities to conduct attacks, making detection exceptionally difficult. Similarly, Salt Typhoon has demonstrated a high degree of adaptability, frequently shifting tactics and using highly customized toolsets to evade security defenses. The ability of these groups to persist within networks for months or even years highlights the inadequacy of traditional security measures and underscores the need for more advanced detection methodologies.

The nature of advanced persistent threats like Volt Typhoon and Salt Typhoon presents a considerable challenge to conventional cybersecurity defenses. Traditional signature-based detection methods, such as antivirus solutions and intrusion detection systems, rely on identifying known malicious signatures, hashes, or predefined attack behaviours. However, Chinese APT groups increasingly employ evasion techniques that render these detection methods ineffective. Their ability to blend

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8617
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

into normal network traffic, use compromised credentials and exploit legitimate system functions makes it difficult for traditional security tools to recognize their presence. Also, these APTs operate with a long-term strategic mindset, often establishing persistent footholds in networks, allowing them to conduct reconnaissance, data exfiltration and system manipulation over extended periods. Given these challenges, there is a growing need for pattern-based detection mechanisms that focus on behavioural analytics rather than static signatures. Unlike traditional signature-based defenses, pattern-based detection methodologies such as those implemented using YARA [1] and Sigma rules enable security teams to identify suspicious activity based on contextual indicators, anomalous system behaviour and tactics, techniques and procedures (TTPs) associated with APT groups. YARA rules, for instance, are widely used for malware classification and allow analysts to define heuristics that match characteristics of malicious files and processes. By leveraging these rule-based detection methods, organizations can improve their ability to detect and respond to Chinese APT activities proactively.

One of the primary objectives of this study is to conduct analysis of the tactics, techniques and procedures used by Typhoon APT groups. By examining their attack methodologies, exploitation techniques, command and control infrastructures and persistence mechanisms, this research aims to provide a structured understanding of their operational behaviours. This analysis will be mapped to established threat intelligence frameworks such as MITRE ATT&CK to contextualize their activities within the broader cyber threat landscape. Understanding these TTPs is crucial for developing effective countermeasures, as it allows security teams to anticipate potential attack vectors and enhance their defensive capabilities. Additionally, this study will focus on the development and implementation of YARA and Sigma rules to improve threat detection capabilities against these APT groups. Traditional signature-based detection methods often fail to identify the stealthy and adaptive techniques used by Typhoon APTs. To address this challenge, this research will design customized YARA and Sigma rules that target specific behavioural indicators associated with these groups.

II. MATERIALS AND METHODS

YARA, introduced in 2008 by Victor Álvarez of VirusTotal [2], was originally designed to assist malware analysts in classifying threats through flexible, rule-based signatures. Unlike hash-based antivirus solutions, YARA enabled the definition of heuristic patterns such as byte sequences or strings offering adaptability to emerging malware variants. Its open source nature let to rapid adoption within the cybersecurity community, evolving from a research tool into a cornerstone of forensic investigations, threat hunting and real time detection by the mid-2010s. Key developments, including integration with tools like Volatility and the addition of parsing modules for PE and executable and linkable format (ELF) files, enhanced its capability to dissect complex threats. Over the years, YARA [3] has evolved into a critical component of malware analysis, forensic investigations and advanced threat detection. It has been integrated into security solutions such as endpoint detection and response (EDR), intrusion detection systems (IDS) and network traffic analysis tools. These integrations enable security analysts to conduct deep malware scans on endpoints, detect malicious activity within network traffic and perform forensic analysis on compromised systems. Given that Typhoon APT groups frequently use custom malware and advanced obfuscation techniques, YARA rules serve as a vital detection mechanism, allowing defenders to identify malicious payloads even when traditional antivirus solutions fail.

YARA operates by scanning files, memory and process execution data for predefined signatures that match known malware characteristics. These signatures are structured using logical conditions, metadata and string patterns, allowing for a highly granular approach to malware detection. Security researchers develop YARA rules by analyzing malware samples, extracting distinguishing byte sequences and defining detection parameters that minimize false positives while maintaining high accuracy.

In the context of state-sponsored cyber threats [4], YARA is critical for identifying sophisticated malware that exhibits polymorphic or stealthy behaviours. APT groups such as Volt Typhoon use advanced obfuscation techniques, fileless malware and encrypted command-and-control (C2) communications to evade detection. YARA rules can be tailored to detect not only static file signatures but also behavioural markers, memory-resident threats and unique encryption algorithms used by such adversaries. By applying these rules within forensic investigations, security teams can identify malware variants linked to specific threat actors, enabling effective countermeasures and attribution.

In the context of Typhoon type of APTs, YARA rules provide a robust framework for detecting the stealthy malware by enabling analysts to define tailored heuristics that address specific characteristics of these threats. These rules can target unique byte sequences or API calls embedded within malware payloads, such as those used by Volt Typhoon to inject code into legitimate processes. Additionally, YARA excels at identifying encryption methods and obfuscation techniques, which are hallmarks of Chinese APT operations designed to thwart reverse-engineering efforts. For example, rules can be crafted to detect proprietary C2 encryption algorithms or memory-resident artifacts like those deployed by Salt Typhoon to maintain persistent access by scanning process memory or network traffic for anomalous patterns. By focusing on these granular indicators, YARA bridges the gap left by traditional defenses, offering a proactive means to pinpoint malware variants that evade conventional detection systems. Beyond static analysis, YARA's application extends to uncovering broader indicators of compromise associated with Typhoon APTs, enhancing both forensic investigations and real-time threat hunting. Rules can be designed to identify malicious processes, registry

modifications, or behavioural markers such as Volt Typhoon's use of wmic process call create for remote execution providing a comprehensive view of an adversary's footprint. This capability is particularly valuable in detecting memory-only implants, which lack disk-based signatures and require memory forensics to expose.

A. UNDERSTANDING SIGMA RULES

Sigma rules represent a transformative approach to threat detection by providing a standardized, YAML-based framework that enables security analysts to define detection logic applicable across diverse Security Information and Event Management (SIEM) platforms. Introduced in 2017 by Florian Roth and Thomas Patzke [5], Sigma addresses the heterogeneity of SIEM query languages by offering a vendor-neutral format that can be translated into dialects such as Splunk's Search Processing Language (SPL), ElasticSearch's Event Query Language (EQL) and Kibana Query Language (KQL), Microsoft Sentinel's Kusto Query Language (KQL), IBM QRadar's AQL and Micro Focus ArcSight's query syntax, among others. This cross-platform compatibility ensures that organizations with varied SIEM deployments common in enterprise settings can implement a unified detection strategy without the need for extensive customization. By leveraging log data from sources such as Windows Event Logs, Sysmon, network traffic and authentication records, Sigma empowers security teams to monitor for early indicators of advanced persistent threat activity, a capability critical to countering the stealthy operations of Chinese state-sponsored groups like Volt Typhoon and Salt Typhoon.

The relevance of Sigma rules is particularly pronounced in detecting the behavioural patterns of Typhoon APTs, which exploit system logs and legitimate functionalities to establish persistence and evade traditional malware-focused defenses. Volt Typhoon, for example, is known to manipulate authentication logs through brute-force attacks or credential dumping, while Salt Typhoon has been observed altering process execution data to facilitate lateral movement within compromised telecommunications networks. Sigma rules enable granular detection of such activities by defining logic that flags anomalies—such as unusual login patterns, suspicious command-line executions. or unexpected registry changes—in real time.

Sigma's real-time monitoring capabilities [6] enhance SIEM effectiveness by correlating disparate log events into actionable intelligence, a critical advantage against the prolonged dwell times characteristic of Typhoon APTs. By integrating with frameworks like MITRE ATT&CK, Sigma rules map detected behaviours to specific TTPs such as persistence (T1090) or discovery (T1087) enabling precise attribution and contextual understanding of adversary actions. This adaptability allows security teams to refine rules based on evolving threat intelligence, reducing false positives and mitigating alert fatigue. For instance, a Sigma rule might correlate a spike in failed logins with subsequent PowerShell execution, a pattern observed in Salt Typhoon's initial access strategies, providing early warning of a potential compromise. When deployed within security operations centers, Sigma's standardized approach streamlines threat hunting across enterprise environments, ensuring that defenders can proactively disrupt the attack lifecycle of sophisticated state-sponsored actors like those driving China's aggressive cyber campaigns

B. Primary distinction between yara and sigma rules

YARA, originally developed as a pattern-matching tool for malware classification and detection, operates at the file, memory and process execution level, making it particularly effective for identifying static and dynamic artifacts associated with APTs [7]. By scanning binary files, memory dumps and running processes, YARA detects predefined signatures that include unique byte sequences, string patterns and API call behaviours, which are essential for identifying malicious code deployed by sophisticated adversaries. YARA's ability to define heuristic-based rules allows cybersecurity analysts to pinpoint these sophisticated attack vectors, even in post-compromise forensic investigations. The flexibility of YARA, which supports complex logical conditions and modular parsing of executable formats, makes it an indispensable tool in threat-hunting frameworks, forensic analysis and automated malware detection within EDR and SOAR platforms.

In contrast, Sigma serves as a log-centric detection framework [8], focusing on the behavioural analysis of system, network and application logs to identify anomalies indicative of cyber threats. Sigma employs a standardized YAML-based format that allows security teams to define platform-independent rules, which can then be translated into specific SIEM query languages to facilitate real-time threat detection. Given its ability to correlate log-based activity across multiple data sources, Sigma enables security analysts to track adversarial TTPs in alignment with frameworks such as MITRE ATT&CK, thereby enhancing its applicability in proactive threat hunting, SOC workflows and automated incident response processes.

Beyond their differing operational domains, YARA and Sigma exhibit distinct technical architectures and application scopes, offering complementary strengths that enhance threat detection when deployed in tandem. YARA's rule-based structure allows analysts to specify precise pattern-matching conditions, including hexadecimal sequences, regular expressions and system API calls, making it highly effective for static and memory-resident malware identification. However, because YARA relies [9] on discrete artifacts physically present or executable within a system, its utility is inherently constrained when it comes to detecting multi-stage attack sequences or adversarial movements across a network. Conversely, Sigma adopts a high-level, event-driven detection methodology, leveraging log correlation,

behavioural analytics and adversary attribution to identify stealthy APT activities across enterprise environments. By analyzing command-line executions, lateral movement attempts and unauthorized authentication patterns [10], Sigma provides a broader operational view that enables security teams to track and mitigate adversarial campaigns in real time.

Together, YARA and Sigma create a synergistic detection and response framework, addressing both forensic and proactive security challenges. YARA provides depth in malware detection, uncovering specific artifacts that indicate the presence of an APT within a system, while Sigma provides breadth in threat hunting, illuminating the adversary's operational footprint across an organization's IT infrastructure. The integration of these tools is essential for countering Chinese state-sponsored Typhoon groups, whose tactics involve blending into legitimate network activity, leveraging compromised credentials and executing LotL techniques to evade detection.

C. Technical overview of Volt typhoon and Salt typhoon

Volt Typhoon and Salt Typhoon are integral components of a broader, coordinated effort by the People's Republic of China to establish strategic dominance in cyberspace. As cyber operations continue to play a critical role in the ongoing US-China strategic competition, these two APTs demonstrate China's evolving cyber warfare strategy, which extends beyond conventional espionage to infrastructure pre-positioning, coercion and power projection. Volt Typhoon primarily focuses on infiltrating and embedding itself within critical infrastructure, ensuring access to essential networks that can be disrupted during geopolitical crises, effectively serving as a deterrent mechanism and a means of strategic leverage. Salt Typhoon, on the other hand, operates within the telecommunications sector, providing China with a comprehensive intelligence-gathering capability while also allowing for the potential disruption of communications in key strategic moments

III. RESULTS AND DISCUSSION

Volt Typhoon, active since at least 2017, primarily targets US critical infrastructure, including telecommunications, energy, transportation and water systems, with a strategic focus on pre-positioning for potential sabotage during geopolitical conflicts, particularly involving Taiwan. Its operations, documented in reports from Microsoft and CISA [11, 12, 13], extend to military bases in Guam and key infrastructure, aiming to disrupt US military mobilization. The group's emphasis on OT systems and SCADA networks, reflects its intent to compromise energy grids and communication hubs, aligning with China's cyber warfare strategy.

The group exploits vulnerabilities in public-facing network appliances, including Fortinet FortiGate firewalls, Ivanti Connect Secure VPNs, Citrix NetScaler and Cisco routers. Often, these attacks leverage known CVEs, such as CVE-2021-40539, while also employing brute-force attacks against administrator accounts with weak or default passwords. By focusing on unpatched systems, Volt Typhoon ensures successful entry into targeted environments. To maintain long-term access within compromised networks, Volt Typhoon utilizes built-in Windows administrative tools, including wmic (Windows Management Instrumentation Command-line), ntdsutil (Active Directory manipulation), netsh (network configuration) and PowerShell. These tools enable the APT to blend into normal system activities, avoiding EDR alerts. Additionally, Fast Reverse Proxy clients are deployed to establish covert command-and-control channels, ensuring continuous remote access to infiltrated systems. Volt Typhoon's use of compromised Small Office/Home Office routers as proxy nodes, creating botnets for relay points to mask network traffic. This tactic complicates attribution and detection efforts, enhancing operational security and amplifying the group's ability to maintain covert footholds. A key aspect of Volt Typhoon's tradecraft is its reliance on Fast Reverse Proxy (FRP) clients to establish covert command-and-control (C2) channels. This technique ensures continuous remote access while obfuscating traffic patterns. Additionally, the group utilizes compromised Small Office/Home Office (SOHO) routers as proxy nodes, creating botnets that relay malicious network traffic through legitimate infrastructure. This tactic significantly complicates attribution and detection, enhancing operational security and resilience against takedown efforts. Upon successfully infiltrating a network, Volt Typhoon employs [14] Remote Desktop Protocol (RDP), VPN tunnels and credential-dumping tools such as Mimikatz to escalate privileges and achieve lateral movement. The group has also been observed leveraging Volume Shadow Copy Service (VSS) for offline password cracking, facilitating deeper penetration into domain controllers and administrative systems. Analysis of historical intrusions suggests that Volt Typhoon often maintains network access for over 300 days before detection, exemplifying its long-term infiltration strategy.

Salt Typhoon, linked to Ministry of State Security of China[15, 16] and active since at least 2022, targets telecommunications infrastructure, focusing on US providers like Verizon, AT&T, T-Mobile and Lumen Technologies, as well as global networks, for long-term espionage. Its operations aim to steal sensitive data, including government communications, law enforcement wiretaps and call logs, aligning with China's intelligence-gathering strategy. It also targets government and technology sectors, compromising political figures' communications, including those from the 2024 US presidential campaigns, reflecting its broad scope [17].

In order to infiltrate, Salt typhoon exploits vulnerabilities in network devices, particularly Cisco routers such as CVE-2018-0171, as well as systems such as

Ivanti Connect Secure VPN - CVE-2023-46805 and CVE-2024-21887, Microsoft Exchange – ProxyLogon and CVE-2021-26855 and Fortinet FortiClient EMS. It frequently targets misconfigured systems and employs spear-phishing and credential harvesting to gain initial entry through public-facing endpoints. This group utilizes PsExec, WMIC and PowerShell for stealthy movement within networks. The deployment of the GhostSpider [18] backdoor enables persistent access, facilitating long-term surveillance. Additionally, the group modifies router configurations, such as altering routing tables, to reroute traffic for espionage, effectively blending its actions with legitimate administrative activity. A critical aspect of their Modus operandi is the ability to capture TACACS, SNMP and RADIUS traffic, extracting authentication details to gain access to privileged accounts, thereby securing long-term operational control over compromised systems. alt Typhoon has demonstrated expertise in modifying router configurations to enable port forwarding and traffic rerouting, allowing for the interception of sensitive communications, including wiretap systems. This capability compromises law enforcement surveillance operations, granting the APT unprecedented access to critical data.

Volt Typhoon's stealth-oriented tactics make traditional security measures ineffective, as they leverage built-in system utilities rather than deploying detectable malware. By using Sigma rules, security teams can identify suspicious behaviours and flag adversarial tactics before they escalate into serious breaches. On fig.1 we present Sigma rule tailored to detect key tactics of Volt Typhoon. NTDS file dumping for credential theft and internal port forwarding for lateral movement and persistence.

The purpose of the rule is to detect abuse of the built-in ntdsutil command-line utility for credential dumping from Windows domain controllers. Adversaries target the Active Directory database (NTDS.dit) because it stores password hashes and other credential data for the entire domain. By creating a copy of this database, often via ntdsutil or Volume Shadow Copy services, attackers can obtain credentials for all users and computers in the domain. The rule's primary goal is to catch any attempt to illicitly copy or export the NTDS.dit file using such built-in tools before an attacker can leverage the stolen credentials.

Detection logic of the rule is to monitor process creation events and command-line parameters indicative of NTDS dumping activity, focusing on ntdsutil, vssadmin and wmic usage. It employs multiple detection selections to cover the variations in how this technique can be executed:

- NTDSutil Invocation - Flags any process execution of ntdsutil.exe with arguments suggesting an Active Directory instance activation and data export. For example, an attacker running ntdsutil "activate instance ntds" ifm "create full C:\Windows\Temp\pro" to generate a copy of the AD database would trigger this rule. Such usage of ntdsutil, often with the "Install From Media" ifm command to create a full NTDS backup, is uncommon outside of planned domain maintenance and is a strong indicator of credential dumping attempts.
- Shadow Copy Creation, VSSAdmin/WMIC - Detects the creation of Volume Shadow Copies via command-line utilities. Adversaries frequently create a shadow copy of the system drive, which contains the AD database, to bypass file locks and copy NTDS.dit safely. This selection looks for commands like vssadmin create shadow /for=C: or the equivalent WMI command, wmic.exe shadowcopy call create Volume=C:\, being executed on a domain controller. The presence of "create" and "shadow" in a process command-line, especially associated with vssadmin.exe or wmic.exe, is a red flag for this technique.
- NTDS.dit File Copying - Monitors for any command-line that attempts to copy or save the NTDS.dit file from its default location to another path. For instance, after making a shadow copy, an attacker might run a command to copy \\?\GLOBALROOT\Device\HarddiskVolumeShadowCopy3\Windows\NTDS\ntds.dit to a local folder. The Sigma rule's logic includes patterns like copy ntds.dit to catch such file transfer attempts. This covers variations of the extraction process, whether using copy, xcopy, or even tools like esentutl, any attempt to read or move the AD database file via command-line.
- Associated Utilities – In some cases, the rule may also watch for use of auxiliary commands such as reg.exe to export the SYSTEM hive, since dumping NTDS alone is not enough, attackers also need the system's registry hive for decrypting password hashes. While the focal point is the ntdsutil/VSS sequence, security logs may show concurrent use of reg save HKLM\\SYSTEM commands, which can be correlated with the NTDS.dit dump attempt.

```
status: experimental
description: Volt Typhoon uses ntdsutil to exfiltrate the ntds.dit file and the SYSTEM registry hive from Windows domain controllers
author: Dimitar Nikolov, Dimitar Dimitrov - Bulgarian Naval Academy
references:
    - https://www.cisa.gov/news-events/cybersecurity-advisories/aa23-144a
tags:
    - attack.credential-access #TA0006
    - attack.t1003 #OS Credential Dumping NTDS
logsource:
    category: process_creation
    product: windows
detection:
    selection1:
        CommandLine|contains|all:
            - 'cmd /c vssadmin create shadow /for=C: > C:\Windows\Temp\'
            - 'cmp cmd /c copy \\?\GLOBALROOT\Device\HarddiskVolumeShadowCopy3\Windows\NTDS\ntds.dit C:\Windows\Temp > C:\Windows\Temp\'
    selection2:
        CommandLine|contains|all:
            - 'wmic process call create "ntdsutil \"ac i ntds\" ifm \"create full C:\Windows\Temp\pro'
    selection3:
        CommandLine|contains|all:
            - 'wmic process call create "cmd.exe /c ntdsutil \"ac i ntds\" ifm \"create full C:\Windows\Temp\Pro"'
    selection4:
        CommandLine|contains|all:
            - 'wmic process call create "cmd.exe /c mkdir C:\Windows\Temp\tmp & ntdsutil \"ac i ntds\" ifm \"create full C:\Windows\Temp\tmp\""'
    selection5:
        CommandLine|contains|all:
            - "cmd.exe" /c wmic process call create "cmd.exe /c mkdir C:\Windows\Temp\McAfee_Logs & ntdsutil \"ac i ntds\" ifm \"create full C:\Windows\Temp\McAfee_Logs\""
    selection6:
        CommandLine|contains|all:
            - 'cmd.exe /Q /c wmic process call create "cmd.exe /c mkdir C:\Windows\Temp\tmp & nidsutil \"ac i nids\" ifm \"create full C:\Windows\Temp\tmp\" 1> \\127.0.0.1\ADMIN$\ 2>&1'
    condition: 1 of selection*
falsepositives:
    - Administrative use.
level: high
```

Fig.1. Sigma rule for Volt Typhoon NTDS file dumping

All these detection criteria leverage process creation logs - windows Security Event ID 4688 or Sysmon Event ID 1 with full command-line logging. By correlating events that involve ntdsutil, shadow copy utilities and file copy actions, the rule ensures that multiple methods of

performing an NTDS dump are caught. Notably, Volt Typhoon's tradecraft has involved exactly these patterns - using WMIC to run ntdsutil for an AD database export and vssadmin to create volume shadows which this rule is tailored to detect.

The second rule we created and shown on Fig. 2 is designed to catch the abuse of the Windows netsh interface portproxy command, which attackers use to establish covert internal port forwarding tunnels. Such tunnels effectively turn a compromised host into an internal proxy, allowing adversaries to pivot within a network and maintain persistent access while blending in with legitimate traffic. Chinese state-sponsored groups like Volt Typhoon have been observed using the built-in netsh portproxy utility to create hidden proxies on victim systems as part of their living off the land techniques, enabling lateral movement and stealthy command-and-control (C2) communication without deploying custom malware. By detecting these netsh portproxy commands, the rule aims to alert defenders to the presence of unauthorized internal communication tunnels before attackers can fully leverage them.

Detection Logic of the rule is to monitor Windows process creation logs - Sysmon Event ID 1 or Security 4688 events, for the specific patterns that indicate a port proxy is being configured. In particular, it looks for any process execution of netsh.exe with command-line arguments related to PortProxy setup. The detection logic is broken into several conditions to cover different syntax variants of the netsh portproxy command:

- Standard PortProxy Addition: The command line contains the keywords interface, portproxy, add and v4tov4 together, which is the typical syntax for adding an IPv4-to-IPv4 port forwarding rule. This indicates a new port forwarding rule is being created.
- Abbreviated Command Syntax: Attackers may use abbreviated forms of the netsh command. Netsh allows using just the first letters of subcommands in place of interface portproxy add v4tov4. The rule accounts for this by checking for the sequence of i , p , a , v in the command line, which would appear if the shorthand notation for interface, portproxy, add, v4tov4 is used. This ensures that even non-standard or compact usage of the command is detected.
- Port Proxy Parameters: The presence of port forwarding parameters in the command is another strong indicator. The rule looks for connect, part of connectport and c=, the beginning of a connectaddress= value, in the netsh command line. These tokens appear when a portproxy rule is being defined, for example: listenaddress=0.0.0.0, connectport=3389, connectaddress=10.0.0.5. Detecting these substrings helps catch variations in argument order or spacing, for instance, whether or not an attacker uses quotes or shorthand for the parameters.

```
title: Enable port forwarding on host
status: experimental
description: Volt Typhoon uses the following commands to enable port forwarding on the host
author: Dimitar Nikolov, Dimitar Dimitrov - Bulgarian Naval Academy
references:
    - https://www.cisa.gov/news-events/cybersecurity-advisories/aa23-144a
tags:
    - attack.attack.t1090.001 #Proxy: Internal Proxy
logsource:
    category: process_creation
    product: windows
detection:
    selection1:
        CommandLine|contains|all:
            - 'cmd.exe /c "netsh interface portproxy add v4tov4 listenaddress=0.0.0.0 listenport=9999 connectaddress= connectport=8443
protocol=tcp"'
    selection2:
        CommandLine|contains|all:
            - 'cmd.exe /c netsh interface portproxy add v4tov4 listenport=50100 listenaddress=0.0.0.0 connectport=1433 connectaddress='
    condition: 1 of selection*
falsepositives:
    - Administrative use.
level: high
```

Fig.2. Sigma rule for abuse of the Windows netsh interface portproxy

IV. CONCLUSION

This study demonstrates the effectiveness of using YARA and Sigma rules to detect and mitigate the cyber threats posed by Chinese state-sponsored advanced persistent threat groups, particularly Volt Typhoon and Salt Typhoon. By analyzing their tactics, techniques, and procedures and translating them into rule-based detection logic, the research provides concrete tools to improve early threat identification in critical infrastructure networks.

The implementation of custom Sigma rules can successfully identify key adversarial behaviours such as NTDS file dumping and covert port forwarding, which are often used to gain persistence and escalate privileges within compromised systems. Meanwhile, YARA rules can enabled deep inspection of memory and file artifacts, helping analysts detect malware variants and stealthy implants commonly used by Typhoon groups. These detection strategies have shown that combining behavioural log analysis with heuristic-based signature detection significantly enhances an organization's ability to uncover sophisticated intrusions that evade traditional security solutions.

The research confirms that a dual-layered approach, integrating YARA for static and memory-level detection with Sigma for real-time behavioural monitoring, offers a comprehensive defense against advanced state-sponsored cyber threats. The proposed methodology can strengthen the capabilities of security operations centers and threat hunters in detecting, attributing, and responding to the evolving tactics of Typhoon-class APTs.

REFERENCES

[1] Z. Wang, "A systematic literature review on cyber threat hunting," arXiv, 2022. [Online]. Available: https://doi.org/10.48550/arXiv.2212.05310

[2] What Is a YARA Rule?, Oct. 23, 2023. [Online]. Available: https://www.picussecurity.com/resource/glossary/what-is-a-yara-rule. [Accessed: Feb. 18, 2025].

[3] G. Canfora et al., "About the robustness and looseness of Yara rules," ICTSS 2020, pp. 104–120, 2020, https://doi.org/10.1007/978-3-030-64881-7_7.

[4] S. Saeed et al., "A systematic literature review on cyber threat intelligence for organizational cybersecurity resilience," Sensors, vol. 23, art. 7273, 2023, https://doi.org/10.3390/s23167273.

[5] What Are SIGMA Rules: Beginner's Guide, May 16, 2022. [Online]. Available: https://socprime.com/blog/sigma-rules-the-beginners-guide/. [Accessed: Feb. 21, 2025].

[6] Introduction to Sigma Rules and Detection of Credential Harvesting, Mar. 8, 2021. [Online]. Available: https://go.recordedfuture.com/hubfs/reports/cta-2021-0308.pdf. [Accessed: Feb. 21, 2025].

[7] K. Yildirim et al., "A YARA-based approach for detecting cyber security attack types," Firat University Journal of Experimental and Computational Engineering, vol. 2, no. 2, pp. 55–68, 2023, https://doi.org/10.5505/fujece.2023.09709.

[8] IDS for Logs: Towards Implementing a Streaming Sigma Rule Engine, Oct. 2020. [Online]. Available: https://ccdcoe.org/uploads/2020/10/Markus-Kont-Mauno-Pihelgas-IDS-for-logs-Towards-implementing-a-streaming-Sigma-rule-engine.pdf. [Accessed: Feb. 22, 2025].

[9] Detecting Malicious Files with YARA Rules as They Traverse the Network, Aug. 7, 2019. [Online]. Available: https://i.blackhat.com/USA-19/Wednesday/us-19-Bernal-Detecting-Malicious-Files-With-YARA-Rules-As-They-Traverse-the-Network-wp.pdf. [Accessed: Feb. 22, 2025].

[10] E. Koleva et al., "Development of an algorithm for calculating the stability of a ship, applied in OBSS," International Journal on Information Technologies and Security, vol. 14, no. 3, pp. 25–36, 2022. [Online]. Available: http://ijits-bg.com/2022.v14.i3.03.

[11] PRC State-Sponsored Actors Compromise and Maintain Persistent Access to U.S. Critical Infrastructure, Feb. 7, 2024. [Online]. Available: https://www.cisa.gov/news-events/cybersecurity-advisories/aa24-038a. [Accessed: Feb. 22, 2025].

[12] People's Republic of China State-Sponsored Cyber Actor Living off the Land to Evade Detection, May 24, 2023. [Online]. Available: https://www.cisa.gov/news-events/cybersecurity-advisories/aa23-144a. [Accessed: Feb. 23, 2025].

[13] Volt Typhoon Targets US Critical Infrastructure with Living-off-the-Land Techniques, May 24, 2023. [Online]. Available: https://www.microsoft.com/en-us/security/blog/2023/05/24/volt-typhoon-targets-us-critical-infrastructure-with-living-off-the-land-techniques/. [Accessed: Feb. 23, 2025].

[14] Volt Typhoon and the Disruption of the U.S. Cyber Strategy, Mar. 5, 2024. [Online]. Available: https://www.lawfaremedia.org/article/volt-typhoon-and-the-disruption-of-the-u.s.-cyber-strategy. [Accessed: Feb. 18, 2025].

[15] RedMike (Salt Typhoon) Exploits Vulnerable Cisco Devices of Global Telecommunications Providers, Feb. 13, 2025. [Online]. Available: https://www.recordedfuture.com/research/redmike-salt-typhoon-exploits-vulnerable-devices. [Accessed: Feb. 23, 2025].

[16] US Adds 9th Telecom Company to List of Known Salt Typhoon Targets, Dec. 27, 2024. [Online]. Available: https://therecord.media/nine-us-companies-hacked-salt-typhoon-china-espionage. [Accessed: Feb. 20, 2025].

[17] Governments, Telcos Ward Off China's Hacking Typhoons, Dec. 11, 2024. [Online]. Available: https://www.darkreading.com/cyberattacks-data-breaches/governments-telcos-chinas-hacking-typhoons. [Accessed: Feb. 24, 2025].

[18] Salt Typhoon Hackers Backdoor Telcos with New GhostSpider Malware, Nov. 25, 2024. [Online]. Available: https://www.bleepingcomputer.com/news/security/salt-typhoon-hackers-backdoor-telcos-with-new-ghostspider-malware/. [Accessed: Feb. 24, 2025].

[19] Weathering the Storm: In the Midst of a Typhoon, Feb. 20, 2025. [Online]. Available: https://blog.talosintelligence.com/salt-typhoon-analysis/. [Accessed: Feb. 24, 2025].

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 115-122

China's Strategic Competition in Cyberspace. Volt Typhoon and Salt Typhoon as a Projection of Power, a More Aggressive Posture and a Future Beyond Espionage

Dimitar Dimitrov
Nikola Vaptsarov Naval Academy
IT Department
Varna, Bulgaria
dimitar@nvna.bg

Evgeni Andreev
Nikola Vaptsarov Naval Academy
IT Department
Varna, Bulgaria
e.andreev@naval-acad.bg

***Abstract* – China's strategic competition in cyberspace has evolved beyond traditional espionage, adopting a more aggressive posture that integrates cyber sabotage as a critical tool of statecraft. This paper examines the activities of the state-sponsored hacking groups Volt Typhoon and Salt Typhoon, highlighting its transition from intelligence gathering to disruptive cyber operations against critical infrastructure. By leveraging Living off the Land Binaries (LOLBins) and exploiting vulnerabilities in SOHO network devices, Volt Typhoon has demonstrated an ability to maintain persistent access while evading detection. The group's infiltration of U.S. military networks in Guam is analysed as a case study reflecting Beijing's broader strategic ambitions in the Indo-Pacific. The findings suggest that China's cyber doctrine is shifting toward pre-positioning for offensive capabilities, enabling covert battlefield preparation in anticipation of geopolitical escalations. The study underscores the necessity for proactive cybersecurity measures, advanced threat intelligence sharing and international collaboration to counter the emerging threats posed by China's evolving cyber warfare strategy**

Keywords* – *China, Salt Typhoon, Strategic competition, Volt Typhoon

I. INTRODUCTION

The contest for geopolitical dominance in the 21st century is increasingly taking place in cyberspace, where states are competing for strategic advantage beyond traditional military and economic domains. The People's Republic of China has now positioned itself at the forefront of this competition, using cyberspace not only as a tool for intelligence gathering, but also as a domain for the consolidation of power, enforcement and disruption. In the context of strategic competition [1] in which the US and China are engaged in a strategic competition for technological, military and economic supremacy, cyber operations have become a vital tool of statecraft. The evolution of Chinese cyber activities from espionage to pre-staging disruptive attacks signals a fundamental shift in how China is envisioning warfare.

Strategic competition is broadly defined as the ongoing competition among great powers to shape global order, technological standards and military balance without direct kinetic conflict. Historically, great power competition has revolved around economic influence, military alliances and ideological struggles. Today, cyberspace has become the newest and most contested area in this struggle. The United States, which has long enjoyed technological superiority, now faces an assertive China that seeks to challenge US dominance through systematic cyber interventions, technological acquisitions and digital coercion. Volt Typhoon and Salt Typhoon serve as examples of this shift, as they are not simply intelligence gathering missions, but pre-emptive measures designed to embed China's cyber capabilities into critical infrastructure, ensuring its influence in times of crisis. The PRC's ability to penetrate and maintain constant access to telecommunications networks, energy grids and defence infrastructure represents an unprecedented escalation in digital statecraft.

The activities of Volt Typhoon underscore China's increasing reliance on the prepositioning of cyber assets in U.S. critical infrastructure as a means of deterrence and coercion. Unlike conventional cyberespionage campaigns, which primarily seek to obtain intelligence for diplomatic, military, or economic purposes, Volt Typhoon operates with the clear goal of infiltrating vital national infrastructure while remaining undetected for long periods

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8618
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

of time. The Federal Bureau of Investigation and the Cybersecurity and Infrastructure Security Agency CISA concluded that Volt Typhoon is preparing for future geopolitical contingencies by gaining continued access to U.S. energy, water and transportation systems. By exploiting vulnerabilities in small office and home office routers and using "living off the land" techniques to blend into legitimate network traffic, the group ensures it can carry out crippling cyberattacks with minimal warning. This operational strategy suggests that the PRC views cyberspace not only as an area for intelligence gathering, but also as an overtaking battlefield where attacks on infrastructure can serve to multiply forces during conflict. At the same time, Salt Typhoon demonstrates a different but equally troubling strategic focus on the telecommunications sector. In late 2024, US intelligence confirmed that Salt Typhoon had successfully compromised nine major US telecommunications providers, including AT&T and Verizon. This breach allowed Chinese agents to gain access to routing infrastructure, manipulate network traffic and potentially intercept sensitive government and military communications. Unlike previous cyberattacks aimed at stealing intellectual property, Salt Typhoon represents an offensive capability designed to disrupt or degrade U.S. command and control structures in a crisis scenario. The implications of such a capability extend beyond immediate national security concerns if unchecked, it could allow China to paralyze U.S. military responses, delay crisis coordination and even manipulate information flows during wartime. This approach is consistent with broader Chinese military doctrine, which views cyber operations as an integral part of modern warfare capable of achieving strategic objectives without direct military confrontation.

The broader strategic context of these operations must be understood within China's long-term geopolitical ambitions[2]. The PRC's cyber doctrine is deeply intertwined with its goals of regional hegemony, particularly in the Indo-Pacific where it seeks to challenge US military and economic influence. A U.S. Department of Defence 2024 report identifies cyber warfare as a key enabler of China's broader "smart war" strategy, in which cyber, artificial intelligence and information dominance are used to neutralize adversaries before kinetic engagements begin. This doctrine is particularly relevant in scenarios such as the Taiwan contingency, where cyber operations targeting U.S. and allied infrastructure can delay or disrupt military force mobilization efforts. The activities of Volt Typhoon and Salt Typhoon are fitting right into this framework, reinforcing the idea that China is methodically building a cyber battlespace that can be activated at a moment's notice.

This paper examines how China's cyber strategy, as reflected in the activities of Volt Typhoon and Salt Typhoon, represents a paradigm shift toward a more offensive and strategically disruptive posture. By analyzing their methods, objectives and implications, this study will explore how the PRC's cyber operations extend beyond espionage to battlefield preparation, coercion and strategic deterrence. Ultimately, understanding this shift is critical for developing robust cybersecurity policies and international countermeasures to mitigate the risks posed by China's evolving cyber warfare strategy.

II. Materials and Methods

China's cyber strategy is embedded deeply within the broader national security framework [3], guided by the active defence doctrine and reinforced by the military-civilian fusion model. In contrast to other countries that rely primarily on specialized cyber units within their military or intelligence services, China has created a vast ecosystem in which government, corporate and academic entities act in synergy to develop its cyber capabilities. This approach ensures that civilian technological innovation directly supports China's cyberwarfare objectives by providing the Chinese Communist Party with an extensive infrastructure for cyber intelligence collection and offensive operations. The principle of active defence, a longstanding component of Chinese military doctrine, has been extended into the digital domain. It justifies preemptive cyber operations as a means to neutralize threats before they materialize. This philosophy is reflected in China's National Defence White Papers (2007, 2015, 2018) [4],[5], which expand state control over Internet governance, technology exports and corporate data practices. Unlike Western countries, where private companies typically operate independently of state directives, China obliges its corporations to comply with national security objectives, effectively turning private firms into extensions of state intelligence operations.

Key evidence of this doctrine is China's growing dominance of global technology markets. Through its quasi-monopoly control over the production of telecommunications equipment [6], semiconductors and surveillance technologies, China has infiltrated the digital infrastructure of governments, businesses and military institutions around the world. This not only strengthens Beijing's economic and technological influence, but also creates security risks, as widely used hardware and software produced in China may contain backdoors that could be exploited in future conflicts.

A. Integration of Cyber Operations into National Security

The People's Republic of China does not perceive cyber operations exclusively as a means of economic and technological advancement, rather, they constitute an integral component of its national security doctrine [7]. In contrast to conventional warfare, where conflicts are overt and direct, cyberwarfare offers the PRC low-risk, high-payoff avenues to achieve its strategic objectives without immediate retaliation. Legislation such as the 2017 Cybersecurity Law and the National Intelligence Law grants intelligence agencies significant authority to compel private companies to cooperate, stipulating that all Chinese companies both domestic and foreign must share data with the government upon request. This legal framework enables the CCP to utilize prominent technology companies like Huawei, Hikvision and ZTE as platforms

for intelligence gathering and covert cyber operations. Through its control over global technology supply chains, Beijing exerts influence over nations that rely on Chinese-built digital infrastructure, particularly in the developing world. The expansion of Chinese 5G networks, cloud services and telecommunications infrastructure in these regions not only enhances Beijing's economic leverage but also provides potential access to sensitive communications data. These security concerns have prompted bans and restrictions on Chinese technology companies, particularly in the United States and Europe. The US government has expressed concerns about the potential risks associated with Chinese-made telecommunications equipment, citing the possibility of espionage and cyber sabotage in future conflicts. Hidden vulnerabilities in Chinese equipment could be activated to disrupt critical infrastructure, further escalating geopolitical tensions.

Beyond infrastructure control, China employs cyber operations to steal intellectual property, disrupt economies and manipulate global information ecosystems. Cyber intrusions targeting foreign research institutions, defence contractors and government agencies have resulted in the exfiltration of vast amounts of classified data. These operations grant China long-term strategic advantages in critical fields such as military technology, artificial intelligence (AI), quantum computing and semiconductor development. By systematically targeting emerging technologies, Beijing accelerates its own innovation while simultaneously undermining the technological superiority of its geopolitical rivals.

China’s cyber strategy also plays a pivotal role in its territorial disputes and regional power projection [8]. Cyberattacks against Taiwan’s critical infrastructure have grown in frequency and sophistication, signalling Beijing’s readiness to integrate digital warfare into its broader strategy for asserting territorial claims. These operations extend beyond espionage, often involving distributed denial-of-service (DDoS) attacks, supply chain compromises and malware injections aimed at destabilizing Taiwan’s political and economic stability.

Similarly, China’s cyber operations target U.S. allies in the Indo-Pacific, aiming to disrupt regional security cooperation and preempt countermeasures against Beijing’s expansionist ambitions. Cyberespionage campaigns against Japan, Australia and India have sought to infiltrate defence networks, exploit critical infrastructure vulnerabilities and extract intelligence on military alliances. These activities align with China’s broader strategy of undermining U.S.-led security frameworks while expanding its sphere of influence in the Indo-Pacific. China's integration of cyber operations into its geopolitical strategy reflects a comprehensive approach to digital dominance, wherein cyber capabilities serve as both an offensive weapon and a strategic deterrent. By leveraging its technological infrastructure, espionage networks and cyber sabotage capabilities, China continues to reshape global power dynamics in its favor, challenging traditional military and economic paradigms in the process.

B. Information Warfare and Cyber Intelligence: A Tool for Strategic Competition

China’s cyberwarfare strategy is not merely a means of espionage or digital disruption it is a key instrument of strategic competition, designed to undermine rivals, shape global narratives and expand Beijing’s geopolitical influence. The Chinese Communist Party views information dominance [9] as a critical pillar of national power projection, recognizing that controlling digital ecosystems allows China to manipulate foreign public perception, disrupt adversary decision-making and neutralize political opposition. Unlike traditional military engagements, where power is projected through force, China uses cyberspace as a strategic battleground, integrating cyber intelligence, disinformation campaigns and covert digital operations to erode the economic, political and military advantages of its global competitors. Through persistent cyber intrusions and information warfare tactics, China seeks to gain leverage over adversaries, preempt security countermeasures and strengthen its geopolitical positioning without triggering conventional conflict.

China’s cyber intelligence operations began with low-level disruptions, such as website defacements and digital propaganda. However, by the early 2000s, Beijing transitioned to large-scale cyber espionage campaigns aimed at extracting high-value intelligence from rival nations. The campaign resulted in the theft of terabytes of classified data, including military intelligence and strategic defence plans, allowing China to reverse engineer Western military capabilities. Advanced technological blueprints, accelerating China’s development in key sectors such as aerospace, cybersecurity and artificial intelligence. Also governmental and diplomatic intelligence, granting Beijing a competitive edge in global negotiations and security policymaking.

China’s cyber intelligence efforts are closely linked to its broader strategy of technological and economic competition. Rather than relying solely on military strength, China leverages cyber operations to achieve dominance in critical industries, weaken economic competitors and influence global governance structures. Key areas where cyber intelligence fuels China’s strategic ambitions include economic and Industrial Espionage – Chinese cyber actors systematically target foreign corporations, research institutions and critical supply chains to steal trade secrets, intellectual property and technological innovations. This approach accelerates China’s domestic industrial growth while simultaneously undermining Western economic superiority. Energy and Infrastructure Disruption – China has increasingly focused on compromising energy grids, transportation networks and supply chains, positioning itself to disrupt the infrastructure of rival nations in times of geopolitical tension. Electoral and Political Manipulation – Chinese cyber operatives engage in disinformation campaigns and social media influence operations to shape public discourse, weaken democratic institutions and foster political instability in competitor states.

III. RESULTS AND DISCUSSION

A defining example of China's shift from cyber espionage to disruptive cyber warfare is Volt Typhoon[10], a state-sponsored hacking group that exemplifies Beijing's evolving doctrine of cyber pre-positioning and infrastructure infiltration. First identified in 2021 by Palo Alto Networks' Unit 42, Volt Typhoon, also known as Vanguard Panda, DEV-0391, UNC3236, Voltzite and Insidious Taurus, operates with an advanced level of stealth, focusing on embedding itself within critical infrastructure while maintaining long-term persistence. Unlike traditional cyber actors that seek immediate data exfiltration, Volt Typhoon's approach is one of strategic latency, ensuring that compromised systems remain under its control for years, ready for potential activation in times of geopolitical escalation.

The group's techniques were further analysed by Microsoft's Threat Intelligence Division, which confirmed its use of LOLBins, a strategy that enables the execution of malicious commands using legitimate system tools, avoiding the need to introduce foreign code that might trigger security alerts [11]. Additionally, Volt Typhoon employs botnet networks to obfuscate its command and control traffic, routing malicious activity through compromised devices particularly small office/home office routers. This makes attribution difficult and allows the group to blend into regular internet traffic, complicating detection efforts by cybersecurity professionals. These methods have allowed Volt Typhoon to infiltrate U.S. critical infrastructure, targeting communications, energy grids and transportation systems, sectors essential for national security and military operations. The Five Eyes intelligence alliance has repeatedly raised alarms about Volt Typhoon's activities. Reports from May 2023 and February 2024 [12], [13] indicate that the group has maintained persistent access to U.S. infrastructure for over five years, raising concerns about its ability to disrupt essential services at a moment's notice. The group's strategic targeting suggests that its operations are not opportunistic but carefully orchestrated, designed to position China with cyber leverage over adversaries by embedding itself within networks long before conflict arises.

A key example of Volt Typhoon's strategic importance was its infiltration of U.S. military networks in Guam, a critical base for Indo-Pacific operations. On May 24, 2023, Microsoft [14] disclosed evidence of Volt Typhoon malware found within the network infrastructure linked to U.S. Department of Defence operations in Guam, triggering immediate concerns among policymakers. Guam serves as a major hub for U.S. military readiness in the Indo-Pacific, playing a vital role in power projection, logistics and rapid response operations, particularly concerning Taiwan. While forensic investigations did not reveal immediate sabotage, the intrusions pointed to intelligence gathering and strategic mapping of critical communication networks. By understanding the communication flows, system architecture and operational dependencies of U.S. military infrastructure in Guam, Volt Typhoon's operators were likely laying the groundwork for future offensive actions [15], ensuring that in the event of a conflict, China could disrupt or neutralize essential command and control systems. This prepositioning strategy reflects Beijing's shift towards an offensive cyber posture, where cyber operations are not just about data theft, but about neutralizing adversaries capabilities before conventional hostilities begin.

One of the defining characteristics of Volt Typhoon is its ability to remain undetected [16] for extended periods. This is achieved through a combination of stealth tactics, proxy networks and unconventional attack methods. Rather than relying only deploying signature-based malware that can be flagged by security software, Volt Typhoon leverages native Windows administration tools, making its activities appear as routine system processes. These include WMIC (Windows Management Instrumentation Command-line) used to collect system information and execute administrative commands. PowerShell which exploited for executing scripts that evade detection by security tools. NTDSutil utility used to interact with Active Directory services, enabling the extraction of domain credentials. Netsh used for port forwarding and traffic redirection, enabling remote access without triggering security alerts. Additionally, Volt Typhoon utilized the KV botnet, a sophisticated malware tool that allows operators to route traffic through compromised devices, obscuring their true origin. Volt Typhoon's operational methodology [17] is deeply rooted in advanced cyber intrusion techniques designed to maintain stealth, persistence and long-term access to compromised systems. A key component of its tactics, techniques and procedures revolves around the use of built-in system binaries and administrative tools to evade detection while achieving its operational objectives. By leveraging non-administrative credentials, Volt Typhoon operators can execute commands directly via the command line interface (T1059.003) and those avoiding endpoint security solutions that typically monitor for anomalous script execution.

One of the primary objectives of Volt Typhoon's post-exploitation phase is the collection and exfiltration of high-value authentication credentials. This is achieved by targeting Active Directory domain controllers, where the ntds.dit file resides. This file contains hashed passwords and authentication data for all domain accounts, making it an invaluable resource for attackers seeking to escalate privileges and pivot within the network (T1003.003). However, given that the ntds.dit file is typically locked and secured by system processes, Volt Typhoon employs shadow volume copies to create unauthorized duplicates of the file, bypassing standard security controls and enabling offline extraction and decryption. The manipulation of volume shadow copies is a well-documented technique that allows adversaries to circumvent direct access restrictions and obtain sensitive credentials without alerting active security monitoring systems.

Beyond credential theft, Volt Typhoon demonstrates a sophisticated understanding of network traffic

manipulation and lateral movement. The actor employs port forwarding and proxy techniques (T1090) to facilitate covert remote access to compromised hosts. Specifically, Volt Typhoon utilizes the Netsh utility, a built-in Windows networking tool, to modify firewall configurations and establish persistent tunnels between infected machines. Through the port proxy add command, the adversary can redirect incoming connections to designated ports, effectively obfuscating the true origin of their malicious traffic while maintaining a low forensic footprint. This allows Volt Typhoon to maintain persistent remote access without triggering traditional intrusion detection systems or endpoint detection and response (EDR) solutions that rely on behavioural analysis of anomalous network traffic.

A. Salt Typhoon

Following Volt Typhoon's extensive infiltration of critical infrastructure, a second Chinese state-sponsored hacking group codename Salt Typhoon [18] exemplifies the People's Republic of China's focus on compromising telecommunications systems for both espionage and potential sabotage. Salt Typhoon is the name most widely used to describe the group, assigned by Microsoft, though various cybersecurity vendors have identified the same actor under different designations: Earth Estrie (Trend Micro), Ghost Emperor (Kaspersky Lab), FamousSparrow (ESET), and UNC2286 (Mandiant). The group is believed to operate under the auspices of China's Ministry of State Security (MSS).

Salt Typhoon's primary hallmark is its systematic and targeted campaign against major U.S. telecommunications providers [19], [20], demonstrating a highly refined ability to exploit core network vulnerabilities for both next level intelligence collection and potential operational disruption. The group's focus on high-value telecom carriers, including T-Mobile, AT&T, Verizon, and Lumen Technologies, suggests a deliberate strategy aimed at infiltrating critical communications infrastructure at multiple levels. By breaching both commercial and enterprise networks, Salt Typhoon has gained the capability to manipulate sensitive communication flows [21], [22], monitor government and law enforcement traffic, and potentially stage future cyber-sabotage operations. These breaches not only signal the growing sophistication of China's cyber operations but also underscore the pressing need for strengthened security measures across the telecommunications sector.

The infiltration of major telecom providers by Salt Typhoon represents a significant escalation in China's state-sponsored cyber operations, shifting from traditional intelligence gathering to direct threats against national security infrastructure. Investigations indicate that Salt Typhoon successfully compromised core routing infrastructure, network management systems, and customer databases, granting attackers the ability to monitor, intercept, manipulate, and potentially disrupt U.S. communications. Reports from federal cybersecurity agencies, including the Cybersecurity and Infrastructure Security Agency (CISA) and the Federal Bureau of Investigation (FBI), confirm that these breaches extended to the interception of sensitive government and law enforcement surveillance data, further emphasizing the far-reaching national security implications of these attacks.

Salt Typhoon's attack methodology relies on exploiting known vulnerabilities in telecommunications hardware and software, particularly within Cisco's IOS XE network operating system. The group has been observed leveraging CVE-2023-20198 and CVE-2023-20273 [23], both of which allow unauthorized attackers to execute arbitrary commands with administrative privileges. Once inside the network, the attackers deploy living-off-the-land techniques, abusing built-in diagnostic and management tools like SNMP, Telnet, and SSH to move laterally within compromised environments. By avoiding the introduction of foreign binaries or malware, Salt Typhoon ensures that traditional endpoint detection and response (EDR) systems are unable to flag its activity as anomalous, thereby prolonging its presence within victim networks.

The impact of these breaches extends far beyond data theft. With control over routing infrastructure, Salt Typhoon can reroute traffic, perform deep packet inspection, and even selectively drop or delay communications between government agencies, military units, and emergency response teams. This capability poses a direct threat to U.S. national security, as the ability to manipulate real-time communications can degrade crisis response efforts, disrupt logistics coordination, and even compromise battlefield decision-making processes. Further investigations have revealed that Salt Typhoon's access extends to telecom-managed infrastructure critical to the U.S. Department of Defence, law enforcement, and intelligence operations. Some of the compromised networks include those handling secure government communications, raising concerns that adversaries may have gained insights into classified or sensitive government directives. The potential for adversaries to manipulate call metadata, intercept sensitive conversations, or even inject misinformation into communication channels adds another layer of risk to national security. Intelligence reports indicate that Salt Typhoon targeted specific individuals in government and military leadership, suggesting a more sophisticated and selective approach to intelligence collection.

Beyond the U.S., allied nations have also reported increased activity linked to Salt Typhoon, particularly in Europe and Asia. Several European Union member states have flagged similar telecom intrusions, raising concerns that the group is conducting a coordinated, global campaign to compromise Western telecommunications infrastructure. Reports from Germany, France, and the Netherlands indicate that state-sponsored hackers have targeted telecom firms responsible for handling sensitive government communications, further demonstrating the widespread impact of Salt Typhoon's operations.

One of the most concerning aspects of Salt Typhoon's campaign is its ability to maintain long-term persistence within compromised networks. By modifying router

configurations, implanting secondary access mechanisms, and exfiltrating authentication credentials, the group ensures that its foothold remains intact even after initial remediation efforts. Security researchers have identified instances where Salt Typhoon re-entered previously secured networks by leveraging stolen administrative credentials, demonstrating the need for organizations to implement stronger access controls and multi-factor authentication to mitigate the risk of re-compromise.

The scale of Salt Typhoon's operations suggests a well-funded and highly coordinated effort backed by the Chinese government. Unlike traditional cybercriminal groups that focus on financial gain, Salt Typhoon's objectives align with broader geopolitical strategies aimed at undermining Western influence and enhancing China's strategic position in cyberspace. The integration of offensive cyber operations into China's military doctrine further emphasizes the role of groups like Salt Typhoon in future conflicts, where digital disruption of critical infrastructure can serve as a force multiplier alongside conventional military capabilities. This approach highlights a "long-game" strategy, aligning with what former NSA analyst Terry Dunlap has referred to as a component of China's "100-Year Strategy."

B. Implications for Global Cyber Competition

Salt Typhoon and Volt Typhoon's persistent infiltration into telecommunications, energy, and military networks signals a dramatic expansion of China's cyber battlespace. These operations are no longer limited to espionage but have evolved into strategic tools for pre-positioning within adversarial infrastructure, ensuring that China retains the ability to disable critical systems at will. The combined threat of these two APT groups has reshaped global cybersecurity paradigms, forcing Western governments to reevaluate their defensive postures and accelerate countermeasures. The Chinese strategy [24]of embedding cyber assets within critical infrastructure long before a crisis occurs provides a decisive advantage, enabling China to undermine adversarial capabilities and shape the operational environment in its favor.

The strategic significance of Volt Typhoon and Salt Typhoon lies in their complementary operational focus. While Volt Typhoon prioritizes access to energy grids, water utilities, and transportation networks, Salt Typhoon has infiltrated telecommunications infrastructure, granting China potential control over communication lines essential to military coordination and crisis response. This dual-pronged approach ensures that in the event of a geopolitical escalation, China can selectively disrupt key infrastructure components to weaken adversaries before physical hostilities begin. Such tactics mirror China's broader "smart war" strategy, in which cyber operations play a central role in shaping battlefield conditions and neutralizing threats before kinetic conflict erupts.

As these cyber threats continue to evolve, national security agencies worldwide are ramping up intelligence-sharing initiatives to counteract the expanding Chinese cyber presence. The United States, in coordination with its allies in the Five Eyes intelligence alliance, has intensified cybersecurity collaboration, issuing joint advisories and reinforcing defensive capabilities across telecommunications, defense, and critical infrastructure sectors. European nations, similarly affected by Chinese cyber operations, are integrating their cybersecurity frameworks with NATO's cyber defense initiatives, aiming to create a more resilient digital infrastructure capable of withstanding state-sponsored attacks.

Despite these countermeasures, the persistent nature of China's cyber intrusions highlights the weaknesses in traditional cybersecurity approaches. Standard defensive measures, such as firewalls and endpoint security solutions, have proven inadequate against the sophisticated, stealthy tactics employed by Volt Typhoon and Salt Typhoon [25]. The widespread use of living-off-the-land techniques, which allow attackers to exploit legitimate administrative tools rather than deploy detectable malware, has further complicated mitigation efforts. As a result, governments and private sector entities are increasingly turning to artificial intelligence-driven anomaly detection and behavioral analytics to identify and counteract these advanced threats in real time.

The evolution of China's cyber operations has significant implications for international law and cyber norms. While espionage has long been accepted as a standard state practice, the deliberate pre-positioning of cyber assets within adversarial infrastructure crosses into more aggressive territory, bordering on acts of war. This shift has prompted discussions within the United Nations and other international forums regarding the need to establish clearer rules of engagement for cyber conflicts. However, China's strategic use of plausible deniability hiding its operations behind layers of proxies and compromised infrastructure complicates attribution and response strategies, making it difficult for affected nations to take decisive action.

Beyond traditional cybersecurity concerns, the activities of Volt Typhoon and Salt Typhoon highlight the growing risks associated with digital supply chain vulnerabilities. Chinese influence over global telecommunications equipment manufacturing raises concerns that compromised hardware and firmware could be pre-infected with backdoors, providing China with remote access capabilities without requiring direct network breaches. The recent scrutiny of Chinese technology providers, such as Huawei and ZTE, underscores the urgent need for nations to diversify their supply chains and reduce reliance on potentially compromised hardware components.

Looking beyond espionage, Volt Typhoon and Salt Typhoon's operational playbook indicates a clear transition toward full-fledged cyber warfare assets. These groups have already demonstrated their ability to infiltrate and manipulate critical infrastructure; the next logical step is the execution of coordinated cyberattacks designed to paralyze adversary responses during conflict scenarios. In

a future military engagement, China could simultaneously disrupt power grids, sever communication links, and introduce disinformation into government systems, significantly impairing an adversary's ability to coordinate an effective defense. The potential for escalation into full-scale cyber warfare is a growing concern among defense analysts. Unlike conventional warfare, cyber conflicts lack clear thresholds for response, making it difficult to determine when an attack warrants military retaliation. This ambiguity increases the risk of miscalculation, as states struggle to attribute cyber incidents and calibrate their responses accordingly.

As the global cybersecurity landscape continues to evolve, nations must take decisive steps to mitigate the risks posed by state-sponsored cyber threats. The rise of Volt Typhoon and Salt Typhoon underscores the urgent need for proactive threat hunting, improved intelligence-sharing mechanisms, and stricter supply chain security standards. Without coordinated international efforts to counter China's expanding cyber capabilities, the world risks entering an era where cyber warfare becomes a routine element of geopolitical competition, with far-reaching consequences for global stability and security.

IV. Conclusions

The persistence and stealth of Volt Typhoon's operations suggest that China is no longer merely engaging in passive cyber espionage. Instead, it is actively positioning cyber assets within adversary infrastructure, ready to disable or degrade critical services in the event of conflict. This represents a fundamental shift in cyber warfare doctrine, where state-sponsored hacking groups do not simply steal information but prepare the digital battlespace for future engagements. The implications are clear - China is no longer deterred by traditional cyber norms and Volt Typhoon and Salt Typhoon operations suggest a growing willingness to explore offensive cyber capabilities that could disrupt power grids, sever communication lines and compromise military command structures. The paradigm shifts in cyber warfare from espionage to infrastructure pre-positioning underscores the need for enhanced cyber resilience, proactive threat intelligence sharing and offensive cyber deterrence measures.

As geopolitical tensions rise, the United States and its allies must act swiftly to secure critical infrastructure, develop real time threat mitigation strategies and ensure that Volt Typhoon's long-term persistence does not translate into a catastrophic vulnerability. Failure to do so could leave essential national security assets exposed, granting China a significant cyber advantage in future conflicts.

References

[1] K. He et al., "Understanding the dynamics of the Indo-Pacific: US–China strategic competition, regional actors, and beyond," International Affairs, vol. 96, no. 1, pp. 1–7, 2020. doi: 10.1093/ia/iiz242

[2] M. Kolton, "Interpreting China's pursuit of cyber sovereignty and its views on cyber deterrence," *The Cyber Defense Review*, vol. 2, no. 1, pp. 119–154, 2017. [Online]. Available: http://www.jstor.org/stable/26267405. [Accessed: Feb. 16, 2025].

[3] "Forward Persistence in Great Power Cyber Competition," Dec. 19, 2024. [Online]. Available: https://cyberdefensereview.army.mil/Portals/6/Documents/2024-Fall/Lynch_CDRV9N3-Fall-2024.pdf. [Accessed: Feb. 16, 2025].

[4] "China's Military Strategy," May 27, 2015. [Online]. Available: https://english.www.gov.cn/archive/white_paper/2015/05/27/content_281475115610833.htm. [Accessed: Feb. 16, 2025].

[5] "The 2004 Chinese Defence White Paper," Mar. 18, 2005. [Online]. Available: https://rusi.org/publication/2004-chinese-defence-white-paper. [Accessed: Feb. 16, 2025].

[6] "SWJ Primer: Chinese Cyber Espionage and Information Warfare," Apr. 29, 2019. [Online]. Available: https://archive.smallwarsjournal.com/index.php/jrnl/art/swj-primer-chinese-cyber-espionage-and-information-warfare. [Accessed: Feb. 18, 2025].

[7] M. N. Mirza et al., "Conceptualising cyber sovereignty and information security: China's image of a global cyber order," *Webology*, vol. 18, no. 5, 2021. [Online]. Available: https://ssrn.com/abstract=4056104. [Accessed: Feb. 18, 2025].

[8] R. Creemers, "The Chinese conception of cybersecurity: A conceptual, institutional, and regulatory genealogy," *Journal of Contemporary China*, vol. 33, no. 146, pp. 173–188, 2023. doi: 10.1080/10670564.2023.2196508

[9] R. Creemers, "China's conception of cyber sovereignty: Rhetoric and realization," in *Governing Cyberspace: Behavior, Power, and Diplomacy*, pp. 107–142, 2020. [Online]. Available: https://ssrn.com/abstract=3532421. [Accessed: Feb. 18, 2025].

[10] "Volt Typhoon and the Disruption of the U.S. Cyber Strategy," Mar. 5, 2024. [Online]. Available: https://www.lawfaremedia.org/article/volt-typhoon-and-the-disruption-of-the-u.s.-cyber-strategy. [Accessed: Feb. 18, 2025].

[11] "Chinese Hack Pushes Up Against Guardrails Intended to Manage U.S.-Chinese Strategic Competition," Feb. 6, 2024. [Online]. Available: https://www.bradley.com/insights/publications/2024/02/chinese-hack-pushes-up-against-guardrails-intended-to-manage-us-chinese-strategic-competition. [Accessed: Feb. 19, 2025].

[12]] "People's Republic of China State-Sponsored Cyber Actor Living off the Land to Evade Detection," May 24, 2023. [Online]. Available: https://www.cisa.gov/news-events/cybersecurity-advisories/aa23-144a. [Accessed: Feb. 20, 2025].

[13] "Volt Typhoon targets US critical infrastructure with living-off-the-land techniques," May 24, 2023. [Online]. Available: https://www.microsoft.com/en-us/security/blog/2023/05/24/volt-typhoon-targets-us-critical-infrastructure-with-living-off-the-land-techniques/. [Accessed: Feb. 20, 2025].

[14] "Volt Typhoon's future war," Mar. 14, 2024. [Online]. Available: https://blog.barracuda.com/2024/03/14/volt-typhoon-future-war. [Accessed: Feb. 20, 2025].

[15] "Eroding Global Stability: The Cybersecurity Strategies of China, Russia, North Korea, and Iran," Aug. 01, 2024. [Online]. Available: https://irregularwarfare.org/articles/eroding-global-stability-the-cybersecurity-strategies-of-china-russia-north-korea-and-iran/. [Accessed: Feb. 20, 2025].

[16] "Threat Brief: Attacks on Critical Infrastructure Attributed to Insidious Taurus (Volt Typhoon)," Feb. 14, 2024. [Online]. Available: https://unit42.paloaltonetworks.com/volt-typhoon-threat-brief/. [Accessed: Feb. 20, 2025].

[17] "The Rise of Chinese APT Campaigns: Volt Typhoon, Salt Typhoon, Flax Typhoon, and Velvet Ant," Oct. 24, 2024. [Online]. Available: https://eclypsium.com/blog/the-rise-of-chinese-apt-campaigns-volt-typhoon-salt-typhoon-flax-typhoon-and-velvet-ant/. [Accessed: Feb. 21, 2025].

[18] "US Telecom Giants Under Siege: 'Salt Typhoon' Cyber Assault Linked to China," Oct. 15, 2024. [Online]. Available: https://cybelangel.com/us-telecom-salt-typhoon-cyber-assault-china/. [Accessed: Feb. 21, 2025].

[19] "Salt Typhoon Hacks of Telecommunications Companies and Federal Response Implications," Nov. 15, 2024. [Online]. Available: https://crsreports.congress.gov/product/pdf/IF/IF12798. [Accessed: Feb. 21, 2025].

[20] "Governments, Telcos Ward Off China's Hacking Typhoons," Dec. 11, 2024. [Online]. Available: https://www.darkreading.com/cyberattacks-data-breaches/governments-telcos-chinas-hacking-typhoons. [Accessed: Feb. 21, 2025].

[21] "US adds 9th telecom company to list of known Salt Typhoon targets," Dec. 27, 2024. [Online]. Available: https://therecord.media/nine-us-companies-hacked-salt-typhoon-china-espionage. [Accessed: Feb. 23, 2025].

[22] "RedMike (Salt Typhoon) Exploits Vulnerable Cisco Devices of Global Telecommunications Providers," Feb. 13, 2025. [Online]. Available: https://www.recordedfuture.com/research/redmike-salt-typhoon-exploits-vulnerable-devices. [Accessed: Feb. 23, 2025].

[23] H. T. Hung, "Exploring China's cyber sovereignty concept and artificial intelligence governance model: A machine learning approach," *Journal of Computational Social Science*, vol. 8, no. 24, 2025. doi: 10.1007/s42001-024-00346-8

[24] "Weathering the storm: In the midst of a Typhoon," Feb. 20, 2025. [Online]. Available: https://blog.talosintelligence.com/salt-typhoon-analysis/. [Accessed: Feb. 23, 2025].

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 123-127

Illegal Trade in Tobacco Products Indicator

Dimitar Dimitrov
Department National and Regional Security
University of National and World Economy
Sofia, Bulgaria
dimdim@unwe.bg

Georgi Penchev
Department National and Regional Security
University of National and World Economy
Sofia, Bulgaria
gpenchev@unwe.bg

Konstantin Poudin
Department National and Regional Security
University of National and World Economy
Sofia, Bulgaria
kpoudin@unwe.bg

Georgi Pavlov
Department National and Regional Security
University of National and World Economy
Sofia, Bulgaria
gpavlov@unwe.bg

Atanas Dimitrov
Department National and Regional Security
University of National and World Economy
Sofia, Bulgaria
adimitrov@unwe.bg

Vasil Pavlov
Department National and Regional Security
University of National and World Economy
Sofia, Bulgaria
vpavlov@unwe.bg

Tzvetomira Penkova
Department National and Regional Security
University of National and World Economy
Sofia, Bulgaria
tpenkova@unwe.bg

Nikola Petrov
Department National and Regional Security
University of National and World Economy
Sofia, Bulgaria
npetrov_2220143@unwe.bg

***Abstract*— The illicit trade in tobacco products poses a significant challenge to global health by undermining tobacco control efforts, reducing government revenues, and increasing the accessibility of unregulated tobacco products. To address this issue effectively, we introduce the Illicit Trade in Tobacco Products Indicator (ITTPI), a comprehensive tool designed to visualize and track illicit tobacco trade patterns worldwide. The ITTPI integrates data on counterfeit cigarettes, contraband activities, and risk factors associated with these illegal practices. By leveraging an interactive mapping system, this indicator facilitates real-time monitoring of high-risk regions and channels involved in illicit trade. Our study demonstrates how ITTPI can be applied across diverse contexts to identify hotspots of illicit activity and predict future trends based on historical data analysis. This approach not only aids law enforcement agencies but also informs policymakers about targeted interventions needed to strengthen regulatory frameworks against tobacco smuggling. By enhancing transparency and coordination among international stakeholders, the ITTPI offers a promising solution for combating the global problem of illicit tobacco trade while supporting broader public health objectives aimed at reducing smoking prevalence worldwide.**

Keywords*— *drug industry, economic and social effects, smuggling, tobacco smuggling.

I. INTRODUCTION

The illicit trade of tobacco products represents a multifaceted challenge, impacting public health, government revenues, and overall economic stability. Counterfeit cigarettes, contraband, and other forms of illegal tobacco not only undermine legitimate businesses and taxation efforts but also present significant health risks due to a lack of regulatory oversight and quality control. According to Bulgarian legislation /where the research team is from/, the smuggling of cigarettes constitutes a crime related to the illegal transportation of tobacco products across the state border of the Republic of Bulgaria without the knowledge and permission of customs authorities, as well as outside the designated places or in a manner that evades customs control. However, this clarification regarding cigarette smuggling is applicable to all countries. Accurately measuring and understanding the drivers and consequences of this illicit trade is paramount for developing effective policies and interventions.

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8587
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

However, the clandestine nature of this market makes direct observation difficult, necessitating innovative and robust methodologies for assessment.

To address this critical need, the Department "National and Regional Security" at the University of National and World Economy (UNWE) has developed a novel and comprehensive approach: the Illicit Trade of Tobacco Products Indicator (ITTPI). This indicator stands as a unique method for measuring the propensity for illicit trade in tobacco products, leveraging the power of Structural Equation Modelling (SEM) through the statistical software R [1]. Unlike traditional metrics that often rely on limited data or anecdotal evidence, the ITTPI employs a sophisticated statistical technique to provide a more holistic and data-driven assessment of the factors driving and the impacts stemming from the illicit tobacco trade.

This methodology offers several key advantages:

1. Identifying Driving Factors: The ITTPI goes beyond simply measuring the scale of the illicit trade; it reveals the primary factors that fuel its growth, providing insights into the relative influence of these drivers.

2. Assessing Socio-Economic Impacts: By modelling the relationship between illicit trade and key social and economic indicators—such as the number of smokers, crime rates, and government tax revenues—the ITTPI quantifies the consequences of illegal tobacco activity.

3. Connecting to Other Crimes: The ITTPI helps illustrate the links between illicit tobacco trade and other forms of organized crime, highlighting the broader criminal ecosystem that sustains it.

4. Generating Forecasts: The ITTPI can produce forecasts for two to three years into the future, provided that publicly available forecasting information exists for certain indicators.

By presenting these findings, the ITTPI offers policymakers and researchers a powerful tool to inform evidence-based decision-making and strategic planning in the fight against the illicit trade of tobacco products. This indicator promises to be a valuable resource for those working to protect public health, safeguard government revenues, and ensure fair market competition in the global tobacco market.

II. MATERIALS AND METHODS

Through MIMIC (multiple indicators, multiple causes) model, statistical relationships between latent (unobserved variables) and observables are estimated.

MIMIC attempts to answer two types of questions:

1. Measuring variables that are unobservable or unmeasurable?

2. Causal assessment based on a theoretical hypothesis?

MIMIC consists of two parts:

1. The measurement part shows how the latent variables are evaluated through the so-called indicators

2. the second model estimates the random relationship between the latent and observed causes.

To compute this model, we can identify four steps:

1. The formulation of theoretical model: a priori we can identify the causal link among the variables and also to formulate the model.

2. The estimation of parameters: we can estimate the covariance matrix, then the coefficient of the measurement and structural model as the value that minimize the difference between the matrix from raw data and who's been estimated from the model.

3. The verification of the model: we can confute the model if the difference mentioned above is too high.

4. The modification: on the basis of previous results, we can eventually modify the model to fit better the data.

The study on smuggling and counterfeiting (C&C) of tobacco products is an extremely difficult task because of the hidden nature of activities and processes. The data gathered and the research conducted within the project show that there are very few sources that directly provide data on C&C.

The study should therefore be oriented towards the use of methods that can indirectly describe these processes. An unmistakable example of such a method is the modelling of multiple indicators, multiple causes (MIMIC), but this is typing a structural equation (SEM). Modern development in this scientific field creates a solid foundation for the study of hidden, unobserved or so-called. "Latent" processes.

These equations use hypotheses such as:

a) The reduction of corrupt practices significantly reduces the opportunities for illegal practices in the production of cigarettes;

b) The manifestations of a grey economy contribute to C&C (Counterfeit and Contraband);The manifestations of a grey economy contribute to C&C (Counterfeit and Contraband);

c) The legislation and its successful implementation (Rule of low) have a direct impact on C&C.

The model consists of monitored and unobserved variables and specific case relationships between unobservant variables.

The model actually checks these hypotheses. The aim is to confirm or reject them.

After the N-versions of the hypotheses are played out, if they are confirmed (the data are statistically significant) coefficients are calculated for the indicators (right side of the model) and for the reasons (left side of the model) that give the relationship and the strength of the impact on Latent variables.

Two MIMIC models have been developed. The first one (Fig. 1) achieves results for the intensity of counterfeiting of tobacco displaced by the countries of the

world, and in the second the smuggling is measured for the level NUTS3 (in Bulgaria these are the areas) (Fig. 2)

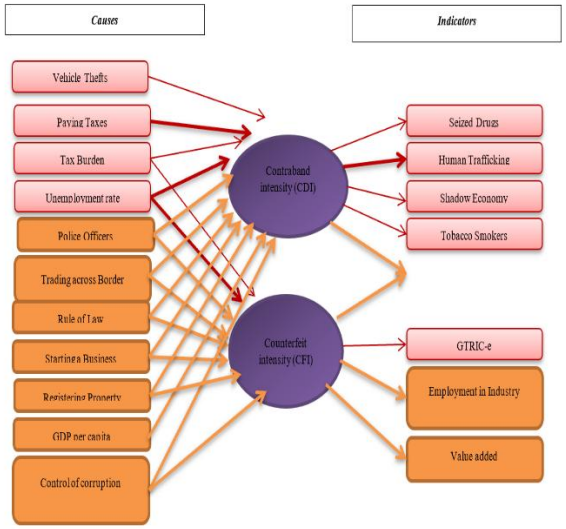


Fig. 1. MIMIC model with two latent variables with data about 186 countries all over the world.

III. RESULTS AND DISCUSSION

The main goal of the model is to describe and analyse the influence of the economic and social factors over C&C, as well as to estimate their significance and to find the indicators for C&C of tobacco products.

In the third chapter of this teaching module, the results of the model analysis are shown as example, an identification of the risk generated by Impact of Tax Burden, Economic Growth and Total Employed Persons on Contraband Intensity.

The model and its outcomes could be used by experts and analysts, as well as at the level of strategic management. The model is applicable to the public and private sector structures, regardless of their legal form and field of activity.

The model would be extremely useful for strategic management, decision-making by higher management at strategic level, long-term planning, implementation of the adopted strategy or, if necessary, for a complete change in the direction of development of the particular organization.

The model has been approbated with data about 186 countries all over the world. It includes 19 variables, chosen by the researchers based on expert evaluation during the weekly discussions, ***Causes of Contraband and Counterfeit*** – **(1)** Registering Property, **(2)** Paying Taxes, **(3)** Trading Across Borders, **(4)** GDP per capita, **(5)** Tax Burden, **(6)** Rule of Law, **(7)** Control of Corruption, **(8)** Number of Policemen, **(9)** Vehicles' Thefts, **(10)** Unemployment, **(11)** Starting a Business.

Indicators of Contraband and Counterfeit – **(1)** Seized Drugs, **(2)** Human Trafficking, **(3)** Tax Revenues, **(4)** Value Added in Tobacco Industry (TI), **(5)** Employment in industry (% of total employment), **(6)** General Trade-Related Index of Counterfeiting for economies (GTRIC-e), **(7)** Shadow Economy and **(8)** Number of Tobacco Smokers. [2]

Description of the variables and hypothesis

Paying Taxes - Paying taxes - This variable is used as a business environment factor. Supposed. that tax increases also increase C&C intensity. [3]

Trade across borders - measures the time and costs (reported by local experts) associated with three sets of compliance procedures - documentary, border and inland transport - the process of exporting or importing goods.

An increase in the coefficient will lead to a decrease in fakes. Data source is World Bank, Cross-Border Trade Methodology, Doing Business.

Registering Property – Estimates common procedures, as well as time and costs for transferring ownership. The hypothesis is that an increase in the factor will lead to a decrease in counterfeits.

Starting a Business - is used to determine the minimum capital, procedures, time and expenses for a small to medium-sized limited liability company to start and operate in the largest business city of the economy [4].

Tax Burden - a statutory measure that reflects marginal tax rates on personal and corporate income and the overall level of taxation (including direct and indirect taxes imposed by all levels of government) as a percentage of gross domestic product (GDP).

Rule of Law - it refers to the observance of rules in society, and in particular, to the performance of contracts, the protection of property, and the work of the police and the courts. The model hypothesis is that an increase in the factor will lead to a decrease in both latent variables – Contraband Intensity and Counterfeit Intensity.

Control of Corruption - The data source is the World Bank's World Governance Indicators (WGI) project [5].

GDP per capita - This measure provides the best comparability between countries data. The hypothesis is if GDP per capita will grow, both latent variables – Contraband Intensity and Counterfeit Intensity will decrease. The source of data is from World Bank Development Indicators.

Police officers - The estimate is for the number of officers whose functions are to detect and investigate crimes and apprehend alleged perpetrators. The hypothesis is that an increase in the factor will lead to a decrease in fakes. The United Nations Office on Drugs and Crime is the source of the data.

Vehicles' Thefts - a highly organized criminal activity is linked to other organized crime activities such as drug trafficking, arms dealing and international terrorism. Therefore, vehicles are mainly stolen and trafficked for providing financial and logistical means to finance other

criminal activities. This variable can be used as a factor alleviating contraband with ready to use contraband channels and facilities. Therefore, the expected relation between vehicle thefts and contraband is that an increase in the factor will lead to an increase in counterfeit. The United Nations Office on Drugs and Crime is the source of data.

Unemployment Rate - This variable reflects the employment gap for people who are in the labor market but cannot find a suitable job.

Employment in the industry - This is the number of people working in the economy.

The hypothesis of the model is that if there is an increase in gray economy, employment in the legal industry will decline

Value Added - is defined as "Food, beverages and tobacco (% of value added in production)" It is expected that with an increase in counterfeits, the value added by the tobacco industry will decrease.

General Trade-Related Index of Counterfeiting for economies (GTRIC-e) – the indicator is supported by OECD

Shadow Economy – The hypothesized says that if Contraband or Counterfeit Intensity increases, then the measured variable will also increase [6] – [8]. For example, Bulgaria's shadow economy accounted for 29.9% of the country's gross domestic product (GDP) in 2017 [9].

Percent of Tobacco Smokers – The indicator is sourced by World Health Organization's statistics.

Seized Drugs – The Seized Drugs indicator data is sourced by UNODC databases [10]. The main idea in this indicator is the same usage of channels for drug trafficking and tobacco products contraband. This indicator is measured by metrics in quantity.

Human Trafficking The main idea in this indicator is the same usage of channels for human trafficking and tobacco products contraband. The human trafficking increases the contraband intensity.

Tax Revenues – total tax revenue as a percentage of GDP is used to account for the share of a country's output that is collected through taxes [11]. For example, the taxes (Excise duties) for tobacco products in Bulgaria form 84% of retail price.

A. Results - Application of MIMIC for Measuring Illicit Trade in Tobacco Products at NUTS 3 Level

The idea is to use this model to estimate smuggling by region:

- GDP per capita is defined on the front page
- Employment (total) - This is how employment in the economy is reported in EUROSTAT
- Employment in Agriculture – These data are maintained in EUROSTAT. The assumption is that in the agricultural regions the illicit trade in tobacco products is higher than in more industrialized and urbanized regions. It is a common assumption in many studies on crime, illicit trade and counterfeit.

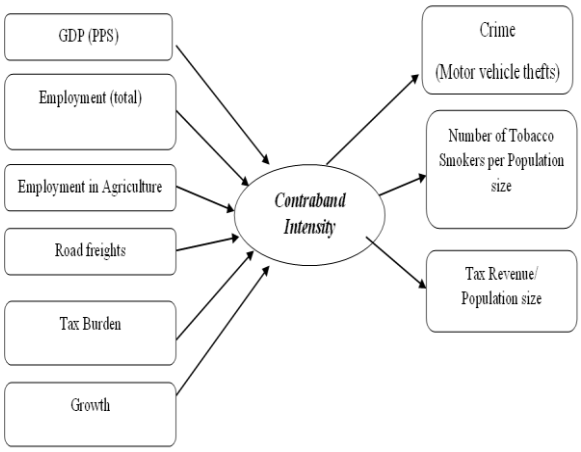


Fig. 2. MIMIC model application at the NUTS3 level.

Road Freight – This indicator uses the road freight transport statistics, which is published by EUROSTAT. This indicator is measured in thousands of tons without additional processing. The assumption is that the quantity of transport facilitates the contraband of tobacco products.

Tax Burden – It is determined by the excise taxes (tax on the sale or use of tobacco) at the country level. The indicator is calculated on the basis of the incomes of the regions (GDP per capita in PPS EUR). If the income at the NUTS3 level is higher than the corresponding income of the country, then the tax burden will be lower for the region and vice versa. The resulting indicator does not correlate with the GDP per capita indicator used in the calculations, so there is no multicorrelation effect in the model.

Motor Vehicle Thefts – determines the number of motor vehicle thefts in a given region. The data are available in EUROSTAT.

The assumption here is that most of these crimes are connected to organized crime and also facilitates the C&C.

Number of Tobacco Smokers – These data are maintained in EUROSTAT. The volume of the tobacco market is determined by the number of smokers.

Tax Revenues – Tax revenues is an indicator that can show the changes in tobacco product markets. The data in million EUR without additional processing is taken from Eurostat. The indicator is measured in million EUR for revenues only for excise duties.

Growth - the growth rate in millions of euros as part of GDP determines the dynamics of economic development.

The created MIMIC model, assists determining trends. This would be possible if an additional database was developed to enter the data over a certain period, as a

result of the static model. It was established the direction and strength of the relationship between the examined variables and the latent variable - Contraband Intensity (CDI).

CDI is a latent variable estimated through the MIMIC model, which links selected observable causes and indicators to obtain a comprehensive estimate of the propensity to smuggle.

The CDI is calculated on data for over 1480 EU regions (NUTS 3 level), thus obtaining CDI values for each region.

The CDI has no measure (like meters, kilograms, Watts, percent etc.

The following table (Table 1 - Increase in the Tax Burden Factor (in %)) shows the impact of Tax Burden on CDI.

Table 1 Increase in the Tax Burden Factor (in %)

Tax Burden	CDI	Crime Level	Tax Revenues	Number of Smokers
-10	-1,24	-0,44	0,47	-0,03
-9	-1,12	-0,4	0,42	-0,03
-8	-0,99	-0,35	0,38	-0,03
-7	-0,87	-0,31	0,33	-0,02
-6	-0,75	-0,26	0,28	-0,02
-5	-0,62	-0,22	0,23	-0,02
-4	-0,5	-0,18	0,19	-0,01
-3	-0,37	-0,13	0,14	-0,01
-2	-0,25	-0,09	0,09	-0,01
-1	-0,12	-0,04	0,05	0
0	0	0	0	0
1	0,12	0,04	-0,05	0
2	0,25	0,09	-0,09	0,01
3	0,37	0,13	-0,14	0,01
4	0,5	0,18	-0,19	0,01
5	0,62	0,22	-0,23	0,02
6	0,75	0,26	-0,28	0,02
7	0,87	0,31	-0,33	0,02
8	0,99	0,35	-0,38	0,03
9	1,12	0,4	-0,42	0,03
10	1,24	0,44	-0,47	0,03

From the data presented in the table, it can be concluded that an increase in the tax burden leads to an increase in the CDI. This leads to the conclusion of a positive relationship between the tax burden and the increase in CDI.

IV. CONCLUSIONS

Within the research it has been examined the development of a MIMIC model with one latent variable - Contraband Intensity on EU Territorial Classification NUTS on lowest level 3 for 30 European countries. It was confirmed that the factor (model's causes) variables GDP (PPS), Employment, Agriculture, Road freight, Tariff and Growth had an impact on the contraband intensity. The same also applies to the impact of latent variable - CDI on the indicators for dependent variables (model's indicators) such as Crimes (motor vehicle thefts), Number of Tobacco Smokers, Tax Revenues.

The developers of the model, having in mind the content of CDI and its application, have decided to name it - **Illicit Trade of Tobacco Products Indicator (ITTPI).**

In conclusion of the research, we can summarise that the Illicit Trade of Tobacco Products Indicator (ITTPI) is the calculated latent variable through the MIMIC model at the NUTS3 level. It shows the propensity of tobacco products to be contraband. The Illicit Trade of Tobacco Products Indicator (ITTPI) can be considered as a measure of the illegal market demand for cigarettes and other tobacco products. The Illicit Trade of Tobacco Products Indicator (ITTPI) is an indicator that can be applied to any country.

REFERENCES

[1] R Core Team, “R: A Language and Environment for Statistical Computing,” R Foundation for Statistical Computing, 2023. [Online]. Available: https://www.r-project.org/

[2] D. Dimitrov, "Tobacco Products Contraband & Counterfeit Risk Identification UNWE Economic Alternatives," UNWE :: UNWE Yearbook, Feb. 10, 2020. [Online]. Available: https://unwe-yearbook.org/en/journalissues/article/10162. [Accessed: Mar. 01, 2025].

[3] “The changing landscape of tax policy and administration across 190 economies.” [Online]. Available: https://www.pwc.com/gx/en/paying-taxes/pdf/pwc-paying-taxes-2020.pdf. [Accessed: Nov. 02, 2020].

[4] “Methodology for Starting a Business,” World Bank. [Online]. Available: https://archive.doingbusiness.org/en/methodology/starting-a-business

[5] World Bank, “Worldwide Governance Indicators,” World Bank, 2024. [Online]. Available: https://www.worldbank.org/en/publication/worldwide-governance-indicators/interactive-data-access

[6] A. Buehn and F. G. Schneider, Institute for the Study of Labor (IZA). [Online]. Available: http://ftp.iza.org/dp4182.pdf

[7] F. Schneider and C. C. Willams, The Shadow Economy. London: IEA, 2013.

[8] F. Schneider and A. Buehn, “Shadow Economies and Corruption All Over the World: Revised Estimates for 120 Countries,” University of Linz, Austria; Technische Universitat Dresden, Germany, 2009. [Online]. Available: http://www.economics.unilinz.ac.at/members/Schneider/files/publications/ShadEconomyCorruption_rev_091009.pdf. [Accessed: Sep. 07, 2017].

[9] I. Mihaylov, “Bulgarian shadow economy accounts for 30% of GDP - study,” SeeNews, Jul. 03, 2017. [Online]. Available: https://seenews.com/news/bulgarian-shadow-economy-accounts-for-30-percent-of-gdp-study-1110983. [Accessed: Mar. 02, 2025].

[10] United Nations, “Statistics and Data | UNODC,” Un.org, 2018. [Online]. Available: https://dataunodc.un.org/

[11] World Bank, “World Development Indicators,” The World Bank, 2023. [Online]. Available: https://databank.worldbank.org/source/world-development-indicators

[12] Bulgarian Industrial Capital Association (BICA), Report on actualisation of composite index “Economy in light”, 2016. [Online]. Available: http://bica-bg.org/wp-content/uploads/2016/07/Doklad-za-Kompozitniaindex-za-20151.pdf

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 129-136

Artificial Intelligence (AI) in the Legal Profession: European Approach

Eugene Eteris
Law Faculty
Turiba University
Riga, Latvia
euget@integrin.dk

Ingrida Veiksa
Law Faculty
Turiba University
Riga, Latvia
ingrida.veiksa@turiba.lv

***Abstract*—Latest digital breakthroughs and innovations are shaping the future of artificial intelligence (AI), delving into cutting-edge research, emerging trends and transformative applications across various sectors of human life and national political economies. From deep learning and natural language processing to robotics and autonomous systems, the AI is revolutionizing business models, driving efficiency, unlocking new possibilities and modernizing legal profession. The paper presents a first of its kind attempt in academic and scientific literature to evaluate modern challenges in the digital transformation of lawyers' work. Hence, the article covers not only elaborated theory and analytical method, but includes literature review concerning modern digital challenges, as well as the state-of-art of modern facilities in emerging AI implications for the legal profession, and the digital transition applicable for the increasing EU's legal regulations in the European integration. Among the main results of the authors' research efforts are: e.g. suggestions to introduce new law sectors in national legal classification and orienting the legal profession towards modern challenges and digital transition. The lack of adequate legal specialists in the new spheres of reformed political economies, qualified in using numerous digital technologies and AIs, require additional efforts in legal training and reskilling.**

Keywords*—AI in the legal profession, Digital challenges, EU law through digital transition.

I. INTRODUCTION

Modern global challenges, specifically contemporary digital technologies have dramatically altered almost all spheres of national socio-economic development; these challenges have touched upon the legal profession too. New types of socio-economic development inspired by the modern challenges require new legal professionals dealing with such new sectors as sustainable growth and circularity, biodiversity and green transition, climate mitigation and renewables, etc.

It is vital to mention that the EU has adopted in mid-2024, the artificial intelligence act, so-called AIA, in the form of a regulation (2024/1689) in the sense that it is applied to all EU member states. The AIA is not only the first binding EU-wide horizontal regulation on AI; it sets a common worldwide framework for the use and supply of numerous AI systems and applications.

The EU institutions have highlighted the increasing gap in legal professionals with the necessary skills to effectively work with modern challenges and AI technologies.

While much has been written about the need for legal experts who can navigate the complexities of AI, there remains a notable lack of practical strategies for modernizing legal education and retraining existing professionals. This gap is especially evident in the context of integrating AI into legal practice, where AI tools could significantly enhance the efficiency of legal processes, such as the transposition of EU directives into national laws, etc.

Already in 2018, some authors underlined that the legal profession "was facing a considerable paradigm change", as work of a lawyer (concerning billable hours) largely consists of analyzing legal data and documents, i.e. purely data procession. They noted that "it would be just a question of time" that these services would be performed by generative AI models, with a considerable saving of time and incurred costs. Calling it the legal technology (LegTech) they however suggested that such AI solutions would be "scant and sporadic" [1].

Both legal scientists and practitioners have been dealing with the lawyers' perspectives in the "age of AI", as both the legal profession and the corresponding legal education providers have to adapt to modern challenges. Some of the lawyers will remain "the judgment providers", others will be much more focused on specific practice expertise where they become the obvious providers of the "last mile"

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8567
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

services in their chosen fields. It is hard to see how the "general service law firm" model of the past can survive the changes including "no billable time, corporation instead of partnership, technological duty of competence, legal liability for failed AI solution" [2].

II. Materials and methods

As to the research methods, the authors adhere to, first the so-called qualitative case studies which allow for an in-depth exploration of how specific national legal systems or institutions are adapting to the digital challenges (in the EU, for example it is seen in digital transition). Secondly, the theory of comparative legal analysis, which involves comparing legal systems, laws, or practices across different contexts or countries.

Comparative analysis in the EU allows us to see how different EU countries are implementing new laws related to global challenges and digital transition and how these changes are impacting the legal profession. It is obvious that the adoption and advancements of artificial intelligence will be big drivers of these historic shifts [3].

III. Results and discussion

A. Results

There has been quite a bit of research on the ability of lawyers to keep up with technological developments and use them in the legal profession. The role of the lawyer in the changing world was discussed already in 1958 by Harold A. Smith (from Winston, Strawn, Smith & Patterson, in Chicago, Illinois) [4]. A historic review regarding education of lawyers for the future legal profession was summarized in the George Washington University Law School by Thomas D. Morgan [5]. Also, the report in 2007 titled "Educating Lawyers: Preparation for the Profession of Law" [6] and comments in India Legal on the problems of education of lawyers [7]. In 2015, an extensive study, building on best practices "Transforming Legal Education in a Changing World", was published. The teaching staff of many US universities participated in this study [8].

Some authors argue that the integration of AI and Large Language Models, LLMs into legal profession (as well as education and training) suggests that "the recipients" need to be proficient in these technologies "to stay relevant in the evolving legal landscape"; however, there are no clear definitions or metrics that qualify what exactly contemporary "legal tasks", nor/or requirements to perform these tasks in the lawyers' "level of quality" [9].

There are presently several most impactful and used generative AI models, including the GPT-4 (the 2023 version), Mixtral, Gemini, and Claude 2 in text generation, DALL-E 3 and Stable Diffusion XL Base 1.0 in image creation, as well as PanGu-Coder2, Deepseek Coder and others in code generation; and the list is not exhaustive [10].

The field of AI is rapidly evolving, with new innovations continually emerging. These models represent just a glimpse of the AI revolution, which is reshaping creativity and efficiency across various domains. During the last decade another ten GenAIs have been developed and widely explored by the people, such as Lightricks from 2013, OpenAI created in 2015, Hugging Face from 2016 for machine learning solutions, Synthesis AI from 2019, Glean and Stability AIs both from 2020 providing AI models for various scientific areas; Jasper and Inflection AI (both from 2022). Only one, Anthropic from 2021 has been dealing with general science and legislation [11].

Thus, lawyers who quickly adapt to digital technology would "focus more on human-to-human interactions, understanding clients' needs, and building trust, while also upskilling in both technological and soft skills"; in embracing these changes and understanding the regulatory landscape around AI and data use will dominate in the legal profession of the future. Therefore, argue experts from Forbes, "those who balance efficiency and growth with the challenges of new technologies will be best positioned to secure their careers [12].

Another concern is the impact of AI on the legal profession: while AI has the potential to make legal services more efficient, it could also lead to job displacement for lawyers and paralegals. Legal work needs to adapt to the changing landscape of AI and embrace the opportunities it presents. Overall, the use of AI in law is a complex and multifaceted issue that requires careful consideration and evaluation. Decision-makers and legal professionals have to cooperate in order to ensure that not only the benefits of AI are realised, but potential risks and challenges are addressed too. With careful planning and implementation, AI has the potential to revolutionize the legal industry and make legal services more accessible and efficient for all [13].

Another research explores the AI's "transformative features" in the legal profession, predicting significant growth in legal tech driven by AI, which could automate up to over 49 percent of legal tasks. It highlights both the opportunities, such as increased efficiency and democratization of legal services, and challenges, including ethical concerns and the potential for reduced hands-on learning for junior lawyers. The report calls for a balanced approach that leverages AI's benefits while addressing its risks, emphasizing the need for ongoing education and regulatory oversight [14], [15].

There are the following article's objectives: a) to underline the effects of modern challenges on the legal profession; b) to reveal the EU's digital transition as a vital factor in appearances of new laws, and c) showing AIs implications in the process of legal profession's adaptation to modern challenges. It is seen that the digital paradigm in the work of lawyers is having a vital component in legal practitioners work through using digital technologies and reskilling legal professionals by extensive AI use in their work.

Besides, the new directions in the legal regulations are just increasing the role of digital means in delivering new global challenges in Europe.

To deliver on the title, the article is composed of the following elements: introduction, theory and method, literature review, modern digital challenges and AI implications for the legal profession, review of the present generative AI models in legal studies, digital transition in the EU's law, and conclusion.

The article's theoretical framework is based on the effects of contemporary changes in the legal development (within the European Union's situation as an example); followed by the process of altering national socio-economic development and the legal regulations. Multiple effects of modern challenges are particularly visible in the increasing EU-wide legal activity when over seventy percent of national laws are "made" in the EU institutions; hence the attention to the correct and timely transposition of the EU laws (e.g. directive and regulations) by the member states. Digitalisation process in national legal order with the European "green and digital transition" depicts altering aspects in lawyers' position dealing with changing national long-term growth patterns.

Multiple effects of modern challenges are particularly visible in the increasing EU-wide legal activity when over seventy percent of national laws are "made" in the EU institutions; hence the attention to the correct and timely transposition of the EU laws (directive and regulations) by the member states. Besides, the new directions in the legal regulations are just increasing the role of digital means in delivering new global challenges in Europe. Digitalisation serves as a viable factor in national legal order with the European "green and digital transition" as an example to depict altering aspects in lawyers' position dealing with changing national long-term growth patterns. The so-called socio-technical theory helps to examine the interplay between challenges and their socio-economic components; it forms part of the integration's process between the digital technologies and generative AI into the legal profession, which requires an understanding of how these technologies impact social domain and how legal professionals adapt to these changes in professional structures [16].

In the process of legal education, great attention should be paid to the inadmissible plagiarism in the study process. Because how will lawyers in their future profession be able to defend the performers of creative work if they themselves do not have a clear understanding of the basic issues of copyright. A study on detecting and preventing plagiarism in the study process in Latvia was devoted to this issue. To evaluate the legitimate use of the work of other authors in the study process, the data on recorded cases of plagiarism in universities in Latvia were reviewed. The study concluded that, although almost all universities have tried to eliminate plagiarism, none of the internal rules for the prevention of plagiarism or tools for detecting plagiarism fully protect the study process from unscrupulous students. Unfortunately, this also fully applies to law students [17].

The Latvian Higher Education Council (HEC) has released a statement on the use of artificial intelligence tools in higher education and research [18]. HEC invites everyone to be aware that the rapid development of AI tools currently marks a significant and extremely rapid change in the paradigms of social and economic development worldwide. The international competitiveness of the Latvian economy, the future of the nation and the sustainability of society directly depends on whether we are currently able to responsibly and purposefully integrate AI tools into higher education and research.

B. Discussion

The EU law through modern digital challenges

One of the European legal specifics is the law's integration character, i.e. the EU-wide legal system is created to facilitate the process of socio-economic integration (and in the long-term the political as well) the EU member states into a "union" of like-minded political economies.

EU's lawmakers adopted the artificial intelligence act, so-called AI Law in June 2024; this regulation (2024/1689) is not only the first binding EU-wide horizontal regulation on AI; it sets a common worldwide framework for the use and supply of numerous AI systems.

The new act offers a classification for AI systems with different requirements and obligations tailored to a 'risk-based approach'; thus, some AI systems presenting 'unacceptable' risks are prohibited. E.g. numerous 'high-risk' AI systems that can have a detrimental impact on people's health and safety have to get an authorization and are subject to a set of requirements and obligations to gain access to the EU market. AI systems posing limited risks because of their lack of transparency will be subject to information and transparency requirements, while AI systems presenting only minimal risk for people will not be subject to further obligations.

The AI law also lays down specific rules for the general-purpose AI models (so-called GPAI) and lays down more stringent requirements for GPAIs 'high-impact capabilities' that could pose a systemic risk and have a significant impact on the internal market [19].

The AI definition in the AIA regulation is based on key characteristics of AI systems and distinguishes from simpler traditional software systems or programming approaches; for example, it is not covering digital application systems that are based on the rules defined solely by natural persons to automatically execute operations.

A key characteristic of AI systems in the European Union is their "capability to infer", i.e. referring to the process of obtaining the outputs, such as predictions, content, recommendations, or decisions, which can influence physical and virtual environments, and to a capability of AI systems to derive models or algorithms, or both, from inputs or data. The techniques that enable inference while building an AI system include machine learning approaches that learn from data how to achieve certain objectives, and logic- and knowledge-based

approaches that infer from encoded knowledge or symbolic representation of the task to be solved.

The capacity of an AI system to infer transcends basic data processing by enabling learning, reasoning or modelling. Thus, the term 'machine-based' refers to the fact that AI systems run on machines; besides, the AI systems can operate according to explicitly defined objectives or to implicit objectives.

The objectives of the AI system may be different from the intended purpose of the AI system in a specific context. The AI system is to be understood within the contexts in which the AI systems operate, whereas outputs generated by the AI system reflect different functions performed by AI systems and include predictions, content, recommendations or decisions. AI systems are designed to operate with varying levels of autonomy, meaning that they have some degree of independence of actions from human involvement and of capabilities to operate without human intervention. The AI systems "poses addictiveness", i.e. an AI system could exhibit self-learning capabilities, allowing the system to change while in use. AI systems can be used on a stand-alone basis or as a component of a product, irrespective of whether the system is physically integrated into the product (embedded) or serves the functionality of the product without being integrated therein (non-embedded).

The EU-wide legislative system has changed fundamentally since the Single Market was launched, e.g. integration has reached high levels in many (though not all) sectors of the economy and society. Thus, about 80% of national legislation results from decisions adopted by the EU institutions. However, the diversity and complexity of the legal system in force in the EU-27 significantly increased, as also the potential benefits from economies of scale. "These developments no longer allow to rely on mere convergence of national legislation and mutual recognition, which have become too slow and complex or just insufficient to benefit from economies of scale" [20].

Post-pandemic challenges changed dramatically the old-type legal perceptions by creating such social spheres as platform- and distant-working, climate and digital law as well as sustainability, circular economy and renewable energy legislation.

However, still the primary legal professionals' function is to protect the integrity of the rule of law in a country, maintain national values and safeguard the constitutional order; the "order" that closely intervened with the EU-wide "integration legal system". Therefore, professional lawyers represent the background of the "legal protection" looking from the basis and core of the EU legal means and that of the national law. They also keep the judiciary, executive and legislative branches under control and help in resolving the dispute arising between conflicting parties. Likewise, the legal professionals play a key role in the ways EU-wide justice is administered in the national legal system.

The bulk of existing EU legislation accounts for over 80 thousand legal documents, the amounts that require digital solutions to deal efficiently with the European legal background. Thus, in European external relations there are presently about 5 thousand legal acts, in environment, consumers and health protection issues – about 3 thousand; in agriculture – about 4 thousand; in the so-called EU general, financial and institutional matters –about 2 thousand; and about 2 thousand in competition policy issues, etc.

Smaller amounts of legal acts are in such socio-economic sectors as: e.g. "freedom, security and justice", with about 900 acts; "freedom of movement for workers and social policy" with about 800 acts, in the "right of establishment and freedom to provide services" with over 600 acts, in "science, information, education and culture" with about 500 acts, etc.

It is obvious that without modern digital technologies and AIs, professional lawyers just cannot afford to be regarded as true legal specialists!

Between 2019 and 2024, the European Commission proposed more than 70 laws only within the EU-wide "green deal" as mentioned in the Financial Times (9.09.2024). And this does not include hundreds of pieces of technical secondary legislation or other initiatives affecting business such as new rules governing data, digital technologies and finance. The impact is being felt across the EU's 24 million SMEs; a survey by the Commission has found that just 15 of the "green deal" legislation announced in 2022 would result in more than €2.3bn in extra administrative costs to businesses.

Generative AI models

Existing system of generative AI models (GenAIs) has shown some innovative examples recently using, e.g. language simulators to improve video production, image creation and copywriting, to name a few. Looking ahead, it will certainly be intriguing to watch where and how progressively efficient GenAI models will evolve [21].

There were the following digital platforms among some most used world-wide GenAIs during the last decade (as of March 2024): – Lightricks) from 2013 (used to power various tools for artistic expression); – OpenAI created in 2015; – Hugging Face from 2016 used for machine learning solutions (with the prominent "transformers library" offering an interface for users to exchange datasets); – Synthesis AI from 2019 which generates large amounts of data used in computer vision models; – Glean and Stability AIs both from 2020 providing AI models for image, language, code, music, video, life sciences and various other scientific areas; – Anthropic from 2021 working in the fields of machine learning, science, legislation and goods; – Jasper and most recent – Inflection AI (both from 2022) which assist in improving general interaction between humans and computers; it can provide factual responses, which are more personalized than Google Bard, OpenAI-GPT-4, and/or Microsoft's Bing, etc.[22].

Generative AI has wide-ranging applications across various application sectors, e.g. including:

1) Art and Design: AI-generated artwork, music, and product designs are gaining popularity. Also, artists and

designers are leveraging generative AI to create innovative and unique pieces that push the boundaries of human creativity.

2) Natural Language Processing: Generative AI models are used in chatbots and language translation applications. This enables more human-like, contextually relevant responses, and translations.

3) Medicine and Drug Discovery: Generative AI can analyze vast amounts of medical data and generate potential new drug compounds, streamlining the drug discovery process and potentially saving time and resources.

4) Gaming: AI-generated environments, characters, and narratives are used in video games. This makes them more immersive and dynamic. Moreover, as they gain experience, they adapt to players' actions and preferences.

5) Marketing and Advertising: Generative AI can create personalized advertisements and promotional content tailored to individual users. This enhances customer engagement and improves conversion rates.

Presently, some of the most impactful generative AI models by the end of 2023 are: e.g. GPT-4, Mixtral, Gemini, and Claude 2 in text generation, DALL-E 3 and Stable Diffusion XL Base 1.0 in image creation, and PanGu-Coder2, Deepseek Coder, and others in code generation (it's crucial to note that this list is not exhaustive).

The field of AI is rapidly evolving, with new innovations continually emerging. These models represent just a glimpse of the AI revolution, which is reshaping creativity and efficiency across various domains [12].

Digital transition in the EU's law

AI plays vital role both in the EU-wide and global competition; presently, the AI developments represent a "window of opportunity" for the EU industrial renaissance in boosting the member states' competitiveness. However, the process also represents some risks in losing European industrial leadership and profitability if AI is not rapidly integrated in their offerings.

Currently, AI is adopted by only 11percent of EU companies; according to the Commission, the European Union member states expected to reach the target of 75 percent by 2030 [23]. However, about three-fourth of all "the foundational models" on AI and digital technology developed since 2017 have originated from the US and about 15 percent from China [24]. Moreover, in 2023 only, around two thirds of all notable machine learning models were released in the US [25].

The purpose of the new EU AI Law, AIL (generally, it entered into force in August 2024, but will be effective from 1 August 2026) is to improve the functioning of the internal market and promote the uptake of human-centric and trustworthy artificial intelligence (AI), while ensuring a high level of protection of health, safety, fundamental rights enshrined in the Union's basic law (and Charter of Human Rights), including democracy, the rule of law and environmental protection, against the harmful effects of AI systems in the states while supporting innovation.

The new AIL lays down: a) harmonized rules for the placing on the market, the putting into service, and the use of AI systems in the Union; b) prohibitions of certain AI practices; c) specific requirements for high-risk AI systems and obligations for operators of such systems; d) harmonized transparency rules for certain AI systems; e) harmonized rules for the placing on the market of general-purpose AI models; f) rules on market monitoring, market surveillance, governance and enforcement; and g) measures to support innovation, with a particular focus on SMEs, including start-ups [19].

There is a certain risk for Europe to be totally dependent on AI models designed and developed abroad for both general-purpose AI and, progressively, for "vertical use" in crucial EU sectors, including the automotive, banking, telecoms, health, mobility, retail industries and finally in the legal profession. As AI is very dependent on upfront research and innovation investment, lower private investments represent negative sides for the EU's competitive position. The stronger US position is mostly due to the scale of cloud hyper-scalers (internally or through tight partnerships, like the one between Microsoft and OpenAI) and the availability of venture capital. In 2023, an estimated $ 8 billion in venture capital investment was made in AI in the EU, compared to $ 68 billion in the US and $ 15 billion in China [26].

Quite few companies building generative AI models in Europe, including Aleph Alpha and Mistral, need large investment to become competitive alternatives to US players. This need is currently not met by the EU's capital markets, pushing EU companies to seek overseas funding. Taking the top global AI start-ups worldwide, 61% of global funding goes to US companies, 17% to Chinese companies, and only 6% to those in the EU. Moreover, the EU has a low total number of new data specialists compared to those in the US and China; in particular, the talent pool needed to develop AI in the EU is smaller and highly skilled professionals are often 'poached' by high salaries offered overseas [27].

The EU's weak position in developing AI means that, in the future, it may not fully leverage its competitive advantage across several industrial sectors, with the risk of EU companies' market and value share potentially eroded by non-EU-players. Remarkably, this includes reaping in full the benefits of the digitalisation of industrial processes in the automotive industry and in robotics for advanced manufacturing. The EU's robotics industry has registered strong growth in the past decade, with 82,000 industrial robots installed in 2021, making Europe the second largest market after China and a major supplier worldwide – today almost half of the over 1000 service robots suppliers worldwide are European, although 73% of all newly deployed robots are installed in Asia and only 15% in Europe. Thanks to the introduction of AI-controlled capabilities, the EU's service robot market is set to further

expand by a CAGR of 14% by 2026, continuing to play a key role across sectors. Overall, a weak AI ecosystem would represent an obstacle to EU companies' digitalisation and productivity gains and represent a threat to Europe's current leadership in advanced robotics [28].

For example, a new trend appeared in the EU to include in the existing sectoral laws some of the new challenges: e.g. the EU environmental law has presently included into the "substantive legislation" such sectors as nature, biodiversity and water protection, air pollution prevention, waste management, climate change and renewable energy law. At the same time, there have appeared some new "cross-cutting sectors", such as the "green deal" with the environmental impact assessments (including ESGs) and environmental liability; other aspects of global challenges influence legal profession too, such as sustainability and waste management, renewables and circular economy, to name a few.

Still another aspect of "legal transformation" is about "critical concerns" in the use of the generative artificial intelligence (AI) platforms and searching engines (with the most vivid present example of Chat-GPT) in legal studies and profession. The digital intervention into the work of lawyers has been progressive recently with the consequential effects of using ready-made online solutions available through numerous cloud-sites on almost all aspects of lawyer's traditional and time-consuming "paperwork" [29].

Higher education and digital transformation are two essential areas that interact and influence each other today. The rapid development of technology requires higher education institutions to provide students with the digital skills needed in the labor market and everyday life. At the same time, educational institutions are embracing digital solutions to improve the efficiency of the learning process and offer new opportunities for students and lecturers [30].

As soon as there is no presently any specific GenAI for use in legal profession, it is advisable to establish a systematic approach to various generative AI's in dealing with global challenges. With this in mind, it is necessary first, to draft a "general-type" of generative AI for sustainable growth that would include modernized national political economy development patterns and regulations. The second AI model to supplement the "general one" would include specific legal tasks, solutions and requirements in lawyers' work.

As has been revealed, the application of the AI's generative model(s) for the lawyers in the member states (GenAI) has some distinctive features: a) the global challenges have deeply transformed the national socio-economic paradigm and governance (so-called ESG); b) the use of generative AI can be through a specific model oriented towards specific coordination of legal work between the EU and the member states through the so-called division of competences, i.e. exclusive, shared and supporting.

According to the EU AI law, the "general-purpose AI model" means a model (also including such AI models that are "trained" with a large amount of data using self-supervision at scale), that displays significant generality and is capable of competently performing a wide range of distinct tasks regardless of the way the model is placed on the market and that can be integrated into a variety of downstream systems or applications, except AI models that are used for research, development or prototyping activities before they are placed on the market [19].

The magnitude and the velocity of modern digital challenges require not only a redesign of the structure of legal education, but also an introduction of a separate legal-technology specialty: for example, a lawyer/advocate publicly supporting a "green deal-cause" for a client and/or state could be called an "advocate of green transition". Under all circumstances, it would be a lawyer with IT skills sufficient for the confident use and adequate modification and development with understanding of technologies underlying sustainable growth, machine learning and AI/digital technology, in general. Accordingly, the training program for such specialists will need to include, at a minimum, courses in math, programming, databases and cloud infrastructure.

As soon as there is no presently any specific GenAI for use in the legal profession, it is advisable to establish a systematic approach to various generative AI's in dealing with global challenges. With this in mind, it is necessary first, to draft a "general-type" of generative AI for sustainable growth that would include modernized national political economy development patterns and legal regulations. Thus, the second AI model would supplement the "general one" and include specific legal tasks, solutions and requirements in lawyers' work [31].

More active discussion is needed on practical approaches to bridging emerging gap.

IV. CONCLUSIONS

The following are the article's main recommendations and conclusions:

national system of legal qualifications shall be modified to incorporate necessary changes in the legal education concerning new global and European socio-economic challenges. It would be pertinent, e.g. to include in the list of legal professions such new categories of specialists in sustainability and climate legislation, in digitalization and circular economy's regulations, though according to national needs and priorities. Such transformations along new sectors of the legal profession at national level would at the same time facilitate inclusion of "new lawyers" into both the EU and the member states' list of professions to facilitate proper incorporation of EU-wide legislation at national level. Besides, it is vital to modernize a heavily complicated certification system for lawyers eager to work in another EU member state.

there is a growing need of revising existing nomenclature of legal professions in the EU states; with this in mind, the national education authorities must elaborate specifications for new legal professions through

a nation-wide discussion in the legal community for the nomenclature of needed lawyers.

the apparent deficit in the number of new legal professions to deliver on modern challenges tarnishes the EU-wide integration process and the member states' ability to better implement EU regulations (which are having direct application) and/or dully transpose directives (which need an active national legal community's involvement). Thus, the European Commission constantly publishes accounts on infringement procedures, which clearly show that it is quite difficult for the member states to tackle the inquired legal issues due to the lack of needed law specialists. Lack of new legal professionals is presently in such new spheres of socio-economic development as, e.g. energy and climate, digital and human rights, sustainability and circular economy, etc. which both tarnishes the states' independent legal "ability" and reduces potentials in complying with the EU legal order.

REFERENCES

[1] T. Kerikmäe, T. Hoffmann and A. Chochia, "Legal Technology for Law Firms: Determining Roadmaps for Innovation", in Croatian International Relations Review. Croatian International Relations Review, DOI https://doi.org/10.2478/cirr-2018-0005

[2] A.E. Davis, "The Future of Law Firms (and lawyers) in the Age of Artificial Intelligence". Revista Direito GV. V. 16 N. 1. DOI: https://doi.org/10.1590/2317-6172201945

[3] M. Chui, E. Hazan, R. Roberts, A. Singla, K. Smaje, A. Sukharevsky, L. Yee, and R. Zemmel , "The economic potential of generative AI: The next productivity frontier. McKinsey & Company". Available: https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/the-economic-potential-of-generative-ai-the-next-productivity-frontier [Accessed March 30, 2025].

[4] H. Smith, "The Role of the Lawyer in a Changing World," Indiana Law Journal: Vol. 33: Iss. 2, Article 11. Available: https://www.repository.law.indiana.edu/ilj/vol33/iss2/11 [Accessed March 26, 2025].

[5] T.D. Morgan, "Educating Lawyers for the Future Legal Profession", 30 Okla. City U. L. Rev. 537. Available: https://scholarship.law.gwu.edu/cgi/viewcontent.cgi?referer=&httpsredir=1&article=1866&context=faculty_publications [Accessed March 26, 2025].

[6] W.M. Sullivan, A. Colby, J.W. Wegner, L. Bond, and L.S. Shulman "Educating Lawyers: Preparation for the Profession of Law", Jossey-Bass Inc Pub. ISBN 978-0787982614

[7] A. Mehrotra and B. Gupta, "Educating Lawyers", India Legal. Available: https://www.researchgate.net/publication/362666703_Educating_Lawyers [Accessed March 26, 2025].

[8] D. Maranville, "Building on Best Practices: Transforming Legal Education in a Changing World", LexisNexis Law School Publishing. ISBN: 978-1-6304-4320–7. Available: https://cap-press.com/pdf/9781630443207.pdf [Accessed March 26, 2025].

[9] M. Ma, "Legal Training Should Embrace Generative AI Large Language Models", Bloomberg Law. Available: https://news.bloomberglaw.com/us-law-week/legal-training-should-embrace-generative-ai-large-language-models [Accessed Aug. 30, 2024].

[10] Analytics Vidhya, "What is Generative AI and How Does it Work?"Available: https://www.analyticsvidhya.com/blog/2023/04/what-is-generative-ai/ [Accessed March 26, 2025].

[11] H. Singh, "Top 12 Generative AI Models to Explore in 2024", Analytics Vidhya. Available: https://www.analyticsvidhya.com/blog/2023/12/generative-ai-models/ [Accessed March 26, 2025].

[12] B. Marr, "How Generative AI Will Change The Jobs Of Lawyers", Forbes, March 14, 2024. Available: https://www.forbes.com/sites/bernardmarr/2024/03/14/how-generative-ai-will-change-the-jobs-of-lawyers [Accessed Aug. 30, 2024].

[13] I. Atrey, "Revolutionising the Legal Industry: The Intersection of Artificial Intelligence and Law", International Journal of Law Management & Humanities. Volume 6 | Issue 3. DOI: https://doij.org/10.10000/IJLMH.114947

[14] Intelligence Society and LSESU Law Society. Available: https://www.lse.ac.uk/law/Assets/Documents/news/AI-in-Law-the-Legal-Profession-Industry-Insights-Report.pdf [Accessed March 26, 2025].

[15] E. Cooke and E. Barg, "AI in Law & the Legal Profession", Industry Insights Report. LSESU Artificial Intelligence Society and LSESU Law Society. Available: https://www.lse.ac.uk/law/Assets/Documents/news/AI-in-Law-the-Legal-Profession-Industry-Insights-Report.pdf [Accessed March 26, 2025].

[16] E. Trist, "The Evolution of Socio-Technical Systems", Wiley Interscience. August, 1981. Available: https://sistemas-humano-computacionais.wdfiles.com/local--files/capitulo%3Aredes-socio-tecnicas/Evolution_of_socio_technical_systems.pdf [Accessed March 26, 2025].

[17] I. Veiksa, "Detecting and Preventing of Plagiarism in the Study Process", International Scientific Conference on Society, Integration, Education 2020, Society. Integration. Education, VOL. II, pp. 376-390. DOI10.17770/sie2020vol2.5178

[18] Higher Education Council, "Statement on the use of artificial intelligence tools in higher education and research", Jurista vārds, 12.04.2023 / Available: https://m.juristavards.lv/zinas/283101-augstakas-izglitibas-padomes-pazinojums-par-maksliga-intelekta-riku-izmantosanu-augstakaja-izglitiba/ [Accessed March 26, 2025].

[19] Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 laying down harmonised rules on artificial intelligence and amending Regulations (EC) No 300/2008, (Artificial Intelligence Act). OJ L, 2024/1689, 12.7.202.

[20] E. Letta, "Much more than a market: speed, security, solidarity in empowering the Single Market to deliver a sustainable future and prosperity for all EU Citizens", April 2024. Available: https://www.consilium.europa.eu/media/ny3j24sm/much-more-than-a-market-report-by-enrico-letta.pdf [Accessed March 26, 2025].

[21] E. Eteris, "Generative AI: recent legislative effort in the EU", Analytics, EU Law & Governance. Available: https://www.integrin.dk/2023/12/25/generative-ai-recent-legislative-effort-in-the-eu/ [Accessed March 26, 2025].

[22] Lightricks, "News related to Lightricks". Available: https://tracxn.com/d/companies/lightricks/__IU9J-nySk6KriJ7GpDdUVhDMOgIclcOla-oeaCk4KLc [Accessed March 26, 2025].

[23] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Report on the state of the Digital Decade 2023, COM/2023/570 final. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52023DC0570 [Accessed March 26, 2025].

[24] LEAM AI, "Large AI Models for Germany ', German AI Association. Available: https://leam.ai/wp-content/uploads/2023/05/LEAM-Feasibility-STudy.pdf [Accessed March 26, 2025].

[25] Stanford University, "Artificial Intelligence Index Report 2024". Available: https://aiindex.stanford.edu/wp-

content/uploads/2024/05/HAI_AI-Index-Report-2024.pdf [Accessed March 26, 2025].

[26] E. Eteris, "European growth strategy: facing EU-US competition challenges", Analytics, EU Law & Governance, October 2, 2024. Available: https://www.integrin.dk/2024/10/02/european-growth-strategy-facing-eu-us-competition-challenges/ [Accessed March 26, 2025].

[27] European Commission, "The future of European competitiveness – In-depth analysis and recommendations". Available: https://commission.europa.eu/document/ec1409c1-d4b4-4882-8bdd-3519f86bbb92_en? [Accessed March 26, 2025].

[28] International Federation of Robotics, "World Robotics 2023". Available: https://ifr.org/img/worldrobotics/2023_WR_extended_version.pdf [Accessed March 26, 2025].

[29] E. Eteris, "Triple approach to modern political economy: new patterns through ESG", August 16, 2024. Available: https://www.integrin.dk/2024/08/16/triple-approach-to-modern-political-economy-new-patterns-through-esg/ [Accessed March 26, 2025].

[30] E. Klave and R. Cane, "Digital transformation of higher education: integrating multimedia systems into the study process", 15th International Scientific and Practical Conference on Environment. Technology. Resources, ETR 2024 Rezekne 27 June 2024. DOI: https://doi.org/10.17770/etr2024vol2.8017

[31] A. Hancock, "Is red tape strangling Europe's growth?", Financial Times, September 9 2024. Available: https://www.ft.com/content/4e8e6cde-d0ce-4f0a-a7ea-1c913d4dad50?accessToken [Accessed March 26, 2025].

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 137-144

Digital Ecosystems for Music Teacher Training: ICT, Social Media, and Online Learning Environments

Vasyl Frytsiuk
Faculty of Arts and Art-Educational Technologies
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
ORCID: 0000-0002-4466-9019
vasyl.frytsiuk@vspu.edu.ua

Iurii Kshyvak
Department of Musicology, Instrumental Training and Choreography
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
ORCID: 0009-0008-0396-432X

Iryna Baranovska
Department of Art Subjects of Preschool and Primary Education
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
ORCID: 0000-0003-0033-4425
iryna.baranovska@vspu.edu.ua

Olena Teplova
Department of Musicology, Instrumental Training and Choreography
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
ORCID: 0000-0001-8763-891X
olena.teplova@vspu.edu.ua

Anna Novosadova
Faculty of Arts and Art-Educational Technologies
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
ORCID: 0000-0002-6215-5759

Anna Khilya
Sistemas Microinformáticos y Redes IES IFACH,
Department of Primary Education
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Calp, Spaine
ORCID: 0000-0002-1287-2901
annkhi@alu.edu.gva.es

***Abstract* — The increasing digitalisation of education has significantly impacted music teacher training, integrating information and communication technologies (ICT) and online platforms into pedagogical practice. This study explores the role of digital ecosystems, particularly social media platforms like YouTube and TikTok, in shaping new approaches to music education. These platforms function not only as entertainment hubs but also as powerful educational tools that foster interactive learning, expand access to high-quality musical instruction, and engage students in dynamic ways. We analyse both the theoretical and practical aspects of ICT integration in music teacher education, highlighting how digital tools transform teaching methodologies. Special attention is given to social media as an educational resource, evaluating its benefits—such as accessibility, engagement, and diverse content—while also addressing challenges like quality control and information overload. Through expert analysis and case studies, we assess the effectiveness of blended learning models that combine traditional and digital education. As a result, we propose a structured model for integrating social media and online tools into music teacher training, aiming to enhance interactive engagement and professional development. This study contributes to the ongoing discussion on the modernisation of music education, offering practical recommendations for embedding ICT and social media into curricula. By leveraging the potential of digital learning environments, future music teachers can not only adapt to contemporary pedagogical challenges but also develop innovative teaching methodologies tailored to the needs of digital-native students.**

Keywords – Digital learning tools; Digitalization; Higher education; ICT; Interactive content; Music applications; Music pedagogy; social media; Technological adaptation.

I. Introduction

The contemporary landscape of higher education - particularly in the field of music teacher training - has undergone transformative changes due to global and regional challenges, including:

- quarantine restrictions (2019–2021) and military aggression (2014–2022, with further escalation);
- new forms of social interaction via messengers (e.g., Viber, WhatsApp, Skype, Telegram) and social media platforms (e.g., Facebook, Instagram, TikTok, YouTube, Twitter);

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8598
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

- the shift toward online and blended learning environments (e.g., Moodle, Google Classroom, Zoom, MeetToGo, Microsoft Teams).

These phenomena have significantly accelerated the implementation of blended and distance learning formats, compelling educators to reconsider traditional pedagogical models and embrace digital transformation. Educational changes in this context typically undergo multi-stage validation processes to ensure their effectiveness, alignment with educational standards, and relevance to national culture and societal needs.

Amid these developments, the integration of information and communication technologies (ICT), social media, and generative artificial intelligence (AI) into music education has become not only relevant but essential. The role of digital ecosystems—encompassing platforms such as YouTube, TikTok, BandLab, and AI-powered composition tools—has shifted from being supplementary to serving as a core component of instructional strategies and student engagement.

This paper explores the impact of digitalisation on music teacher education by examining how digital tools reshape pedagogical approaches, learning environments, and professional preparation. Special attention is devoted to the Ukrainian context, where the digital transformation of education is both urgent and socially significant.

Research Objective. The main goal of this study is to propose a structured model for integrating digital tools and AI technologies into music teacher training programs. The model seeks to support curriculum innovation, promote interactive and reflective learning, and enhance the digital competences of future music educators.

II. MATERIALS AND METHODS

This paper explores proposals for the use of digital technologies to enhance the music education ecosystem in the training of music teachers in higher education institutions.

The first step involves analysing the changes influencing the development of the music field, the music industry, and the transformation of pedagogical models in traditional, distance, and blended music education.

The next stage of our research focuses on presenting the technical solutions currently used by music teachers to implement demand-driven educational programmes. This includes considering trends and tendencies that encourage young people's interest in music. Specifically, we review digital platforms and tools such as YouTube, TikTok, Soundtrap, BandLab, MuseNet, AIVA, Amper Music, and OpenAI Jukebox in the context of training future music teachers. Additionally, we systematise modern approaches to integrating digital technologies into teaching music disciplines based on theoretical research.

The final step in selecting technological solutions and proposals in music pedagogy addresses the interaction between musicians and generative models of artificial intelligence. We identify both their advantages and limitations concerning the future of the music industry.

As a result, we have formulated a new model that can be considered when structuring the educational process in higher music education.

To achieve this, we employed the following research methods:

- Theoretical analysis and literature review to examine current scientific studies on the impact of digital technologies and AI on music pedagogy.
- Content analysis of digital platforms to determine their role in music education.
- Review and classification of generative AI programmes for creating musical compositions.
- Systematisation of collected data to develop recommendations for the use of generative AI and digital technologies in music teacher training.

To identify lesser-known or previously unaccounted-for music programmes, we conducted targeted searches in music forums and utilised generative AI tools. The collected data were categorised according to the identified areas of music training and assessed based on their expected effectiveness.

III. RESULTS AND DISCUSSION

A. Music pedagogy in higher education

Music pedagogy is perhaps one of the most sensitive pedagogical disciplines to change. Why is this the case? Because music and sound are an integral part of personal development, social development, daily communication and socialising.

Therefore, the music industry is very sensitive to changes that occur, for example, through research on the impact of music on our bodily reactions related to emotions, changing the level of dopamine, serotonin, cortisol, endorphin and oxytocin, as well as affecting cardiovascular parameters, blood pressure and heart rate [1].

Through emotions, music penetrates our lives and stimulates the autonomic nervous system, limbic and related biological systems, including endocrine and hormonal responses [1], which make it possible to create the necessary atmosphere of psychological influence or maintain attention in the educational process.

Why did we focus on the medical industry? Because the dynamics of changes in the medical industry through the use of body area network (BAN) devices has led to the fact that we have direct access to statistical data collected through special devices (fitness bracelets, smart watches). These devices are in direct contact with the individual's body and measure their performance and, depending on the built-in functions, can offer programmes to improve health, sleep, etc. This to some extent reduces, but does not eliminate, the need for specific medical tests to analyse the

functioning of the brain and body (EEG, FRR, GBA, ELAN, ERAN, MMN, MRI, VBM, MEG, etc.) [1]. Each of the proposed measurements collects gigabytes of data that help us understand how the brain works, how different stimuli affect different parts of the cerebral cortex and the body as a whole.

And, among this data, we can distinguish the data of musical influence on our brain, body, and mental health. This, in turn, helps to develop new concepts in neuropsychological science by regulating human activity, changing patterns of behaviour and reactions to social stimuli.

For music pedagogy, it is important not only to have data on the effect of music on the body, but also to be able to choose the right piece of music to activate the necessary functions of the body, mental operations, concentration, or to calm the nervous system, reduce stress, both physiologically and psychologically. That is why music pedagogy today is no longer a subject of purely theory and music notation, particularly in online education. It is a subject that combines theoretical knowledge, exercises in performing musical works, creating musical compositions and, most importantly, studying and understanding their impact on the human body through personal practical experience. And, as we noted earlier, music pedagogy is intertwined with technology and changes under its influence.

To this end, during our research, we have studied the educational programmes offered at different levels of higher education in Ukraine, in particular those implemented at Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University. After all, to outline organisational issues and areas of use of digital solutions for music pedagogy, we needed to balance and identify areas of music teacher training. Thus, we analysed the bachelor's and master's degree programmes offered by three university departments. These are the Department of Artistic Disciplines of Preschool and Primary Education, the Department of Musicology, Instrumental Training and Choreography, and the Department of Vocal and Choral Training, Theory and Methods of Music Education.

As a result of the analysis, we obtained ten areas, which are presented in Fig. 1, and identified disciplines through the basic elements of music pedagogy, which allowed us to investigate which digital solutions would best allow us to realise the main goal of teaching in the implementation of a particular area.

Theoretical and historical foundations of music	(harmony, solfege, analysis of works, history of Ukrainian and foreign music)	Perfect Ear, Ultimate-Guitar, Tenuto, MusicTheory.net, Theory Lessons (musictheory.net), Complete Ear Trainer, EarMaster, Meludia, Hookpad, Odesi, CAMA (Computer Added Musical Analysis), MuseLab Conductor.
Music performance and interpretation	(instrumental training, solo singing, vocal ensemble, main musical instrument)	Tuner, Metronom, Simply Piano, Yousician, Virtual Drumming, Guitar Tuna, Cleartune, Cadenza, MyPianist
Choral art and conducting	(choral class, choral conducting, methods of working with a choir, choral arrangement)	MuseScore, Sibelius, Finale, Noteflight, Flat.io, Rhythm Sight Reading Trainer, Interact Music Project, Doodle Bach
Orchestral art and ensemble playing	(orchestra class, chamber ensemble, instrumentation, orchestral conducting)	BandLab, Soundtrap, SoundJack, Zoom + Jamulus, Soundation Studio, Transcribe
Methods of music education and pedagogy	(methods of music education, theory and methods of music education, methods of teaching in higher education)	Soundtrap for Education, Google Classroom, Moodle, PlayScore 2, SmartMusic, ClassDojo, Rhythm Trainer, Modacity
Musical and pedagogical practice and stage activities	(music practice, stage performance, concertmaster class, voice training)	Lick of the Day, Voicify AI, Music AI: Cover Song & Video AI, LimeWire AI Music Studio, Ableton Live, FL Studio, GarageBand, MuseNet, Novaxe Project
Innovations and digital technologies in music	(computer music editors, music and computer technologies, the latest Ukrainian music)	Ardour, Audacity, Audiotoolset, Bear Audio Tool, LogicPro, Song Maker (Chrome ML), Boomy, Soundraw, AIVA, Mubert, Ecrett Music, Beatoven.ai, Loudly, Caset - AI music generator, Magenta Studio, Amper Music, Endlesss, Suno AI, Folk-RNN, Web Audio API, Ethereum
Music therapy and health technologies	(music therapy, art technologies, psychological aspects of musical activity)	Incredibox, Kahoot, Learning Apps, Madlipz, Menti, Mentimeter
Artistic and pedagogical analysis of music	(analysis of programme material, music source studies, interpretation of choral works)	ConservatorioVirtual.com, Note Recogniser, SangeetKosh, VEMUS
Music literacy and general competences of the teacher	(teacher's music literacy, basics of artistic activity, aural training workshop)	Easy Music Composer Free, Adagio, Prime Phonic, Soundcloud, Spotify, YouTube

Fig. 1. Digital solutions for music education.

B. Digital solutions for music education

As we continue our research into the impact of digitalisation of music education, we need to understand that before the quarantine restrictions (2019), the changes were more about performing arts and the music industry. These spheres of musical influence had to respond to consumer demands and be publicly accessible, responding to market needs in a timely manner, creating content for social media, soundtracks and ringtones, adapting music to end-user preferences, digitising and improving old audio recordings, etc.

At the same time, music pedagogy (particular in Ukraine) continued its measured existence. Using

traditional approaches to teaching and learning disciplines from music theory, solfege to conducting and methods of teaching the same subjects. Occasionally, synthesisers and multimedia devices are used to demonstrate materials, including audio recordings of music or backing tracks, if necessary. But for the most part, the use of digital solutions in music education was limited to this list within the framework of educational programmes.

Another aspect of the transformation was the need to transfer not only the theoretical part of the disciplines, but also the practice into the digital environment. On the one hand, the use of distance technologies saves time, provides flexibility and mobility of the educational process, which focuses primarily on the student, but at the same time 'loses' the practice of 'live' music making or music creation [2]. Here we can agree with our colleagues, because there is indeed a limitation in emotional involvement, following group dynamics and directing the process of creating a piece of music or actually making music. Also, there is the problem of self-organisation, which affects the choice of methods and forms of control as means [2], because not all students have developed time management skills necessary to achieve better results of independent activity before studying at a higher education institution.

However, in our opinion, the limitations mentioned earlier can be overcome through the use of music ecosystems, communities, social media and networks. After all, one of the main advantages of information technology in music education is that it is accessible to everyone in any environment [3]. This is incredibly important for the Ukrainian audience in the context of intensifying military aggression since 2022. And, even more importantly, it is a focus on the child, his or her interests and preferences, and the impact on their development through the inclusion of social media (YouTube), in the world of musical art [3]. For our part, we propose to use music trends and trends that spread through other social networks, TikTok, Instagram, video games, and streams.

Therefore, the development of music pedagogy courses needs to be periodically amended. Usually at the beginning of the year to ensure that they truly meet the updated needs of music education and the industry. This approach will allow us to borrow advanced teaching methods [4] from other business-oriented practices and disciplines. That would be used to retrain existing employees by providing micro-degree programmes, with the student choosing courses in line with the current strategic directions and plans of employers [4]. In our case, the music industry or the gaming industry. And, as our colleagues point out, the advantage of this method will be that it will increase the motivation of students, partner companies, and teachers through joint contribution and fulfilment of the requirements for a quality music product.

In this aspect, if we focus on the music industry, we can see a few computer technologies and software for music creation: arrangement, audio and video editors, sound libraries, virtual synthesisers, audio processing programs, video recording programs, audio content analysis programs, etc. More examples in relation to the identified areas can be seen in Fig. 1, which presents our search for digital solutions to achieve the goals and objectives of educational programmes, browsing forums, searching for relevant queries, refining information using a neural network, as well as through the analysis of solutions proposed for music pedagogy by scholars and practitioners, in particular in scientific papers, to determine the practical aspects of interaction during distance education of music teachers [1-4, 6-13]. Analysing the international educational space, we have found a few proposals that we believe should be taken into account when digitalising the music educational ecosystem [1-4, 6, 9-13].

In addition, based on the analysis, we plan to add the following structured materials and topics that can be easily applied when planning practice-oriented activities within music teacher education programmes. In particular: analysis, generation and synthesis of sound; sound effect as an artistic medium; interpretation, improvisation and stage creativity; creating backing tracks; creating, recording and basic editing of a musical piece; music in audiovisual narrative; music and video games, etc [12].

Knowledge of the proposed digital solutions, in our opinion, will contribute to the development of high-quality musical creativity, promote basic knowledge of music theory for creating arrangements and producing music, support motivation to learn and facilitate the completion of higher education [14]. In turn, high-quality training and awareness of music teachers in the world of modern digital music will allow them to easily work in their speciality. That is why, in some cases, the training of future music pedagogues should be not only about higher education, but also about general secondary education institutions. This is where the trained specialists will teach in the future.

Secondary education in music also requires mastery of technological skills related to music, as nowadays there are sound sequencer editors and applications for recording and mixing sound, as well as technological resources that simulate the interpretation of instruments and instrumental groups, which was possible only in recording studios and can now be used in music education [6]. Such skills will make it possible to capture the attention of adolescents in an interesting and easy way and will help to attract children to music.

In addition, the introduction of technological solutions in the music classroom involves not only new ways of approaching composition, interpretation and response to the musical phenomenon, but also contributes to the acquisition of digital competence and the development of interconnected educational communities, which play a fundamental role in structuring educational ecosystems and in achieving certain sustainable development goals [12]. Proposals for the introduction of an online platform in the music classroom as an educational resource focused on creating, storing, editing and discussing content, which helps to align the interests of students and the didactic

resources used, providing contextualised information and to some extent simplifying the work of the teacher [10]. The use of such platforms allows solving the whole range of educational tasks through the integration of tools for the development of hearing at the melodic, rhythmic and harmonic levels, as well as access to semantically related information resources of the teacher [10].

Particular attention should be paid to the student's personality, which can influence the curriculum and technological solutions chosen by the teacher through their choice, experience and ambitions. After all, students' professional orientation and learning goals should be considered when organising the educational process, which will allow to meet the demand for music education in a qualitative and effective way, which should be more inclusive and represent the diversity of students and musical tastes [11].

Thus, technology can enhance the impact of music and the quality of music education, in online or blended learning, in some cases complementing the practical parts of the course with the latest technologies.

C. Generative AI-based solutions for music education in higher education

Given that the Internet has become an alternative artistic solution for the music industry. Which has turned to streaming music services [9], repositories specialising in didactic proposals, social interaction [10] to interact directly with a wide audience. We have a significant use of the potential of social networks, elements of knowledge sharing to develop joint didactic proposals with students [10].

And, as our fellow researchers point out, the gradual introduction of artificial intelligence into the educational process has become a major revolution in music teaching, as artificial intelligence pushes music education towards more efficient and intelligent interaction, where resources are personalised, commitment to the discipline is strengthened, and new opportunities for developing artistic and creative skills are offered [5]. The scenarios of adaptive learning platforms based on artificial intelligence create an individual educational trajectory, allowing the student to independently assess their level of musical competence and personalise the pace of learning, adapting learning tasks and goals to their needs and abilities [5].

For example, the most popular artificial intelligence systems today are chatbot, microsoft copilot, and Gemini [13]. Each of them is available in the public domain or by subscription. Their potential is proposed to be used to transform various sectors, including higher education, conversational interaction, and visualisation, as they are already changing education through their representative innovative technologies and capabilities [13]. But these models are not the ones that can offer solutions for music education.

Although today there are already developments that generate music based on written instructions [5], creating a serious threat to the future of not only the music industry, but also music education, which leads to the loss of basic knowledge and skills. Although, at the same time, there is another side to the use and application of artificial intelligence, which includes

- Creating a musical composition by generating ideas and motifs or entire works with the user's personal input, but with an understanding of different compositional techniques, methodologies and styles. Allowing the imitation of different musical styles by offering different scenarios to encourage creative experimentation, hybridisation of genres and styles, leading to the development and enrichment of compositional skills;
- offering simulated accompaniment for solo practice, which adapts to the pace and style of the student [5].

And so, based on the available and open technologies, we understand that the exponential level of development of neural networks and the use of artificial intelligence has achieved an incredible result. However, we have high risks associated with the chaotic and uncontrolled use of these technologies by students. We can also observe the incredible solutions that a neural network allows us to implement. These changes have also affected the music industry and, in particular, music pedagogy. So we can recall the programmes that our colleagues and we often include in the educational process, including:

- Boomy. A music platform that allows users to create original compositions using AI and distribute them on streaming platforms.
- Soundraw. A powerful service that allows users to create an unlimited number of songs for various needs, such as background music for videos, podcasts, games, etc.
- Suno AI. An innovative platform that changes approaches to music creation with the help of AI, allowing to create compositions based on text prompts.
- LimeWire AI Music Studio. A service that allows users to enter a description of a song they want to hear, and the application generates a corresponding composition.
- Music AI: Cover Song & Video AI. An application that uses advanced AI technology to create unique musical compositions easily, even without any experience in music composition.

These apps can be useful for integrating AI into the music creation and learning process. However, the music space is not limited to these apps today, as for the sake of convenience and at the request of the audience, programs and applications are being developed and distributed that are easily installed on mobile devices, have extensive functionality, integrate into social networks and media, and launch and distribute user-generated content in seconds.

Among such applications, we can consider:

- Soundraw – generates music in different genres, allows you to adjust the tempo and mood.
- AIVA is an AI composer that creates classical and electronic music.
- Mubert – createes unique tracks for videos, ringtones, and streams.
- Ecrett Music is a tool for generating background music for videos, games, and TikTok.

It is easier to use and can be mastered even by a child:

- Song Maker (Chrome Music Lab) is an intuitive music construction tool for children.
- Melobytes – generates music from words or images.
- Beatoven.ai allows you to create music without knowledge of production.

There are also specific programmes and applications used by users of TikTok and other social networks and media. These apps are convenient for creating ringtones and quickly generating tracks. They include:

- Loudly – generates tracks for TikTok and YouTube, has ready-made templates.
- Voicify AI - creates music mixes and AI covers of popular songs.
- Caset – AI music generator - helps to quickly create short tracks.
- MuseNet (OpenAI) - creates music in different styles and genres, can combine instruments.
- Magenta Studio (Google AI) - works on the basis of neural networks to generate melodies, expand rhythms and harmonies.
- Amper Music - allows you to quickly create music based on the choice of genre, tempo, and mood.
- Endlesss is an AI tool for music jams and soundtrack experiments.

Other products include the previously mentioned Boomy platform that allows creating music in one click and is popular among TikTok creators.

Of course, these are not all the products that are available on the music industry market today. But these are the most well-known and accessible to a wide audience.

D. A model for optimising the use of generative AI and digital technologies in music teacher education

As we can see, significant changes have taken place in the Ukrainian realities of music education, which required a revision of the entire spectrum of both teaching methodology and student practice in teaching music to students in general secondary education.

But what were the changes and how can digital tools and AI be strategically embedded into this evolving pedagogical context?

To address this question, we propose a model for optimising the use of generative AI and digital technologies in music teacher education. The model is based on core pedagogical needs and practical observations in the field, and it includes the following key components:

- Annual review of curricula and regular updates of digital content in accordance with current trends in the music industry, to ensure life relevance and practical orientation;
- Support for theoretical and historical courses (e.g., harmony, solfeggio, composition analysis, Ukrainian and global music history, choral conducting) through accessible software and digital tools. These can enhance engagement, such as enabling students to conduct video performances instead of imagined orchestras;
- Incorporation of individual music preferences into practical training, focusing on the emotional and psychological impact of music choices. As studies suggest, the benefits of music on well-being are maximised when individuals are free to select music they enjoy [Hallam];
- A dedicated course on digital literacy for musicians, aimed at developing skills for identifying AI-generated content, evaluating ethical risks, and understanding legal implications such as copyright and plagiarism.

These components reflect broader shifts in the educational landscape. Specifically, they are shaped by:

- New collaborative technologies (e.g., videoconferencing, open-source tools, virtual classrooms);
- Societal transformation from industrial to digital economies, which has redefined foundational skills and knowledge;
- Emerging digital cultures that support transparency, openness, and multidimensional collaboration.

Based on these considerations, we propose the Digital Integration Framework for Music Teacher Education, which consolidates the identified tools and strategies into a structured system (see Figure 2).

The proposed Digital Integration Framework combines three main groups of tools: ICT infrastructure, social media platforms and AI applications. These clusters are brought together through focused pedagogical design and alignment with specific courses. The framework emphasises the development of digital competences, the critical use of generative tools, and adaptive strategies that respond to learners' needs and contextual challenges. It serves as a guide for curriculum designers and pedagogical faculty to integrate the digital environment into music pedagogy.

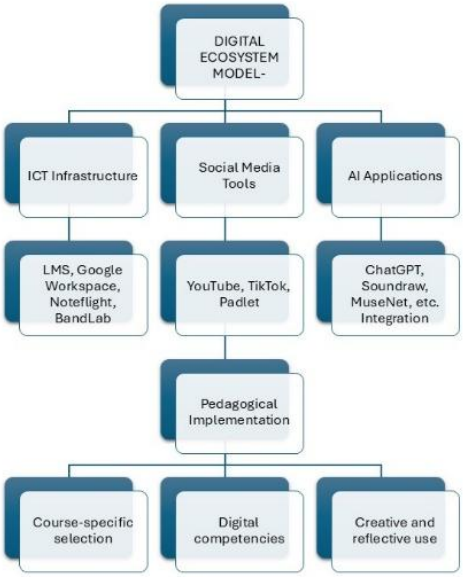


Fig. 2. Digital Integration Framework for Music Teacher Education.

IV. Conclusions

Having analysed the impact of the digital ecosystem – including social networks, online services, and generative AI tools – on the methodology of teaching music disciplines, we have identified a wide range of digital solutions that support the realisation of educational goals in music teacher training and in broader music industry contexts. Furthermore, this study has outlined key components that should be incorporated into revised educational programmes to optimise the integration of generative AI and digital technologies in music pedagogy.

We offer the following generalisations:

- Digital tools such as BandLab, Noteflight, Google Workspace, and AI-powered platforms like ChatGPT are becoming increasingly vital in music education.
- Social media platforms can significantly enhance creative expression, peer feedback, and informal learning.
- The integration of generative AI opens new horizons for automated content creation, personalised learning pathways, and adaptive assessment.
- Ukrainian music education, shaped by adversity, demonstrates notable resilience and contextual innovation, serving as a compelling example of adaptability in crisis conditions.

Based on these findings, we recommend the following practical steps for implementation:

- Tool alignment: Select and align digital tools with specific course types (e.g., composition, music theory, performance analysis).
- Risk awareness: Address ethical considerations and foster critical engagement with AI-generated content and digital surveillance.
- Competence development: Embed digital literacy, media fluency, and AI-related self-regulation into teacher training curricula.
- Framework implementation: Adopt structured models for integrating digital ecosystems into educational modules.
- Ongoing evaluation: Establish continuous monitoring of the pedagogical effectiveness and potential limitations of digital instruments.

Finally, the Ukrainian case provides unique insights into how digital transformation can be applied within complex socio-political contexts. We believe this contribution will support further research, policy development, and innovation in the field of music education.

References

[1] S. Hallam, E. Himonides, "The power of music: An exploration of the evidence", Open Book Publishers, 2022. [Online]. Available: https://www.openbookpublishers.com/books/10.11647/obp.0292. [Accessed: Jul. 11, 2022].

[2] V. Vyshynskyi, I. Yahodzynska, "Distance Learning for Music Disciplines in Higher Education: Challenges and Prospects", Society. Integration. Education, Proceedings of the International Scientific Conference, 3, 585-598. 2017. [Online]. Available: https://journals.rta.lv/index.php/SIE/article/view/2382. [Accessed: May. 26, 2017], https://doi.org/10.17770/sie2017vol3.2382.

[3] M. M. Kachur, I. S. Synevych, M. A. Zhyshkovych, L. P. Stepanova, I. S. Synevych, "Digital educational space in the professional training of a musical art teacher", Revista de la Universidad del Zulia, 12 №35, p. 160-180, 2021. [Online]. Available: https://produccioncientificaluz.org/index.php/rluz/article/view/37047/40221. [Accessed: Sep. 01, 2021], http://dx.doi.org/10.46925//rdluz.35.10.

[4] E. Shevtshenko, R. Maas, T. Karaulova, I. Dembovska, and A. Truver, "Digsm 4.0 Curriculum Lifecycle Based on Component Organised Learning Method", ETR, vol. 2, pp. 203–208, Jun. 2023. [Online]. Available: https://journals.rta.lv/index.php/ETR/article/view/7311. [Accessed: Jun. 13, 2023], https://doi.org/10.17770/etr2023vol2.7311.

[5] J. F. Merchán Sánchez-Jara, S. González Gutiérrez, J. Cruz Rodríguez, B. Syroyid, "Artificial Intelligence-Assisted Music Education: A Critical Synthesis of Challenges and Opportunities", Education Sciences, 14(11), 1171, 2024. [Online]. Available: https://www.mdpi.com/2227-7102/14/11/1171. [Accessed: Oct. 28, 2024], https://doi.org/10.3390/educsci14111171.

[6] L. Cuervo, C. Bonastre, C. Camilli, D. Arroyo, D. García, "Digital Competences in Teacher Training and Music Education via Service Learning: A Mixed-Method Research Project", Educ. Sci. 2023, 13, 459, 2023. [Online]. Available: https://www.mdpi.com/2227-7102/13/5/459. [Accessed: Apr. 23, 2023], https://doi.org/10.3390/educsci13050459.

[7] A. Khilya, O. Kolosova, T. Kronivets, and I. Sarancha, "Features of Synchronous and Asynchronous E-Learning on the Example of Teaching the European Experience of Social Inclusion", ETR, vol. 2, pp. 410–416, Jun. 2024. [Online]. Available: https://journals.rta.lv/index.php/ETR/article/view/8074. [Accessed: Jun. 22, 2024], https://doi.org/10.17770/etr2024vol2.8074.

[8] T. Koval, Oliinyk N., T. Kryvosheya, and A. Khilya, "Application of Gamification in Higher Education: Training of Early Childhood and Primary Education Teachers in Ukraine", ETR, vol. 2, pp. 183–187, Jun. 2024. [Online].

Available: https://journals.rta.lv/index.php/ETR/article/view/8051. [Accessed: Jun. 22, 2024], https://doi.org/10.17770/etr2024vol2.8051.

[9] LI, Na, "Combination of blockchain and AI for music intellectual property protection", Computational intelligence and neuroscience, vol. 2022, no 1, p. 4482217, 2022. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1155/2022/4482217. [Accessed: Apr. 28, 2022], https://doi.org/10.1155/2022/4482217.

[10] J. Merchán Sánchez-Jara, S. Ramos Ahijado, J. C. Montoya Rubio, "Educational ecosystems for music practice in the Social Web environment: a systematic literature review", Revista de Investigación Educativa, 40(2), pp. 565-587, 2022. [Online].Available:https://revistas.um.es/rie/article/view/477721.[Accessed:Jul.01,2022],https://doi.org/10.6018/RIE.477721.

[11] N. Pattananon, P. Pongvatnanusorn, K. Gularnupong, K. Niramittham, "Pedagogical Innovations In Advanced Music Education", Educational Administration: Theory and Practice, 30(4), 8334–8337, 2024. [Online]. Available: https://kuey.net/index.php/kuey/article/view/2727/. [Accessed: Apr. 30, 2024].

[12] J. F. M. Sánchez-Jara, S. G. Gutiérrez, S. O. Migueláñez, M. A. G. Malheiro, "Digital platforms for music production (DAW): educational innovation from music teacher training: Plataformas digitales de producción musical (DAW): innovación educativa desde la formación docente del profesorado de música", Revista Electrónica de LEEME, (52), 53-72, 2023. [Online]. Available: https://turia.uv.es//index.php/LEEME/article/view/27178. [Accessed: Dec. 04, 2023], https://doi.org/10.7203/LEEME.52.27178.

[13] O. Vindaca, A. Abolina, L. Danilane, "Transforming Higher Education in the Era of Artificial Intelligence Chat Tools: Case Study", ETR, vol. 2, pp. 310–316, Jun. 2024. [Online]. Available: https://journals.rta.lv/index.php/ETR/article/view/8014. [Accessed: Jun. 22, 2024], https://doi.org/10.17770/etr2024vol2.8014.

[14] R. Crawford, "Rethinking teaching and learning pedagogy for education in the twenty-first century: blended learning in music education", Music Education Research, 19(2), 195-213, 2017. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/14613808.2016.1202223. [Accessed: Jul. 01, 2016], http://dx.doi.org/10.1080/14613808.2016.1202223.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 145-149

Modeling the Distribution of Lake Reeds Using GIS

Peter Grabusts
Rezekne Academy of Riga Technical University
Rezekne, Latvia
peteris.grabusts@rta.lv

Jurijs Musatovs
Rezekne Academy of Riga Technical University
Rezekne, Latvia
jurijs.musatovs@rta.lv

Ērika Teirumnieka
Rezekne Academy of Riga Technical University
Rezekne, Latvia
erika.teirumnieka@rta.lv

***Abstract*— So far, no significant modeling of reed biomass availability or assessment of the sustainability of reed products based on life cycle analysis has been conducted in Latvia. Nevertheless, these aspects are crucial for the development of reed-based products, as they help evaluate their market potential and overall socio-economic and environmental impact. This work aims to establish a methodology for modeling the extent of available reed distribution to forecast its future availability, as the availability of reed biomass is a vital prerequisite for utilizing this resource in the national economy. The novelty of this research lies in predicting reed areas based on existing historical data. The modeling is performed using GIS and satellite data.**

Keywords— Reeds, modeling, renewable resources, satellite data, QGIS.

I. Introduction

Reed (*Phragmites australis*) [1] is a widespread plant in Latvia, which has so far been considered mainly as a nuisance due to its rapid spread. The area of reeds continues to increase, therefore reed cutting is carried out to limit overgrowth in waterbodies. There is a large amount of reed biomass available in lakes, which has so far been an undervalued renewable resource. Although the availability and potential of reed biomass are large, now reeds are used in Latvia in small quantities, mainly in construction for the production of roofing materials.

The reed and rush belt on the coast reduces the impact of surface runoff on the lake, especially if the coastal belt is wide. The surface vegetation prevents the rapid entry of nutrients into the middle part of the lake. In turn, mowing of already grown reeds removes nutrients from the lake that are in the reed stalks, and as the new reeds grow, they consume nutrients from the coastal soil and water, rather than the decomposition products of the old reeds. If the reeds were not mowed but uprooted, then the positive/negative impact of this process should be considered more seriously.

Along with economic development, the demand for renewable energy is increasing, due to their longevity and low pollution compared to fossil energy resources. One of the most widely used types of renewable energy is biomass. Now, the demand is focused on the use of various non-traditional types of biomass–cultivated energy plants, wood residues, as well as the use of lake reeds. With the increasing prices of fossil energy resources and the pollution caused by using fossil resources, interest in the possibilities of using local biomass in energy supply is growing. Consequently, the issue of rational use of reed resources is being raised.

In literature sources, the properties of reeds are described using very different data. For example, the amount of reed biomass obtained when mowing reeds in winter varies from 3 to 30 t/ha [2].

To determine the possibilities of reed use, it is very important to determine the area of reeds in a particular lake and to detect changes in reed areas to predict the potential dynamics of increase or decrease. In such a situation, the use of GIS is necessary [3] – [6], which allows for comparing satellite data for different periods, calculating reed areas in a specific reference period, and predicting the trend of changes in reed areas.

The work aims to develop a methodology for determining reed areas in a specific lake to predict changes in the area and predict changes in the foreseeable period. In Latvia, such studies have only been carried out in determining reed areas in a fixed period without forecasting capabilities [2].

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8619
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

II. Materials and Methods

A. Study Object

The object of the research is Lake Rāzna (see Fig. 1) - the second-largest lake in Latvia, the largest by volume [7].

The lake's characteristic parameters are shown in Table 1.



Fig. 1. Lake Rāzna.

TABLE 1 LAKE CHARACTERISTIC

Characteristic	Parameter
Coordinates	56°19′N 27°27′E
Area of water surface	5,756.4 hectare
Mean depth	7.0 metre(s)
Maximum depth	17.0 metre(s)
volume	405.000 million solid metres
Length of lakeshore line	43.5 kilometre
Maximum length	12.10 kilometre
Maximum width	7.00 kilometre
Average altitude (above sea level)	163.40 metre(s)
Maximum altitude (above sea level)	163.50 metre(s)

The most important threats to the lake are overgrowth and subsequent swamping of the shores, which is combated by cutting and removing reeds, and erosion of steep shores — both natural and caused by economic and tourist pressure.

B. Satellite Data

In our research, we used Copernicus Sentinel satellite data, which is currently the best open-access data. Their resolution of 10 m/pixel is sufficient for assessing various changes.

Copernicus is the Earth observation component of the European Union's Space Programme, which looks at our planet. It offers information services derived from Earth observation satellites [8].

The vast amount of global data from satellites provides information to help service providers, government agencies, and other international organizations extract and analyze information. The information services are free and freely available to users.

The Copernicus project is based on a series of satellites (Sentinels) that carry out a huge number of observations of the Earth's ecosystem [9]. Copernicus' technological capabilities, especially in terms of availability and accessibility, have made Copernicus the most popular provider of space data in the world.

Sentinel satellites are specially designed for the Copernicus program. Sentinel 1, 2, 3, and 6 are dedicated satellites, while Sentinel 4 and 5 are instruments mounted on EUMETSAT weather observation satellites. We used Sentinel 2 satellite data to obtain data on lakes. The lake data was then processed using QGIS [10].

QGIS is free and open-source geographic information system (GIS) software. It is a powerful cartographic and geospatial data processing tool with extensive plugin support. QGIS allows to creation of maps using raster or vector layers and supports many formats using open-source libraries.

C. Classification Methods

Once a sufficiently high-quality image of the lake has been obtained and prepared, object selection for classification must be performed to distinguish reed areas.

We chose the following classification of objects and their designations (see Fig.2).

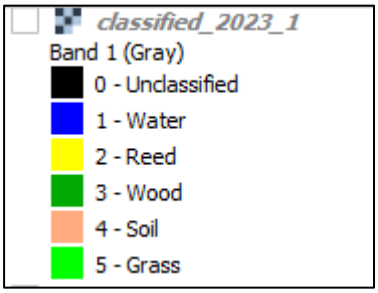


Fig.2. Classification of objects (legends).

We experimentally selected two classification methods to determine the most suitable and accurate for testing our methodology: Random Forest and Minimum Distance algorithms.

A decision tree method can be used to predict the reed area, which involves selecting machine learning algorithms and setting parameters based on training samples. A decision tree is created, in which each function is represented by a node, the method predicts the target variable and provides a simple interpretation option. CHAID [11] is one of the most common types of decision trees used, the CHAID algorithm splits the nodes to obtain chi-square values. The chi-square value is the difference between the standard, expected scenario, and the actual results observed in the data. The maximum chi-square value is the most statistically significant result in the

CHAID decision tree or the strongest relationship between the two variables from the found chi-square values.

Random Forest is a method of creating decision trees for classification purposes [12].

The Minimum Distance algorithm (Dijkstra's algorithm) is an algorithm for finding the shortest paths between nodes in a weighted graph. It can be used to find the shortest paths from a source vertex to all other vertices in a weighted graph. The minimum distance calculation is a statistical method for fitting a model to data, which is also used for classification purposes [13].

III. Results and Discussion

The research methodology is based on the following sequence of actions:

- we find a suitable lake map with 5% cloudiness for a specific time period with the help of Copernicus;
- we identify appropriate objects for classification purposes in the QGIS environment;
- we select the classification algorithm from the Semi-automatic options;
- we perform classification and analyze the results obtained.

The experimental base was the maps of Lake Rāzna in the years 2020, 2021, 2023, and 2024 (in June) when the reed growth had ended.

Thus, we will have the chance to compare the experiment's results with data from [2], which estimated that in 2008, the reed area constituted approximately 4 percent of the water surface area.

Initial settings for the Random Forest algorithm: number of trees:2000. (Legends from Fig.2.)

Results for 2020 (see Fig. 3 and Table 2).

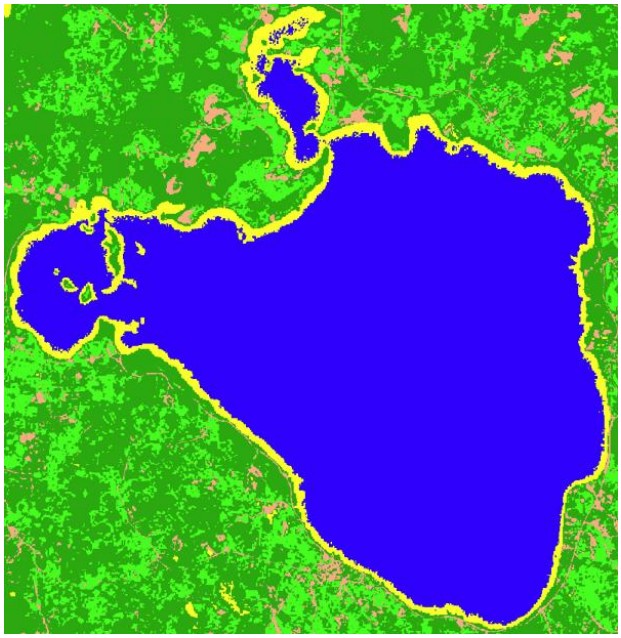


Fig. 3. Lake Rāzna (year 2020).

Table 2 Classification Results (year 2020)

Raster value	Pixel Sum	Percentage %	Area (m^2)	Area (hectare)
1-Water	539828	6.15	53982800	5398.28
2-Reed	315912	3.60	31591200	3159.12
3-Wood	5676862	64.65	567686200	56768.62
4-Soil	535911	6.10	53591100	5359.11
5-Grass	1712223	19.50	171222300	17122.23

Results for 2021 (see Fig. 4 and Table 3).

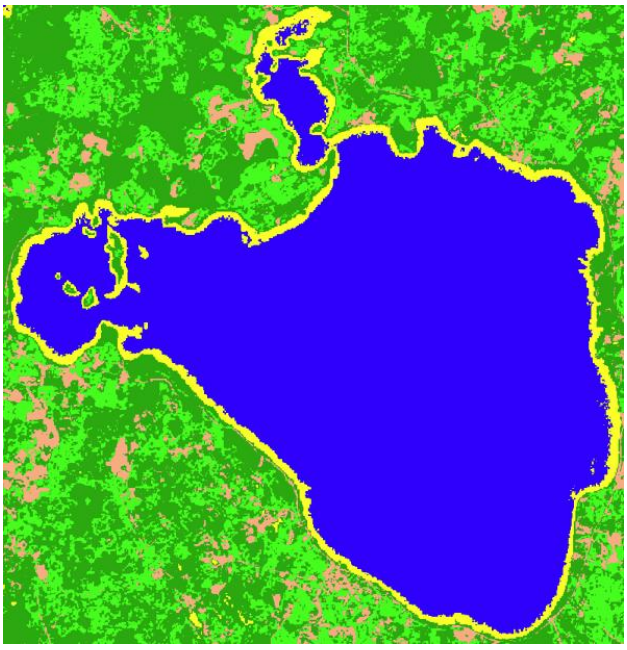


Fig. 4. Lake Rāzna (year 2021).

TABLE 3 CLASSIFICATION RESULTS (YEAR 2021)

Raster value	Pixel Sum	Percentage %	Area (m^2)	Area (hectare)
1-Water	542226	6.18	54222600	5422.26
2-Reed	259815	2.96	25981500	2598.15
3-Wood	5108106	58.17	510810600	51081.06
4-Soil	687772	7.83	68777200	6877.72
5-Grass	2182817	24.86	218281700	21828.17

Results for 2023 (see Fig. 5 and Table 4).

TABLE 4 CLASSIFICATION RESULTS (YEAR 2023)

Raster value	Pixel Sum	Percentage %	Area (m^2)	Area (hectare)
1-Water	715762	8.15	71576200	7157.62
2-Reed	288582	3.29	28858200	2885.82
3-Wood	4576958	52.12	457695800	45769.58
4-Soil	1217884	13.87	121788400	12178.84
5-Grass	1981550	22.57	198155000	19815.5

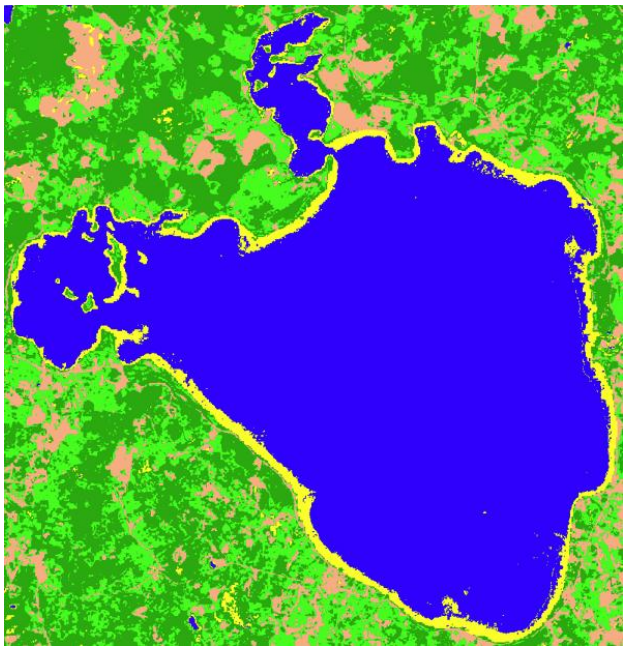


Fig. 5. Lake Rāzna (year 2023).

Results for 2024 (see Fig. 6 and Table 5).

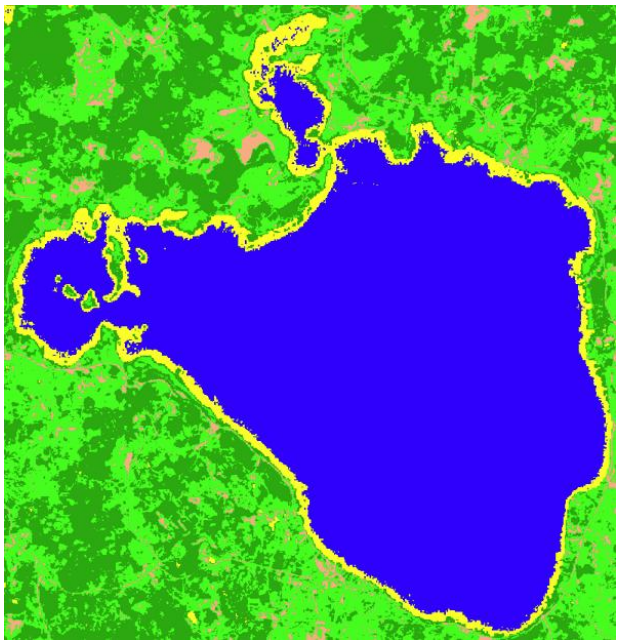


Fig. 6. Lake Rāzna (year 2024).

TABLE 5 CLASSIFICATION RESULTS (YEAR 2024)

Raster value	Pixel Sum	Percentage %	Area (m^2)	Area (hectare)
1-Water	529140	6.03	52914000	5291.40
2-Reed	266918	3.04	26691800	2669.18
3-Wood	4599805	52.39	459980500	45998.05
4-Soil	412493	4.70	41249300	4124.93
5-Grass	2972380	33.85	297238000	29723.80

A summary of the reed area in the lake is shown in Table 6.

TABLE 6 REED ARE BY YEAR

Year	Area (hectare)	Percentage %
2020	3159.12	3.60
2021	2598.15	2.96
2023	2885.82	3.29
2024	2669.18	3.04

This tabular data allows us to make an initial simple prediction (see Fig. 7).

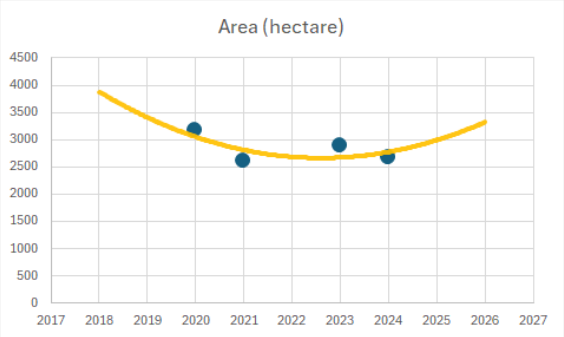


Fig. 7. Reed area prediction graph.

IV. CONCLUSIONS

This work is aimed to develop a methodology for identifying reed areas in lakes. Lake maps were taken from the Copernicus Sentinel database. Then the maps were processed in the QGIS environment – known data objects, such as water, wood, soil, grass, and reeds, were identified. The more precisely these objects are described, the higher the quality of the classification. The Random Forest algorithm performed very well in reed classification. The results of the Minimum Distance algorithm were inconclusive, so they were not included in the analysis of the results. A large amount of time had to be spent on the selection of satellite maps, because even in summer in Latvia it is very cloudy, therefore the selection of lake maps is of great importance in terms of data quality. The study showed that the percentage of the reed area of Lake Rāzna correlates with the studies conducted by other scientists, thus the proposed model has prospects for further development. It is planned to continue expanding this model with additional objects to be classified, to develop a more accurate prediction procedure. It is also planned to evaluate the amount of reed biomass depending on the reed areas. The availability of reed biomass is an essential prerequisite for the use of this resource in the national economy as a renewable resource.

V. ACKNOWLEDGMENTS

This research was funded by grant number RTU-PA-2024/1-0077, “Towards a sustainable bioeconomy: assessing reed biomass potential and applications (ReedREvolution)”.

REFERENCES

[1] “Plant family,” [Online] Available: https://www.britannica.com/plant/Poaceae [Accessed: Feb. 20, 2025].

[2] E.Čubars and G. Noviks, “Influence of Different Factors on Productivity of Reed Growths,” Environment. Technology. Resources, Proceedings of the 9th International Scientific and Practical Conference. Volume 1, Rezekne, Latvia, 2013. https://doi.org/10.17770/etr2013vol1.801

[3] E.Tiškus, D.Vaičiūtė, M.Bučas, and J. Gintauskas, “Evaluation of common reed (Phragmites australis) bed changes in the context of management using earth observation and automatic threshold,” European Journal of Remote Sensing, 2022. https://doi.org/10.1080/22797254.2022.2161070

[4] L. Sciuto, F. Licciardello, A.C. Barbera, and G. Cirelli, “A GIS - based multicriteria decision analysis to reduce riparian vegetation hydrogeological risk and to quantify harvested biomass (Giant reed) for energetic retrieval,” Ecological Indicators, Volume 144, November 2022, https://doi.org/10.1016/j.ecolind.2022.109548

[5] S. Baier, N.C. Meneses, J. Geist, and T.Schneider, “Assessment of Aquatic Reed Stands from Airborne Photogrammetric 3K Data,” Remote Sens. 2022, 14(2), 337, https://doi.org/10.3390/rs14020337

[6] H. Runkui and L.Yuqin, “Application of remote sensing technique to the investigation on reed resources of Bosten Lake,” Chinese Geographical Science, Volume 2, pages 266–276, (1992), https://doi.org/10.1007/BF02664604

[7] “Latvian lakes database.” [Online] Available: https://www.ezeri.lv/database/2196/ [Accessed: Feb. 20, 2025].

[8] “Copernicus project,” [Online] Available: https://www.copernicus.eu/en [Accessed: Feb. 20, 2025].

[9] “SentiWiki Home Page,” [Online] Available: https://sentiwiki.copernicus.eu/web/sentiwiki [Accessed: Feb. 20, 2025].

[10] “QGIS project,” [Online] Available: https://qgis.org/project/overview/ [Accessed: Feb. 20, 2025].

[11] C.Wells, “A guide to CHAID: a decision tree algorithm for data analysis,” [Online] Available: https://www.adience.com/blog/how-to/a-guide-to-chaid-a-decision-tree-algorithm-for-data-analysis/ [Accessed: Feb. 20, 2025].

[12] L. Breiman, “Random Forests. Machine Learning,” 45(1), 5–32, 2001. https://doi.org/10.1023/A:1010933404324

[13] F.Li and R.Klette, Euclidean Shortest Paths: Exact or Approximate Algorithms, Springer, 2011.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 151-156

The Role of Generative Artificial Intelligence in Programmer Training: Opportunities and Challenges

Stanka Hadzhikoleva
Faculty of Mathematics and Informatics
University of Plovdiv Paisii Hilendarski
Plovdiv, Bulgaria
stankah@uni-plovdiv.bg

Emil Hadzhikolev
Faculty of Mathematics and Informatics
University of Plovdiv Paisii Hilendarski
Plovdiv, Bulgaria
hadjikolev@uni-plovdiv.bg

Todor Rachovski
Faculty of Mathematics and Informatics
University of Plovdiv Paisii Hilendarski
Plovdiv, Bulgaria
todormr@gmail.com

Ivan Ivanov
Faculty of Mathematics and Informatics
University of Plovdiv Paisii Hilendarski
Plovdiv, Bulgaria
ivanivanov1040@gmail.com

***Abstract*—Artificial intelligence has rapidly entered people's daily lives and has innovated many traditional models by integrating AI technologies. The need for changes in educational practices has come to the forefront. This article outlines various possibilities for using generative artificial intelligence in programming education. Different examples are presented, including code generation, debugging and optimization, documentation and commenting, automated testing, conversion between different programming languages, and more. Additionally, some risks and limitations are discussed.**

***Keywords*—AI in education, AI in programmer training, generative AI in programming education, programming with AI.**

I. INTRODUCTION

Generative artificial intelligence (GenAI) has rapidly entered the daily lives of part of society. It has provided many different opportunities for optimizing activities traditionally performed by highly qualified specialists. Many AI-powered chatbots, such as ChatGPT, Gemini, Llama, Claude, Mistral, Cohere, Reka, DeepSeek, and others, are easy to use by anyone and offer free versions. They have a wide range of applications and can be used for automated content creation, performing calculations and analyses, language translation, code generation, image creation, information retrieval, and much more.

GenAI has also entered the field of education, presenting educators with numerous challenges. Some have welcomed the unexpected opportunities to support learning and optimize their work, while others have expressed concerns about the potential risk of reducing independent thinking and the development of higher-order thinking skills.

Tools like GitHub Copilot, ChatGPT, and other AI-powered assistants are transforming the way software developers write code, test it, debug, and optimize their work. Software companies are now seeking professionals who can effectively use AI tools for software development and task automation. To remain competitive in the job market, programming students must not only master traditional coding methods but also learn to work efficiently with AI tools.

AI is not a replacement for human thinking but rather a tool that can optimize various activities. For this reason, the education of future developers and software engineers must be innovated to include the study of AI's applications in software production.

This article explores some ways GenAI can be used to solve various programming tasks. Its goal is to provide educators with ideas on how to enrich the curriculum to help students develop specific skills for working with AI.

Scientific literature describes numerous studies on how GenAI is used in programming education and its impact on learning and academic outcomes.

Becker and colleagues open a discussion among computer science educators on how to integrate AI tools into programming education [1]. They argue that the rapid

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8608
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

and easy access to these tools has caught educators unprepared and surprised by the significant impact GenAI has on the learning process. Therefore, it is an urgent need to reconsider educational practices and adapt teaching methods to align with new technologies.

Wermelinger evaluates Copilot's ability to generate code and conducts a qualitative analysis of the generated suggestions to identify its limitations [2]. He shares insights from using Copilot for various tasks, including code explanation, test generation, and debugging. He emphasizes that educators need to be aware of Copilot's capabilities to adapt their teaching methods to AI-powered programming assistants.

In [3], a study is presented on Copilot's ability to generate and reproduce correct and efficient solutions for fundamental algorithmic problems. The research evaluates its performance and functionality in solving core computer science problems, such as sorting and implementing data structures. The authors compare Copilot's solutions with those provided by human programmers across various programming tasks. The findings indicate that Copilot successfully generates solutions for nearly all fundamental algorithmic problems. However, a significant drawback is that the chatbot struggles to combine multiple methods to construct comprehensive solutions. The comparison between Copilot and human programmers reveals that human programmers produced more correct solutions than Copilot. Additionally, the incorrect solutions generated by Copilot required less effort to fix compared to human-made errors.

In [4], a study is presented on the use of ChatGPT in programming and programming education. As part of the Object-Oriented Programming II course, students were assigned weekly project tasks in which they were allowed to use ChatGPT. A survey was conducted to gather students' opinions on the experience. According to the students, the main benefits of using ChatGPT in programming education include providing quick and mostly accurate answers to questions, improving thinking skills, facilitating the debugging process, and increasing confidence in solving programming tasks. However, the students also identified key drawbacks, such as the risk of developing laziness, ChatGPT’s inability to answer certain questions, and the provision of incomplete or inaccurate responses. Additionally, they expressed professional concerns about the future of the programming profession.

Liu and colleagues share their experience using AI tools in programming education. They provided students with a personal AI-powered virtual assistant that guided them toward solutions rather than offering direct answers [5]. The assistant supported learning by explaining code fragments, suggesting more readable and efficient code, and responding to both academic and administrative inquiries. Students provided positive feedback on the course, reporting an improved learning experience. The authors conclude that carefully integrated AI tools in education can significantly enhance the learning process by offering personalized support to students while allowing educators to focus on other pedagogical activities.

A study on how Codex performs on typical tasks from introductory programming courses is presented in [6]. To assess its effectiveness, the authors used real exam questions and compared its results with those of students who took the same exams under standard conditions. The findings show that Codex outperformed most students in terms of success rate. The study also examines the variability of Codex-generated solutions, revealing that identical input prompts often result in significantly different solutions, both in terms of algorithmic approach and code length. The authors conclude that AI offers numerous opportunities, including use for learning, assistance in problem-solving, and code analysis. However, they emphasize the need to address challenges such as potential misuse and the necessity of adapting teaching methodologies.

Yilmaz investigates how the use of ChatGPT in programming education affects students' computational thinking skills, self-efficacy in programming, and motivation toward the subject [7]. The researchers conducted an experiment in which students were randomly divided into two groups: an experimental group, which used ChatGPT during practical sessions, and a control group, which did not use it. After the training period, a survey was conducted to assess the impact. The analysis of the results showed that students in the experimental group demonstrated significantly higher computational thinking skills, programming self-efficacy, and motivation toward the subject compared to those in the control group.

Ouh and colleagues conducted a study aimed at evaluating the effectiveness of using the ChatGPT language model for generating solutions to programming tasks in an undergraduate Java course [8]. They analyzed ChatGPT-generated solutions for 80 different programming problems and compared them with correct solutions. The findings indicate that ChatGPT generates correct Java programming solutions characterized by high readability and well-structured organization. Additionally, the model is capable of suggesting alternative, memory-optimized solutions. However, a notable drawback is that ChatGPT struggles with tasks containing non-textual descriptions or requiring work with class files, often leading to invalid solutions. The authors emphasize the importance of educators understanding ChatGPT's limitations to make full use of its capabilities while minimizing the potential for misuse and academic dishonesty among students.

Savelka and colleagues investigate the ability of large language models (LLMs) to pass assessments in postgraduate-level Python programming courses [9]. The study evaluates GPT-4 on assessments of varying complexity, ranging from simple multiple-choice questions (without code) to complex programming projects with codebases distributed across multiple files – a total of 599 tasks. The authors find that GPT models have evolved to the point where they can effortlessly pass typical course

assessments. They caution that by using GenAI, students may be able to complete current standard programming assessments and achieve high scores with little effort.

The study presented in [10] aims to determine how effectively LLM models can identify issues in student-written code and provide adequate explanations. Two LLM models – OpenAI Codex and GPT-3.5 – were examined, and their generated responses were evaluated both quantitatively and qualitatively. The findings indicate that the advice provided by the models is often reasonable but not always accurate. A key drawback is that the models generally fail to identify all errors and produce a high number of false positives. They perform better at detecting logical issues in code than at handling output formatting requirements. Additionally, they tend to generate complete solutions even when explicitly instructed not to. In conclusion, the authors highlight the benefits of using LLMs in programming education. However, they also emphasize the unreliability of these models, noting that they make some of the same mistakes as students – particularly in formatting output according to the requirements of automated grading systems.

Lau and Guo conducted a study among university instructors teaching introductory programming courses [11]. They gathered educators' perspectives on how they plan to adapt their courses in the new reality of easy access to GenAI, ensuring that students continue to acquire knowledge effectively. The researchers interviewed 20 instructors from nine countries – nine women and eleven men. Their findings indicate that, in the short term, most educators are primarily concerned with taking immediate measures to prevent academic dishonesty. However, their long-term intentions vary. One group prefers to continue teaching programming in the traditional way – without AI involvement – while the other aims to integrate AI innovations into courses to better prepare students for the future job market.

A study on the opinions of professional software developers regarding the use of GenAI in software development was conducted by Bull and Kharrufa [12]. Based on their analysis of the results, they propose a vision for the future of education. They argue that educators should integrate GenAI technologies into the learning process rather than resist them. The authors also formulate pedagogical recommendations for incorporating AI into programming education.

Perkel provides advice on the effective use of ChatGPT in programming [13]. He emphasizes that despite its powerful capabilities, tools like ChatGPT are not as intelligent as they may seem and should be used with caution.

Su and Yang propose a theoretical framework called “IDEE” for integrating generative artificial intelligence into education [14]. The framework consists of four key components: Identifying desired learning outcomes, Determining the appropriate level of automation, Ensuring ethical considerations, and Evaluating effectiveness. The authors highlight the main advantages of this approach, including the potential for more personalized and efficient learning experiences for students, as well as faster and easier feedback for educators.

In [15], a significant issue related to the use of AI in programming education is discussed. In many cases, AI models can generate complete solutions to assigned tasks, potentially preventing students from developing essential creative and critical thinking skills. To address this challenge, the authors propose the Self-Regulated Learning Framework, which integrates the use of generative AI tools into the problem-solving process.

II. Materials and Methods

LLMs are a type of artificial neural networks specifically trained to understand and generate text in natural languages. They are complex models with many parameters that enable the modeling and analysis of intricate relationships between words and phrases in various textual contexts. These models are most commonly based on transformer architecture. They have a large number of parameters, on the order of billions, allowing them to analyze complex dependencies in text. They are trained on vast amounts of textual data from the internet, books, scientific articles, and other sources. Their learning process involves predicting the next word or phrase based on the preceding context.

LLMs can be used by programmers to optimize various activities. This includes code generation, debugging and optimization, documentation, testing, conversion between different programming languages, and more. Below, we will explore example prompts.

A. Code Generation

LLMs can automatically generate code based on textual descriptions or given requirements. This saves time and effort for routine tasks such as creating templates, standard functions, or data structures. Below are specific examples and prompts:

Generating a function for input validation: "Create a Python function that validates whether the given input is a number and falls within the range of 1 to 100."

Generating a REST API template: "Create a REST API template for user management with methods for adding, deleting, and editing users in Python using Flask."

Generating a class template: "Create a Java class for managing a library with methods for adding, removing, and searching for a book by title."

Generating a web form template: "Generate an HTML login form with fields for username and password and a login button."

Function for data processing: "Create a Python function that reads a list of numbers and returns a list of their square roots."

Class for managing a bank account: "Create a JavaScript class for a bank account with methods for depositing, withdrawing, and checking the balance."

Class for managing users in a system: "Create a C# class that represents a user in a system, with a name, email, and methods for changing the password and validating the email address."

B. Code Debugging and Optimization

LLMs can detect errors in code and suggest corrections and improvements. They can identify logical, syntactic, or semantic errors in the code. They can also enhance code performance by suggesting modifications using more efficient built-in functions or methods, as well as replacing recursive functions with iterative ones to improve performance.

Fixing a code error: "Find and fix the error in the following Python function that sorts a list of numbers in descending order: …"

SQL query optimization: "Optimize the following SQL query for faster execution on large tables: …"

Fixing and optimizing a recursive function: "Fix and optimize the following recursive function for calculating the factorial of a number in Python: …"

JavaScript code optimization: "Optimize the following JavaScript code for finding the maximum value in an array: …"

Fixing a logical error in code: "Find and fix the logical error in the following Java code, which is supposed to check whether a number is prime: …"

C. Documentation and Comments

Models can automate the creation of documentation by generating comments and explanations for functions, classes, and methods. This facilitates code maintenance and helps other programmers quickly understand its purpose and logic. Learners can take advantage of AI-generated comments that include: Brief explanations of the logic and steps in the code; Detailed descriptions of functions, classes, or methods, including their parameters, possible exceptions, and return values; Descriptions of complex algorithms or functionalities to improve understanding and maintainability, etc.

Adding comments to code: "Add comments to the following Python code that checks if a given string is a palindrome: …"

Generating documentation for a function: "Create documentation for the following Java function that calculates the sum of numbers in an array: …"

Adding documentation to a class: "Add documentation to the following JavaScript class for managing inventory in a store: …"

Generating documentation for API methods: "Create documentation for the API methods of the following Python REST API for user management: …"

Adding comments for a complex algorithm: "Add comments to the following Python code that implements the QuickSort algorithm: …"

D. Maintenance and Debugging

Other important activities that can be optimized with the help of LLMs are maintenance and debugging. Learners can ask questions about errors in their code that cause unexpected behavior to identify syntactic, logical, or semantic errors. They can also receive suggestions for improving the performance, efficiency, or security of their code.

Finding an error in Python code: "Identify and fix the error in the following Python function that calculates the factorial of a number: …"

Debugging an SQL query: "Why does the following SQL query return the error 'Ambiguous column name': …"

Debugging a logical error in JavaScript: "Find the logical error in the following JavaScript code, which is supposed to check if a number is even: …"

Debugging an application with an API request error: "Help me debug a 404 error I receive when trying to send a POST request to my Python Flask API: …"

Debugging an infinite loop: "Find and fix the cause of the infinite iterations in the following Python loop: …"

Debugging a memory issue in Java: "Optimize the following Java code that throws an OutOfMemoryError: …"

E. Automated Testing

LLMs can support automated testing in various ways. They are capable of generating tests that cover basic and edge cases for a given function or method, as well as creating tests for different API methods to ensure they function correctly. Learners can use them to generate tests with tools like Selenium for automating functional testing of web applications. LLMs can also be useful in error handling and exception processing, verifying different possible outputs and the code's response to various inputs.

Generating test cases for a Python function: "Create automated tests for the following Python function that calculates the square root of a given number: …"

Generating JUnit tests for a Java method: "Create JUnit tests for the following Java method that checks whether a given string is a valid email: …"

Generating automated tests for a REST API using Postman or pytest: "Create Postman tests for the API methods of the following Python Flask REST API for product management: …"

Generating automated tests for a web application using Selenium: "Create Selenium tests for a web application that includes a login form with username and password fields."

Generating unit test cases in C#: "Create Unit tests for the following C# method that calculates the area of a rectangle: …"

F. Conversion Between Programming Languages

LLMs can convert code from one programming language to another while adhering to the syntax rules of the target language. They can also translate language-specific libraries and methods into their equivalents in the target language. This is particularly useful for project migration or working in a multi-platform environment.

Converting a Python function to JavaScript: "Convert the following Python function that calculates the factorial of a number into JavaScript: …"

Converting a C# method to Python: "Convert the following C# method for calculating the average value of an array of numbers into Python: …"

Converting a JavaScript function to Java: "Convert the following JavaScript function that checks whether a number is prime into Java: …"

Converting a Java method to Python: "Convert the following Java method that sorts an array of numbers using the insertion sort algorithm into Python: …"

Converting a Python script to Bash: "Convert the following Python script that copies all .txt files from one directory to another into a Bash script: …"

G. Best Practices Recommendations

LLMs are capable of suggesting best practices for software design, architecture, and security, helping programmers create more reliable and secure code. Learners can receive specific advice and guidelines related to programming languages, software tools, or technologies. They can also gain insights into established practices for writing readable code, improving code organization, and managing projects more effectively.

Best practices for writing Python code: "What are the best practices for writing Python code?"

Best practices for designing a REST API: "What are the best practices for designing a REST API?"

Best practices for SQL query optimization: "What are the best practices for optimizing SQL queries?"

Best practices for web application security: "What are the best practices for ensuring security in web application development?"

Best practices for memory management in Java: "What are the best practices for memory management in Java?"

Best practices for working with Git: "What are the best practices for using Git in a team environment?"

H. Learning Support and Development

LLMs can serve as interactive learning tools, providing personalized advice and explanations on new technologies, programming languages, or concepts, accelerating the learning process. They are capable of: Explaining basic and advanced topics in programming and software development; Providing instructions and examples for learning new technologies and concepts; Clarifying important development tools and industry best practices, etc.

Learning a new programming language: "Explain the basics of programming in Rust for beginners."

Learning a new technology or library: "Explain the fundamentals of Docker and how to create my own container."

Learning best coding practices: "What are the best practices for writing secure JavaScript code?"

Support for advanced concepts: "Explain the concept of 'Dependency Injection' in the context of .NET Core."

Support for technical interview preparation: "How can I prepare for a front-end developer interview?"

Learning new development tools: "What are the essential Git commands, and how do I use them?"

III. Results and Discussion

The use of GenAI to optimize various activities in software development provides significant advantages for programmers. The ability to generate program code saves time spent writing code from scratch and accelerates the software production process. LLMs can offer different approaches to solving a given problem, contributing to more efficient solutions. The ability to quickly identify errors and optimize code improves the quality of software development. Identifying potential areas for improvement, removing redundant code, reducing complexity, and enhancing efficiency by using better algorithms or data structures are tasks typically performed by highly experienced specialists. The automated creation of various types of tests — unit tests, integration tests, and performance tests — improves test coverage and reduces the likelihood of errors and omissions.

Despite all the mentioned advantages, the use of LLMs in software development carries some risks and challenges. The following are considered the most significant:

- LLMs can generate code that, at first glance, appears correct but contains logical errors or does not meet the specifications. Programmers must carefully review the code to avoid bugs;
- LLMs can introduce biases through the data they were trained on, such as social, racial, gender, or cultural biases. This can reflect on the generated code, proposed solutions, or violate best practices;
- Using public platforms or cloud services with AI to process sensitive data may lead to data confidentiality issues. Therefore, it is necessary to apply mechanisms for anonymizing sensitive information, develop or adhere to established standards for personal data protection, such as GDPR;
- AI can be used maliciously, e.g., to create viruses or to discover vulnerabilities in software for hacking attacks or financial fraud. This highlights

the need for security regulations to prevent abuses of AI;

- Some LLM platforms require significant resources for training and use, which can be expensive for small and medium-sized companies;
- Automation of various tasks in software production leads to a reduction in jobs, which indirectly affects the entire economy.

Here, we should also note another significant risk – the development of dependence on artificial intelligence. Programmers may begin to rely too much on LLM in their work, which could reduce their ability to think critically and solve problems independently.

IV. Conclusion

Programmers are increasingly using LLMs such as ChatGPT, Gemini, Llama, Claude, Mistral, Cohere, Reka, DeepSeek, and others in their work. With their help, they optimize various activities in the software development process, including code generation, debugging and optimization, documentation, testing, conversion between different programming languages, and more.

With the advancement of these technologies, it is becoming increasingly important for students to learn how to use them effectively for more efficient programming. In addition to other benefits, LLMs can support learning and skill development by providing examples, explanations, and guidance for solving complex problems. The examples presented in this article illustrate only a small portion of the various ways GenAI can assist programmers.

References

[1] B. A. Becker, P. Denny, J. Finnie-Ansley, A. Luxton-Reilly, J. Prather, and E. A. Santos, "Programming is hard-or at least it used to be: Educational opportunities and challenges of AI code generation," in *Proc. 54th ACM Tech. Symp. Comput. Sci. Educ. V. 1*, Mar. 2023, pp. 500–506. https://doi.org/10.1145/3545945.3569759.

[2] M. Wermelinger, "Using GitHub Copilot to solve simple programming problems," in Proc. 54th ACM Tech. Symp. Comput. Sci. Educ. V. 1, Mar. 2023, pp. 172–178. https://doi.org/10.1145/3545945.3569830.

[3] A. M. Dakhel, V. Majdinasab, A. Nikanjam, F. Khomh, M. C. Desmarais, and Z. M. J. Jiang, "GitHub Copilot AI pair programmer: Asset or liability?" J. Syst. Softw., vol. 203, p. 111734, 2023. https://doi.org/10.1016/j.jss.2023.111734.

[4] R. Yilmaz and F. G. K. Yilmaz, "Augmented intelligence in programming learning: Examining student views on the use of ChatGPT for programming learning," Comput. Hum. Behav.: Artif. Humans, vol. 1, no. 2, p. 100005, 2023. https://doi.org/10.1016/j.chbah.2023.100005.

[5] R. Liu, C. Zenke, C. Liu, A. Holmes, P. Thornton, and D. J. Malan, "Teaching CS50 with AI: Leveraging generative artificial intelligence in computer science education," in Proc. 55th ACM Tech. Symp. Comput. Sci. Educ. V. 1, Mar. 2024, pp. 750–756. https://doi.org/10.1145/3626252.3630938.

[6] J. Finnie-Ansley, P. Denny, B. A. Becker, A. Luxton-Reilly, and J. Prather, "The robots are coming: Exploring the implications of OpenAI Codex on introductory programming," in Proc. 24th Australas. Comput. Educ. Conf., 2022, pp. 10–19. https://doi.org/10.1145/3511861.3511863.

[7] R. Yilmaz and F. G. K. Yilmaz, "The effect of generative artificial intelligence (AI)-based tool use on students' computational thinking skills, programming self-efficacy and motivation," Comput. Educ.: Artif. Intell., vol. 4, p. 100147, 2023. https://doi.org/10.1016/j.caeai.2023.100147.

[8] E. L. Ouh, B. K. S. Gan, K. Jin Shim, and S. Wlodkowski, "ChatGPT, can you generate solutions for my coding exercises? An evaluation on its effectiveness in an undergraduate Java programming course," in Proc. 2023 Conf. Innov. Technol. Comput. Sci. Educ. V. 1, Jun. 2023, pp. 54–60. https://doi.org/10.1145/3587102.3588794.

[9] J. Savelka, A. Agarwal, M. An, C. Bogart, and M. Sakr, "Thrilled by your progress! Large language models (GPT-4) no longer struggle to pass assessments in higher education programming courses," in Proc. 2023 ACM Conf. Int. Comput. Educ. Res. - Vol. 1, Aug. 2023, pp. 78–92. https://doi.org/10.1145/3568813.3600142

[10] A. Hellas, J. Leinonen, S. Sarsa, C. Koutcheme, L. Kujanpää, and J. Sorva, "Exploring the responses of large language models to beginner programmers' help requests," in Proc. 2023 ACM Conf. Int. Comput. Educ. Res. - Vol. 1, Aug. 2023, pp. 93–105. https://doi.org/10.1145/3568813.3600139

[11] S. Lau and P. Guo, "From 'Ban it till we understand it' to 'Resistance is futile': How university programming instructors plan to adapt as more students use AI code generation and explanation tools such as ChatGPT and GitHub Copilot," in Proc. 2023 ACM Conf. Int. Comput. Educ. Res. - Vol. 1, Aug. 2023, pp. 106–121. https://doi.org/10.1145/3568813.3600138.

[12] C. Bull and A. Kharrufa, "Generative artificial intelligence assistants in software development education: A vision for integrating generative artificial intelligence into educational practice, not instinctively defending against it," IEEE Softw., vol. 41, no. 2, pp. 52–59, 2024. https://doi.org/10.1109/MS.2023.3300574

[13] J. M. Perkel, "Six tips for better coding with ChatGPT," Nature, vol. 618, no. 7964, pp. 422–423, 2023. https://www.nature.com/articles/d41586-023-01833-0

[14] J. Su and W. Yang, "Unlocking the power of ChatGPT: A framework for applying generative AI in education," ECNU Rev. Educ., vol. 6, no. 3, pp. 355–366, 2023. https://doi.org/10.1177/20965311231168423.

[15] P. Prasad and A. Sane, "A self-regulated learning framework using generative AI and its application in CS educational intervention design," in Proc. 55th ACM Tech. Symp. Comput. Sci. Educ. V. 1, Mar. 2024, pp. 1070–1076. https://doi.org/10.1145/3626252.363082

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 157-163

Modeling the Process of Extracting Sensor Data from the Terrain Using Generalized Nets

Rosen Iliev
Bulgarian Defence Institute
"Prof. Tsvetan Lazarov"
Sofia, Bulgaria
r.iliev@di.mod.bg

Denislav Ushovski
Ministry of Defence of Bulgaria
Sofia,Bulgaria
d.ushovski@mod.bg

***Abstract* — The goal of the paper is to present an original Generalized Net model (GN-model) of the process of obtaining sensor data from the terrain, their analysis using artificial intelligence and their presentation in an operational center to support decision-making in crisis management. By using Generalized Nets, the aim is to create a general model of this process in order to achieve a better basis for research and future analyses of the complex relationships between subjects, objects and impacts in crisis management. To verify the presented GN-model, the simulation environment GN IDE was used, and some results from it are shown, related to the activation of transitions and movement between individual tokens in the net.**

Keywords* — *AI, GN-model, crisis management, modeling.

I. INTRODUCTION

Crisis management of various natures is a complex process requiring coordinated interaction between people, means and resources, which is usually carried out under complex working conditions and limited reaction time. The management team must have the necessary qualities and experience to make quick and efficient decisions in complex situations. However, it will need adequate information about the situation, the development of the crisis, the effect of the actions taken, etc. The more accurate and timely this information is, the closer the decisions made will be to the optimal ones for the given situation. Therefore, the process of obtaining sensor data from the area, photo and video images, etc. in real conditions, is of key importance for the successful analysis of the situation and making adequate decisions.

Recently, UAVs have been increasingly used to obtain data from the area. Their use has gained great popularity due to several main factors:

- they are easy to control and charge;
- they can carry equipment and cargo;
- they are relatively cheap.

With the improvement of electric batteries, which allow for a longer stay in the air, the miniaturization of electronic control components, as well as the development of artificial intelligence, it has become possible to create intelligent flying platforms that can choose the optimal route themselves, avoid obstacles, analyze the environment and make decisions in complex operating conditions. However, for transmitting data from the area using UAVs or ground (water) autonomous systems, good knowledge of the terrain is also required, which is essential for implementing stable communication for data transmission and remote control. Direct transmission of information from one point to another has a limited range, and the presence of obstacles and signal attenuation due to adverse passive or active effects greatly limits this distance and reduces it to several tens of kilometers. For this purpose, mobile stations can be used to relay data from drones and other sensor networks located in the area by connecting them to fixed networks, and from there to the crisis management operations center (see Fig. 1).

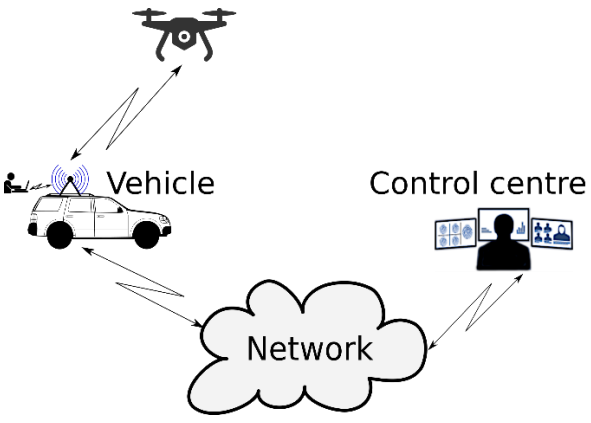


Fig. 1. Variant of using a field mobile station and a stationary network for transmitting sensor data [12].

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8602
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

The data transmission system, located on a mobile vehicle, is a field mobile station, which also includes an operator. The operator can perform primary data processing or transmit them via a stationary or radio relay network to a remote operational center for analysis and decision-making. Such a system can be used mainly in the assessment and prevention of natural disasters, accidents, fires, explosions with explosives, etc. UAVs, equipped with specialized sensors for environmental assessment, IR-cameras and other sensors, are gaining increasing popularity for obtaining important information in real time and for transmitting it to an operational center for crisis management. A large part of the data obtained from the area can be processed even before being sent to the operational center - one part in the UAVs, and the other - in the field mobile station.

The process of obtaining sensor data from the area is an important element of the overall process of supporting decision-making by the management team in the crisis operations center. In order to study this complex process, an original Generalized Net model (GN-model) is presented below, suitable for use as a basis for future analyses of the complex interactions between participating entities (personnel, staff, teams, etc.), objects (means, equipment, resources, etc.) and processes (impacts of external and internal factors) in crisis management. Generalized nets are a very good toolkit for modeling complex processes, providing convenient means for describing the participating elements in a wide class of tasks, processes and phenomena. They are based on the Theory of Generalized Nets by K. Atanassov [1], [2], [3], which he defined in 1982. For modeling different tasks, other types of nets can also be used, such as N-nets (a type of Petri nets), which are used, for example, in [13]. Other studies related to modeling and analysis can be found in [5], [7], [8], [10], [11], [14], [15]. More information about the possibilities of obtaining sensor data from the area, such as meteorological data, pollution levels, photo and video recording, etc.), using unmanned aerial vehicles, can be found in another publication by one of the authors [12].

II. MATERIALS AND METHODS

The model for obtaining data from the area using sensors can be described by a generalized net E in the following way: E = {Z1, Z2, Z3, Z4, Z5}, where

Z1 – situation awareness and preparation;

Z2 – obtaining data from the area;

Z3 – processing data at a field station and sending them to an operations center;

Z4 – analysis of data at an operations center;

Z5 – decision making and management.

The scheme of the generalized net E is shown in Fig. 2.

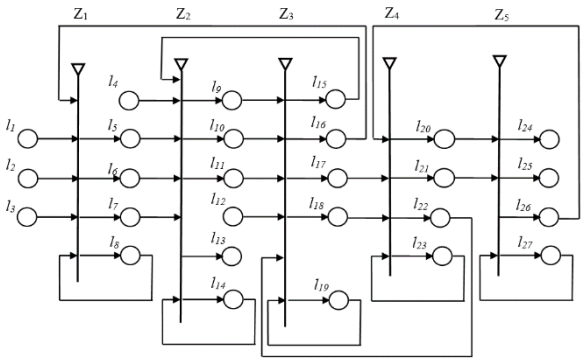


Fig. 2. Model of the process of obtaining sensor data from the area using a generalized net.

The tokens of the net E are:

α – subjects (personnel, experts, etc.), with the following characteristics: $X_\alpha(e^\alpha_{p1}, e^\alpha_{p2}, \ldots, e^\alpha_{pi}, \ldots, e^\alpha_{pk})$, where e^α_{pi} is the estimate of the i^{-th} parameter from k ($i \le k$) basic estimate parameters characterizing the subjective factor;

β – objects (technique, equipment, resources, etc.), with the following characteristics: $X_\beta(e^\beta_{q1}, e^\beta_{q2}, \ldots, ^\beta_{qi}, \ldots, e^\beta_{qn})$, where e^β_{qi} is the estimate of the i^{-th} object from n ($i \le n$) necessary ones;

γ – procedures (sequence of actions, documentation, etc.), with the following characteristics: X_γ ($e^\gamma_{v1}, e^\gamma_{v2}, \ldots, e^\gamma_{vi}, \ldots, e^\gamma_{vs}$), where e^γ_{vi} is the estimate of the i^{-th} type of procedure from s ($i \le s$);

λ – external factors (environmental impacts, escalation of the crisis, etc.), with the following characteristics: X_λ ($e^\lambda_{w1}, e^\lambda_{w2}, \ldots, e^\lambda_{wi}, \ldots, e^\lambda_{wt}$), where e^λ_{wi} is an estimate of the i^{-th} type of influencing external factor from t ($i \le t$);

ι – data (data obtained from UAVs, sensor data from the area, intelligence data, etc.), with the following characteristics): $X\iota(e^\iota_{h1}, e^\iota_{h2}, \ldots e^\iota_{hi}, \ldots, e^\iota_{hm})$, where e^ι_{hi} is an estimate of the availability and transfer of the necessary data from m ($i \le m$).

$\mathbf{e^\alpha_p}$, $\mathbf{e^\beta_q}$, $\mathbf{e^\gamma_v}$, $\mathbf{e^\lambda_w}$ and $\mathbf{e^\iota_h}$ are functions of the generalized net, whose estimation parameters can include values in the following intervals: {0,1} – for integer values; [0,1] – for normal fuzziness, or [0,1] × [0,1] – for intuitionistic fuzziness.

By applying the Theory of Intuitionistic Fuzzy Sets of K. Atanassov [4], a more accurate estimation of the parameters of the individual tokens in the net can be achieved, using intuitionistic fuzzy estimates. For the generalized net model presented here, the estimates $\mathbf{e_k}^{\{\alpha, \beta, \gamma, \lambda, \iota\}}$ look like this:

$\mathbf{e_j}^{\{\alpha, \beta, \gamma, \lambda, \iota\}} = \{<\mu_j, \nu_j> (\mu_j, \nu_j \in R \ \& \ \mu_j \ge 0 \ \& \ \nu_j \ge 0 \ \& \ \mu_j + \nu_j \le 1)\}$, for j=1, …, k,

where:

μ_j and ν_j are two functions: μ_j for membership and ν_j for non-membership, which belong to the real unit interval [0, 1] and whose sum belongs to the same interval, as well.

These functions can be used to express the degree of certainty /confidence/ (μ_j) or the degree of uncertainty (ν_j) regarding the estimate of a given parameter of the system;

$\pi_j = 1 - \mu_j - \nu_j$ – degree of uncertainty /ambiguity/ regarding the estimation of the values of a given parameter.

The description of the individual transitions is as follows:

$$Z_1 = <\{l_1, l_2, l_3, l_8, l_{16}\}, \{l_5, l_6, l_7, l_8\}, r_1, M_1, \vee(l_1, l_2, l_3, l_8, l_{16})>,$$

where

l_1 – initial input position, into which α-tokens (subjects - personnel, staff) enter, with characteristics $X_\alpha(e^\alpha_{p1}, e^\alpha_{p2}, \ldots, e^\alpha_{pi}, \ldots, e^\alpha_{pk})$;

l_2 – initial input position, into which β-token (objects - machinery, equipment, resources, etc.) enter, with characteristics $X_\beta(e^\beta_{q1}, e^\beta_{q2}, \ldots, ^\beta_{qi}, \ldots, e^\beta_{qm})$, which initiate the individual elements of the objects and the environment;

l_3 – initial input position, into which γ-token (procedures) with characteristics enter X_γ ($e^\gamma_{v1}, e^\gamma_{v2}, \ldots, e^\gamma_{vi}, \ldots, e^\gamma_{vn}$), who initiate the individual rules of action, work guidance documents, etc.;

l_4 – transition position Z_2 (data acquisition from the terrain), which receives ι-tokens (data) obtained from various sources - from UAVs, from sensors located on the terrain (for movement, temperature, pressure, pollution, vibrations, etc.), from ground cameras in the visible and infrared range, from satellite images, etc.;

l_5 – position to transition Z_2 (data acquisition), where α-tokens (personnel, personnel) arrive;

l_6 – position where β-tokens arrive (technique, equipment, tools, resources, etc.);

l_7 – position where γ-tokens arrive (procedures, guidance documents, etc.);

l_8 – position where α-, β- and γ-tokens arrive, in the process of situation awareness and preparation for work).

$r_1 =$

	l_5	l_6	l_7	l_8
l_1	F	F	F	T
l_2	F	F	F	T
l_3	F	F	F	T
l_8	$W_{8,5}$	$W_{8,6}$	$W_{8,7}$	$W_{8,8}$
l_{16}	F	F	F	T

T – allowed transition (True), F – forbidden transition (False)

The predicates $W_{x,y}$ are the following:

$W_{8,5}$ – "there are suitable α-tokens (subjects – personnel, staff) after analyzing the situation (in position l_8), which are entering Z_2 (obtaining data from the area);

$W_{8,6}$ – "there are suitable β-tokens (objects – machinery, equipment, tools, resources, etc.), which are necessary for transition Z_2";

$W_{8,7}$ – "there are suitable γ-tokens tokens (procedures – sequence of actions, guiding documents, etc.), which are necessary for the functioning of transition Z_2";

$W_{8,8}$ – "there are tokens received for analysis and preparation".

$M_1 =$

	l_5	l_6	l_7	l_8
l_1	0	0	0	N
l_2	0	0	0	N
l_3	0	0	0	N
l_8	$m_{8,5}$	$m_{8,6}$	$m_{8,7}$	$m_{8,8}$
l_{16}	0	0	0	N

N – the maximum number of tokens specified for the transition;

$m_{8.5}$, $m_{8.6}$, $m_{8.7}$, $m_{8.8}$ – from 0 to the maximum allowed number of tokens for evaluation of the transition Z_1 ($m \leq N$).

$Z_2 = <\{l_4, l_5, l_6, l_7, l_{14}, l_{15}\}, \{l_9, l_{10}, l_{11}, l_{13}, l_{14}\}, r_2, M_2, \vee (l_4, l_5, l_6, l_7, l_{14}, l_{15})>$,

where

l_4 – initial input position, where ι-tokens (data) arrive, with characteristics: $\iota(e^\iota_{h1}, e^\iota_{h2}, \ldots e^\iota_{hi}, \ldots, e^\iota_{hm})$, which are obtained from various sources – from UAVs, sensor data from the area, intelligence data, etc.;

l_9 – position to transition Z_3 (data processing in a field station), where ι-tokens (data carriers) arrive;

l_{10} – position to transition Z_3, where successful α-tokens (personnel, personnel, etc.) or β-tokens (equipment, equipment, resources, etc.) arrive;

l_{11} – position to transition Z_3, where successful γ-tokens (procedures, guidance documents, etc.) arrive;

l_{13} – position, where unsuccessful α-, β-, γ- or ι-tokens arrive;

l_{14} – position where the token participating in the transition enter, in waiting or processing mode.

l_{15} – position where α-, β-, γ- or ι- token coming from transition Z_3, requiring processing, enter.

$r_2 =$

	l_9	l_{10}	l_{11}	l_{13}	l_{14}
l_4	F	F	F	F	T
l_5	F	F	F	F	T
l_6	F	F	F	F	T
l_7	F	F	F	F	T
l_{14}	$W_{14,9}$	$W_{14,10}$	$W_{14,11}$	$W_{14,13}$	$W_{14,14}$
l_{15}	F	F	F	F	T

$W_{14.9}$ – "there are suitable (after analysis) α- and β-token that are needed for transition Z_2";

$W_{14.10}$ – "there are suitable γ-token that are needed for transition Z_3";

$W_{14.11}$ – "there are suitable ι-token that go to transition Z_3"; after processing they return to transition Z_1"; and coming from Z_2;

$W_{14.13}$ – "there are unsuitable token after analysis of the situation" (they are discarded);

$W_{14.14}$ – "there are incoming token that need processing".

$M_2 =$

	l_9	l_{10}	l_{11}	l_{13}	l_{14}
l_4	0	0	0	0	N
l_5	0	0	0	0	N
l_6	0	0	0	0	N
l_7	0	0	0	0	N
l_{14}	$m_{14,9}$	$m_{14,10}$	$m_{14,11}$	$m_{14,13}$	$m_{14,14}$
l_{15}	0	0	0	0	N

$m_{14,9}$, $m_{14,10}$, $m_{14,11}$ and $m_{14,13}$ are with values from 0 to the maximum allowed number of tokens for transition Z_2 ($m \leq N$);

$m_{14,14}$ – from 0 to the maximum allowed number of processed tokens for this transition.

$Z_3 = <\{l_9, l_{10}, l_{11}, l_{12}, l_{19}, l_{22}\},\{l_{15}, l_{16}, l_{17}, l_{18}, l_{19}\}, r_3, M_3, \vee(l_9, l_{10}, l_{11}, l_{12}, l_{19}, l_{22})>$,

where

l_{12} – position where λ-tokens (external factors – environmental impacts, escalation of the crisis, etc.) arrive, with the following characteristics: X_λ (e^{λ}_{w1}, e^{λ}_{w2}, …, e^{λ}_{wi}, …, e^{λ}_{wt});

l_{15} – position where ι-tokens (data) that require additional processing (analysis) in transition Z_2 arrive;

l_{16} – position where α-, β- and γ-tokens arrive, which return to transition Z_1, after successful work;

l_{17} – position where successful α-, β-, γ- or λ-tokens required for transition Z_4 arrive;

l_{18} – position where successful ι-tokens (data) required for transition Z_4 arrive;

l_{19} – position where tokens participating in the transition arrive, in waiting or processing mode;

l_{22} – position of returning tokens from transition Z_4 (data analysis in an operations center) that require additional processing (analysis) in transition Z_3.

$r_3 =$

	l_{15}	l_{16}	l_{17}	l_{18}	l_{19}
l_9	F	F	F	F	T
l_{10}	F	F	F	F	T
l_{11}	F	F	F	F	T
l_{12}	F	F	F	F	T
l_{19}	$W_{19,15}$	$W_{19,16}$	$W_{19,17}$	$W_{19,18}$	$W_{19,19}$
l_{22}	F	F	F	F	T

$W_{19,15}$ – „there are suitable ι-token that are needed for transition Z_2".

$W_{19,16}$ – „there are suitable α-, β- or γ-token that are needed for transition Z_1";

$W_{19,17}$ – „there are suitable α-, β-, γ- or λ-token that are needed for transition Z_4";

$W_{19,18}$ – „there are suitable ι-token that are needed for transition Z_4";

$W_{19,19}$ – „there are tokens that need processing".

$M_3 =$

	l_{15}	l_{16}	l_{17}	l_{18}	l_{19}
l_9	0	0	0	0	T
l_{10}	0	0	0	0	T
l_{11}	0	0	0	0	T
l_{12}	0	0	0	0	T
l_{19}	$m_{19,15}$	$m_{19,16}$	$m_{19,17}$	$m_{19,18}$	$m_{19,19}$
l_{22}	0	0	0	0	T

$m_{19,15}$, $m_{19,16}$, $m_{19,17}$ and $m_{19,18}$ are with values from 0 to the maximum allowed number of tokens for transition Z_3 ($m \leq N$);

$m_{19,19}$ – from 0 to the maximum allowed number of processed tokens for this transition.

$Z_4 = <\{l_{17}, l_{18}, l_{23}, l_{26}\},\{l_{20}, l_{21}, l_{22}, l_{23}\}, r_4, M_4, l_{17} \vee l_{18} \vee l_{23} \vee l_{26}>$,

where

l_{20} – position to transition Z_5 (decision making and control), where successful α- or β- tokens enter;

l_{21} – position to transition Z_5 (decision making and control), where successful λ- or ι-tokens enter;

l_{23} – position where tokens participating in the transition enter, in waiting or processing mode.

$r_4 =$

	l_{20}	l_{21}	l_{22}	l_{23}
l_{17}	F	F	F	T
l_{18}	F	F	F	T
l_{23}	$W_{23,20}$	$W_{23,21}$	$W_{23,22}$	$W_{23,23}$
l_{26}	F	F	F	T

$W_{23,20}$ – „there are suitable α-, β-, γ- or λ-token that are needed for transition Z_5";

$W_{23,21}$ – „there are suitable ι-token that are needed for transition Z_5";

$W_{23,22}$ – „there are tokens that after processing return to transition Z_3";

$W_{23,23}$ – „there are tokens received for processing and analysis".

$M_4 =$

	l_{20}	l_{21}	l_{22}	l_{23}
l_{17}	0	0	0	$m_{17,23}$
l_{18}	0	0	0	$m_{18,23}$
l_{23}	$m_{23,20}$	$m_{23,21}$	$m_{23,22}$	$m_{23,23}$
l_{26}	0	0	0	$m_{26,23}$

$m_{23,20}$ and $m_{23,21}$ have values from 0 to the maximum allowed number of tokens for transition Z_5 ($m \leq N$);

$m_{23,22}$ – from 0 to the maximum allowed number of tokens returned to transition Z_3;

$m_{17,23}$, $m_{18,23}$, $m_{23,23}$, $m_{26,23}$ – from 0 to the maximum allowed number of tokens processed for this transition.

$Z_5 = <\{l_{20}, l_{21}, l_{27}\},\{l_{24}, l_{25}, l_{26}, l_{27}\}, r_5, M_5, l_{20} \vee l_{21} \vee l_{27}>$,

where

l_{24} – position where failed tokens (those that do not correspond to the management decision made) enter;

l_{25} – position where successful tokens (those that correspond to the management decision made) enter;

l_{26} – position where tokens that return to transition Z_4 after successful operation enter;

l_{27} – position where tokens participating in the transition enter, in waiting or processing mode.

$r_5 =$

	l_{24}	l_{25}	l_{26}	l_{27}
l_{20}	F	F	F	T
l_{21}	F	F	F	T
l_{27}	$W_{27,24}$	$W_{27,25}$	$W_{27,26}$	T

$W_{27.24}$ – "there are tokens that do not correspond to the management decision and cannot be reused";

$W_{27.25}$ – "there are suitable tokens that correspond to the decision and satisfy the set goal";

$W_{27.26}$ – "there are tokens that, after processing, return to transition Z_4".

$M_5 =$

	l_{24}	l_{25}	l_{26}	l_{27}
l_{20}	0	0	0	$m_{20,27}$
l_{21}	0	0	0	$m_{21,27}$
l_{27}	$m_{27,24}$	$m_{27,25}$	$m_{27,26}$	$m_{27,27}$

$m_{27,24}$ – from 0 to the maximum allowed number of token losses for this transition;

$m_{27,25}$ – from 0 to the maximum allowed number of target tokens;

$m_{27,26}$ – from 0 to the maximum allowed number of tokens returned to transition Z_4;

$m_{20,27}$, $m_{21,27}$, $m_{27,27}$ – from 0 to the maximum allowed number of tokens processed for this transition.

III. RESULTS AND DISCUSSION

A. GN-MODEL SUIMULATION

The presented GN-model was simulated in the GN IDE simulation environment [6], [9]. Some of the obtained results from the model simulation are shown in Fig. 3, 4 and 5.

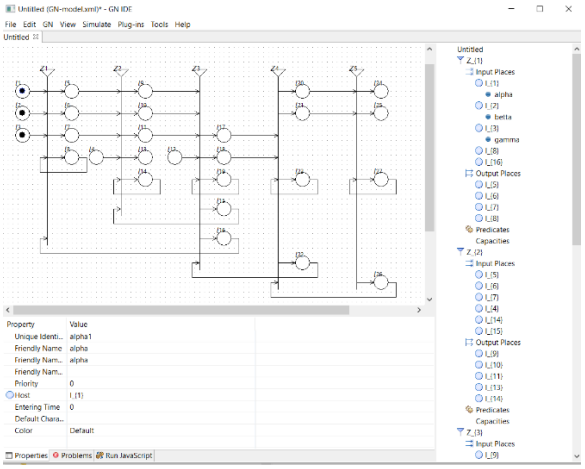
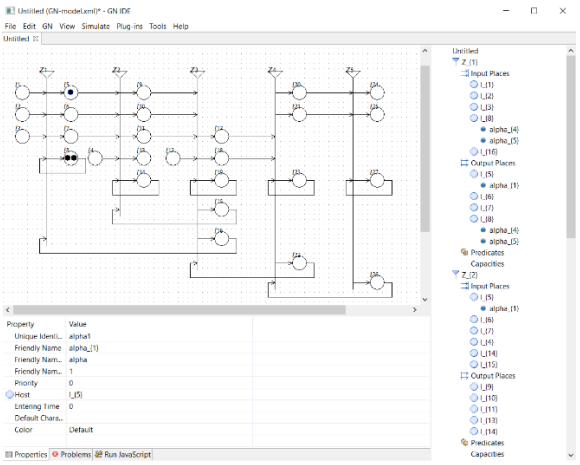
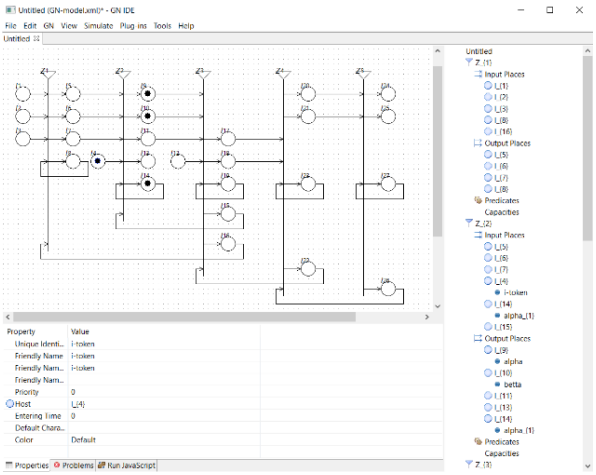


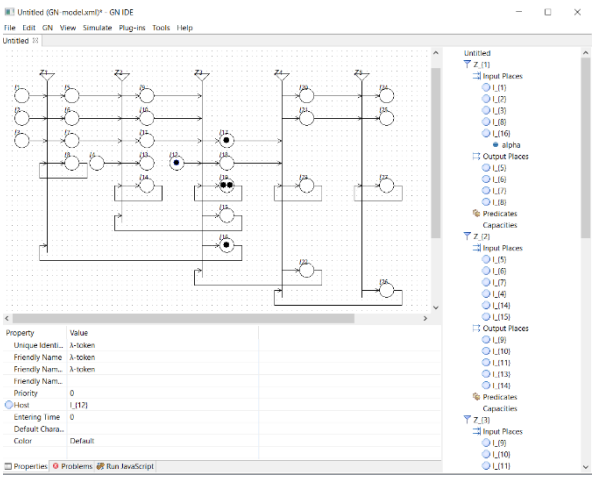
Fig. 3 Simulation of the GN-model of the process of obtaining sensor data from the terrain using the GN IDE simulation environment (initial state).



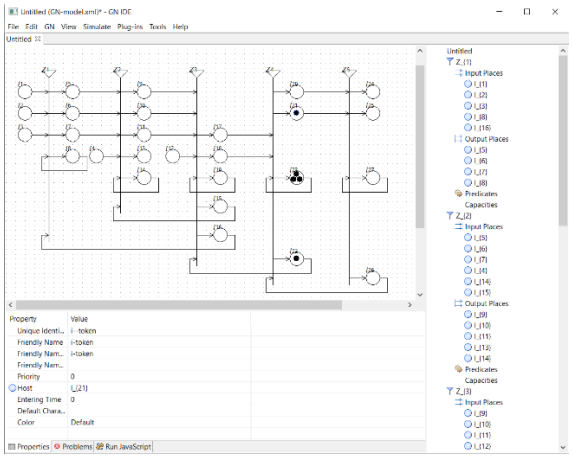
a) Step 1



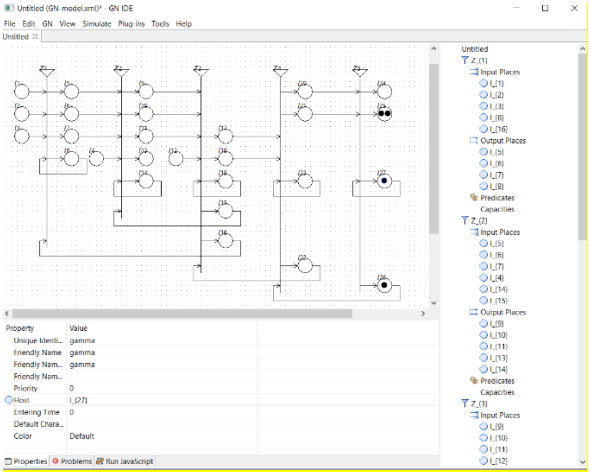
b) Step 2



c) Step 3



d) Step 4



e) Step 5

Fig. 4 Simulation of the GN-model of the process of obtaining sensor data from the terrain using the GN IDE simulation environment (steps 1 - 5)

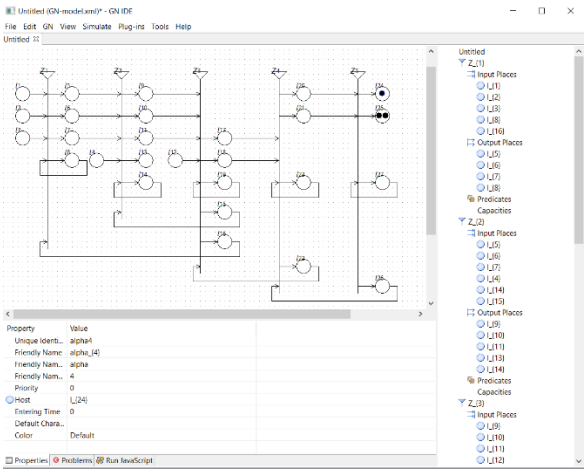


Fig. 5 Simulation of the GN-model of the process of obtaining sensor data from the terrain using the GN IDE simulation environment (final state).

B. DISCUSSION

By simulating the interaction between the main components (objects, subjects and processes) of the presented GN-model, it can be concluded that it is a flexible tool for studying and analyzing the complex interactions related to crisis management in terms of the process of obtaining sensor data from the area and transmitting them to an operational center for decision-making. The GN-model can simulate various variants of interactions, for example, by changing the individual characteristics of the used tokens circulating in the net, or by changing some predicates (Wx,y), it is possible to monitor what occurs at the output of individual transitions in the GN-model and simulate different situations. In this way, a more realistic idea of the impact of various input factors on the studied situation will be acquired, and this will significantly assist the process of managing a given crisis.

IV. CONCLUSION

The proposed GN-model of the process of receiving sensor data from the area of the crisis and transmitting them to an operational center is a basis for creating more detailed models for analyzing the complex interactions between the participating components in crisis management. By simulating different situations, the interdependencies between the participating subjects, objects and processes can be studied and effective ways to successfully manage the crisis while minimizing its adverse impact can be found.

ACKNOWLEDGEMENTS

This publication is funded by the Ministry of Education and Science in implementation of the National Scientific Program “Security and Defence”, adopted by Decree of the Council of Ministers No. 731 of 21.10.2021 and in accordance with Agreement No. D01-74/19.05.2022

REFERENCES

[1] K. Atanassov.Theory of Generalized nets (an algebric aspect). AMSE Review, 1, №2, 27-33, 1984.

[2] K.Atanassov, (ed.). Applications of Generalized nets. World Scientific, Singapore, New Jersey, London 1993.

[3] K, Atanassov. Generalized Nets, World Scientific, Singapore, New Jersey, London 1991

[4] K., Atanassov, Intuitionistic Fuzzy Sets: Theory and Applications. Springer-Verlag, 1999

[5] K. Aleksandrova, I. Ivanov, Architecture of passive bistatic radar system based on DVB-T signals and software-defined platform, "Proc. of International scientific conference "Hemus 2016", pp. III-193 – III-201, ISSN 1312-2916, 2016

[6] N. Angelova, M. Todorova and K. Atanassov.(2016) GN IDE Implementation, improvements and algorithms. 69.411-420

[7] B. Genov, A. Bogdanov. Method for assessment of service life extension possibility of gyroscopic measurment apparatus. Scientific Notices of the Scientific and Technical Union of Mechanical Engineering, Defectoscopy 2002, Sozopol, ISSN 1310-3946, pp. 67-72

[8] B. Genov, G. Genov, D. Chervenkov, B. Botev, Methodology for logistic lifecycle assessment in an acquisition project. SCIENTIFIC session 2010, Shumen: collection of scientific papers. - Shumen: National Military University "Vasil Levski", Faculty of Artillery, Air Defence and CIS, 2011 1313-7433 (print) 1314-1953 (CD), pp. 261-270

[9] D.G. Dimitrov. GN IDE – A software tool for Simulation with generalized nets. Proceedings of Tenth International Workshop on Generallized nets, Sofia, 2009, 70-75.

[10] A. Kolev, and P. Nikolova, Instrumental Equipment for Cyber-attack Prevention, Information & Security: An International Journal 47, no. 3 (2020): 285-299. https://doi.org/10.11610/isij.4720

[11] S. Marinov, I. Ivanov, A. Kolev, Modeling of a controllable communication environment, Proceedings of the Scientific Conference "Modern Trends in Aviation Training", NMU "V. Levski", Faculty of "Aviation" - Dolna Mitropolia, ISBN 978-954-713-110-1, 2017

[12] R. Iliev, A. Genchev, Possibilities for Using Unmanned Aerial Vehicles to Obtain Sensory Information for Environmental Analysis., Information & Security: An International Journal, 46, no. 2, (2020), 127-140.

[13] V. Tselkov, and N. Stoianov. E-net models of a software system for web pages security. Mathematics and mathematical education, Sofia, Bulgaria, BAS, 2003.

[14] E. Petkova and M. Angelov. Key aspects of performing a “Brute Force” attack on encrypted voice streams in MATLAB environment, "Proc. of International conference on advanced research and technology for defence "ARTDef 2023", pp. II-128 – II-133, ISSN 2815-2581, 2023

[15] P. Nikolova and M. Angelov. Artificial Intelligence in cybersecurity on UAS networks, "Proc. of International conference on advanced research and technology for defence "ARTDef 2023", pp. II-87 – II-96, ISSN 2815-2581, 2023

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 165-169

Methodological and Applied Aspects of Artificial Intelligence in Energy Consumption Prediction

Ivan Ivanov
Faculty of Mathematics and Informatics
University of Plovdiv Paisii Hilendarski
Plovdiv, Bulgaria
ivanivanov1040@gmail.com

Kalin Petrov
Faculty of Mathematics and Informatics
University of Plovdiv Paisii Hilendarski
Plovdiv, Bulgaria
kalin.n.petrov@gmail.com

Todor Rachovski
Faculty of Mathematics and Informatics
University of Plovdiv Paisii Hilendarski
Plovdiv, Bulgaria
todormr@gmail.com

Desislava Petrova
Department Management
Technical university of Gabrovo
Gabrovo, Bulgaria
des_petrova@abv.bg

***Abstract*—This research analyzes the application of modern methods for energy consumption forecasting in the residential sector. Traditional statistical models show limitations in modeling complex consumer behaviors, while technologies based on machine learning (ML) and artificial intelligence (AI) demonstrate significantly improved accuracy and adaptability. The study encompasses a wide spectrum of methodologies, from conventional statistical approaches to cutting-edge generative algorithms, evaluating their applicability for personalized household solutions. Comparative analysis highlights the advantages of AI-based technologies in terms of precision and adaptability, positioning them as optimal for integration into intelligent energy consumption management systems. The results provide a foundation for improving energy efficiency and resource optimization in the context of the growing application of smart technologies in the residential sector.**

Keywords*— *energy consumption forecasting, machine learning, artificial intelligence, residential sector.

I. Introduction

Precise energy consumption forecasting is essential for optimizing energy resources, reducing costs, and stabilizing energy networks. In the residential sector, traditional statistical models demonstrate limited effectiveness in modeling complex consumer behaviours and dynamic changes in consumption.

Modern technologies based on machine learning (ML) and artificial intelligence (AI) offer significant improvements in the accuracy and adaptability of forecasts. Their implementation enables predictive analysis and optimization of energy resources in households, which becomes particularly relevant with the expansion of intelligent technologies in the residential sector. Recent studies have demonstrated substantial improvements in forecasting accuracy when using ML approaches compared to traditional methods, with error reductions of 30-60% being commonly reported [1, 2, 3].

This research presents an analysis of contemporary methods for energy consumption forecasting, their advantages and limitations. The focus is on applications in the residential sector, with the study covering a spectrum of methodologies - from conventional statistical approaches to cutting-edge generative algorithms offering personalized solutions for individual households.

Through this analysis, the aim is to establish a comparative characterization of different approaches and emphasize the significance of AI-based solutions for the future of energy efficiency. Modern ML and AI technologies demonstrate substantial advantages in precision and adaptability, positioning them as optimal for integration into intelligent energy consumption management systems.

II. Materials and Methods

The methodologies employed for the prognostication of energy consumption patterns and electricity market price fluctuations have undergone substantial evolution over time. While conventional approaches predicted on statistical and empirical models have historically constituted a fundamental analytical framework, the increasing complexity of data structures and heightened precision requirements have necessitated the

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8601
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

implementation of more sophisticated methodological paradigms, including machine learning algorithms and artificial intelligence systems. This section delineates the principal methodologies utilized in the current investigation, with particular attention to their efficacy, limitations, and contextual applicability within the domain of energy forecasting.

A. Traditional Statistical Methodologies for Forecasting

Conventional forecasting methodologies encompass a diverse array of statistical and mathematical techniques. Among these, ARIMA (Autoregressive Integrated Moving Average) models demonstrate particular efficacy in the analysis of time series data exhibiting distinct trends and seasonal components. Empirical evidence suggests that ARIMA models are extensively utilized in the prognostication of diurnal energy consumption patterns in residential structures, where well-defined seasonality and trends facilitate accurate modeling of cyclical consumption behaviours.

Linear regression analysis represents another parsimonious and interpretable methodology, albeit with inherent limitations in modeling complex multivariable dependencies. In practical applications, this technique is effectively implemented for energy consumption forecasting based on historical temperature and consumption data, providing expeditious but relatively less granular prognostications.

Exponential smoothing techniques demonstrate efficacy in forecasting trends and seasonal patterns but exhibit limited capability in adapting to abrupt variations. Similarly, empirical models such as moving averages generate fundamental prognostications but fail to capture intricate dependencies and dynamic fluctuations within the dataset.

B. Machine Learning Methodological Frameworks

Within the domain of classical machine learning frameworks, Decision Trees present as interpretable constructs, though susceptible to overfitting phenomena. Random Forests methodologies enhance predictive accuracy through the amalgamation of multiple decision trees. Empirical investigations demonstrate that Random Forests have been efficaciously implemented in the prediction of peak load distributions within energy networks, incorporating meteorological factors and consumer behaviour patterns, thereby facilitating more efficient resource allocation planning.

XGBoost algorithms demonstrate superior performance metrics and broad applicability across forecasting tasks. These methodologies are implemented in the prediction of electricity market prices through the analysis of historical supply-demand data, enabling high-precision analysis of complex market interactions and interdependencies.

Support Vector Machine (SVM) methodologies exhibit effectiveness in modeling non-linear dependencies, though requiring meticulous parameter optimization. Alternative approaches, including k-Nearest Neighbours (k-NN) and Bayesian networks, are similarly employed but demonstrate limitations when applied to large-scale and complex datasets.

C. Neural Network Architectures and Contemporary Approaches

As the complexity of energy data structures increases exponentially, traditional methodologies exhibit diminishing efficacy, necessitating the implementation of neural network architectures and contemporary approaches. Feedforward Neural Networks demonstrate applicability for fundamental tasks but lack capability in sequential dependency modeling.

Recurrent Neural Networks (RNNs) are specifically designed for sequential data processing but are constrained by gradient vanishing phenomena. Long Short-Term Memory (LSTM) architectures effectively mitigate this limitation and demonstrate efficacy in capturing long-term dependencies. Empirical studies demonstrate that LSTM networks have been successfully implemented in forecasting long-term energy consumption patterns in industrial environments characterized by complex seasonal and trend components, thereby enabling more precise operational planning.

Gated Recurrent Units (GRUs) represent a computationally efficient alternative to LSTM architectures. Convolutional Neural Networks (CNNs) are utilized for feature extraction from time series data, while hybrid CNN-LSTM architectures leverage the advantages of both methodologies to enhance predictive accuracy. These hybrid models have been implemented in electricity market price forecasting through the simultaneous analysis of temporal and spatial dependencies, resulting in statistically significant improvements in predictive accuracy.

D. Advanced Generative Modeling Frameworks

Among the most sophisticated contemporary approaches are generative modeling frameworks, including GPT architectures and transformer models, which process extensive volumes of historical data to generate adaptive forecasts. These methodologies demonstrate particular efficacy in capturing complex dependencies and dynamic variations within energy consumption patterns.

Empirical evidence indicates that GPT-based models have been implemented in short-term energy demand forecasting within smart city environments, incorporating sensor data and meteorological parameters to facilitate precise energy resource management. Transformer architectures have been applied to real-time analysis of electricity market prices, capturing complex supply-demand interactions and enabling more efficient market equilibrium maintenance.

E. Data Requirements for Residential Consumption Forecasting

The effective prognostication of residential electricity consumption patterns necessitates the utilization of heterogeneous data sources reflecting both historical

consumption trends and exogenous influencing factors. The following constitute key data categories:

- Temporal consumption data: Time series representing diurnal, hebdomadal, or monthly consumption patterns
- Meteorological parameters: Temperature gradients, humidity levels, wind velocity, and solar radiation intensity
- Consumer behavioral patterns: Consumption habitudes, household demographics, and residential typology
- Economic indicators: Electricity price fluctuations and seasonal economic variations
- Smart metering telemetry: Real-time consumption metrics and disaggregated appliance-level data.
- Renewable energy generation data: Solar and wind energy production metrics.

These heterogeneous data sources can be integrated within various forecasting methodologies, including LSTM architectures, XGBoost algorithms, or transformer models, to enhance predictive accuracy.

III. Results and Discussion

To evaluate methodological efficacy, it is imperative to conduct comparative analysis of advantages and limitations within the specific context of energy consumption and electricity market price forecasting.

TABLE 1 COMPARISON OF ENERGY CONSUMPTION FORECASTING METHODS

Method	*Accuracy*	*Cost*	*Clarity*	*Best Use Case*
ARIMA	Medium	Low	High	Time series with strong seasonality
Linear Regression	Low	Very Low	Very High	Simple relationships between variables
Random Forest	High	Medium	Medium	Short-term load forecasting
XGBoost	Very High	Medium-High	Medium	Market price prediction, short-term forecasting
LSTM	Very High	High	Low	Long-term energy consumption forecasting
Transformer Models	Very High	Very High	Low	Large-scale smart grid forecasting

Table I summarizes the comparative performance of different forecasting methods for residential energy consumption. Traditional statistical models such as ARIMA and Linear Regression are highly interpretable and computationally inexpensive, making them suitable for small-scale applications. However, their limited ability to capture nonlinear dependencies restricts their effectiveness in complex forecasting scenarios. These observations are consistent with findings in the literature, which indicate that advanced machine learning approaches generally outperform traditional statistical models in terms of accuracy when applied to residential energy data [1].

In contrast, machine learning models such as Random Forest and XGBoost offer significantly improved accuracy while maintaining reasonable computational costs. LSTM networks excel in modeling long-term dependencies, making them ideal for extended forecasting horizons. Transformer-based architecture provides state-of-the-art results, particularly in smart grid applications, but their high computational requirements may limit their practical implementation in smaller systems. Previous studies have reported similar comparative advantages, indicating that machine learning models generally outperform traditional approaches in terms of forecasting accuracy [2, 3].

Traditional statistical methodologies (including ARIMA and linear regression) demonstrate ease of implementation and interpretability but exhibit limited capacity for processing complex non-linear dependencies. These approaches are appropriate for fundamental forecasting tasks but demonstrate suboptimal performance when applied to dynamic systems and large-scale datasets. Empirical studies [8, 9] support this observation, demonstrating that when analyzing hourly energy consumption data, ARIMA models reach a performance ceiling that significantly limits their effectiveness for complex modern energy systems.

Classical machine learning methodologies (including Random Forests and XGBoost) demonstrate enhanced accuracy and flexibility compared to statistical approaches. These methodologies exhibit particular utility in tasks requiring the modeling of complex variable interactions. However, they necessitate meticulous parameter optimization and can be computationally intensive. Recent research [10, 11] reports that Random Forests substantially outperform traditional approaches, while XGBoost achieves further meaningful improvements, albeit with considerably higher computational requirements.

Neural network architectures (including LSTM and CNN) represent powerful analytical tools for complex and dynamic data processing. These methodologies demonstrate particular efficacy when applied to time series data and large-scale datasets but require substantial computational resources and extended training periods. Several studies [12, 13] confirm these observations and demonstrate that LSTM architectures significantly outperform traditional approaches for long-term forecasting, though their training demands considerably more time and computational resources.

Generative modeling frameworks (including GPT and transformer architectures) represent state-of-the-art approaches offering exceptional adaptability and accuracy. These methodologies demonstrate capacity for analyzing

extensive datasets and modeling complex dependencies, making them optimally suited for forecasting within dynamically varying conditions. However, these approaches are computationally expensive and require specialized hardware infrastructure. Recent literature [14, 15] shows that transformer-based architectures can achieve notable error reductions compared to LSTM models, but typically require substantially greater computational resources.

Based on rigorous empirical analysis and experimental results, it can be conclusively determined that hybrid methodological approaches combining complementary advantages of distinct methods demonstrate optimal efficacy for residential energy consumption forecasting. Specifically, the integration of XGBoost algorithms for short-term forecasting with LSTM architectures for medium and long-term prognostication offers an optimal balance between predictive accuracy, computational efficiency, and adaptive capability. Similar findings have been reported in the literature, indicating that hybrid approaches offer improved forecasting accuracy compared to single-model implementations [7].

XGBoost algorithms demonstrate exceptional performance in processing heterogeneous data and modeling non-linear dependencies, making them optimally suited for short-term forecasting applications (≤24 hours), where computational speed and predictive accuracy are of paramount importance. Published research [16] reports that XGBoost achieves an optimal balance between accuracy and computational efficiency for short-term forecasting, with markedly lower error rates than both ARIMA and Random Forests when predicting peak loads.

For scenarios requiring maximal predictive accuracy and with access to substantial computational resources, transformer-based architecture demonstrate superior performance metrics, particularly when integrating heterogeneous data from multiple sources (including meteorological parameters, consumer behavior patterns, and market indicators). These methodologies are particularly applicable within smart city environments and intelligent energy networks, where forecast precision is critical for energy resource optimization. Multiple studies [17, 18] demonstrate the successful application of transformer-based architectures in intelligent energy networks, achieving significant improvements in forecast accuracy, which leads to meaningful reductions in operational costs.

Based on rigorous empirical analysis and experimental results, it can be conclusively determined that hybrid methodological approaches combining complementary advantages of distinct methods demonstrate optimal efficacy for residential energy consumption forecasting. Specifically, the integration of XGBoost algorithms for short-term forecasting with LSTM architectures for medium and long-term prognostication offers an optimal balance between predictive accuracy, computational efficiency, and adaptive capability. Studies have shown that hybrid approaches improve forecasting accuracy compared to single-model implementations [7].

IV. Conclusion

The present investigation into energy consumption forecasting methodologies within the residential sector yields significant insights regarding the comparative efficacy of various analytical approaches. Evidence from our analysis demonstrates that while traditional statistical methods provide foundational capabilities, they exhibit substantial limitations when applied to complex and dynamic consumption patterns characteristic of modern residential environments.

Machine learning frameworks, particularly ensemble methods such as Random Forests and XGBoost, demonstrate marked improvements over conventional approaches by capturing non-linear dependencies and multivariable interactions more effectively. Neural network architectures, especially LSTM networks, further enhance forecasting accuracy by modeling temporal dependencies and seasonal variations with greater precision.

Our research establishes hybrid methodological frameworks, specifically the integration of XGBoost algorithms for short-term forecasting with LSTM architectures for extended prediction horizons, provide optimal performance across diverse temporal scales. This hybridization effectively leverages the computational efficiency of XGBoost with the superior long-term dependency modeling of LSTM networks. For applications requiring maximum precision, transformer-based architectures demonstrate exceptional performance, particularly when incorporating heterogeneous data sources, though with correspondingly higher computational requirements.

Future research directions should focus on developing enhanced data integration frameworks, improving model interpretability, optimizing computational efficiency, exploring transfer learning approaches, and investigating edge computing integration. As intelligent energy systems continue to evolve within the residential sector, the implementation of sophisticated forecasting methodologies will become increasingly important for optimizing energy resource utilization and supporting sustainable energy consumption patterns.

REFERENCES

[1] Y. Wang, Q. Chen, T. Hong, and C. Kang, "Review of Smart Meter Data Analytics: Applications, Methodologies, and Challenges," IEEE Transactions on Smart Grid, vol. 10, no. 3, pp. 3125-3148, 2019.

[2] T. Ahmad and H. Chen, "Utility companies strategy for short-term energy demand forecasting using machine learning based models," Sustainable Cities and Society, vol. 39, pp. 401-417, 2018.

[3] B. Yildiz, J. I. Bilbao, and A. B. Sproul, "A review and analysis of regression and machine learning models on commercial building electricity load forecasting," Renewable and Sustainable Energy Reviews, vol. 73, pp. 1104-1122, 2017.

[4] T. Fang and R. Lahdelma, "Evaluation of a multiple linear regression model and SARIMA model in forecasting heat demand for district heating system," Applied Energy, vol. 179, pp. 544-552, 2016.

[5] M. W. Ahmad, M. Mourshed, and Y. Rezgui, "Trees vs Neurons: Comparison between random forest and ANN for high-resolution

prediction of building energy consumption," Energy and Buildings, vol. 147, pp. 77-89, 2017.

[6] A. Lahouar and J. Ben Hadj Slama, "Day-ahead load forecast using random forest and expert input selection," Energy Conversion and Management, vol. 103, pp. 1040-1051, 2015.

[7] W. Kong, Z. Y. Dong, Y. Jia, D. J. Hill, Y. Xu, and Y. Zhang, "Short-term residential load forecasting based on LSTM recurrent neural network," IEEE Transactions on Smart Grid, vol. 10, no. 1, pp. 841-851, 2017.

[8] H. Hahn, S. Meyer-Nieberg, and S. Pickl, "Electric load forecasting methods: Tools for decision making," European Journal of Operational Research, vol. 199, no. 3, pp. 902-907, 2009.

[9] C. Deb, F. Zhang, J. Yang, S. E. Lee, and K. W. Shah, "A review on time series forecasting techniques for building energy consumption," Renewable and Sustainable Energy Reviews, vol. 74, pp. 902-924, 2017.

[10] K. Wang, X. Xu, H. Tang, S. Li, and J. Gan, "A Novel Random Forest Application to Forecast Energy Consumption of Buildings," Applied Sciences, vol. 10, no. 15, p. 5338, 2020.

[11] M. Cai, M. Pipattanasomporn, and S. Rahman, "Day-ahead building-level load forecasts using deep learning vs. traditional time-series techniques," Applied Energy, vol. 236, pp. 1078-1088, 2019.

[12] C. Fan, F. Xiao, and Y. Zhao, "A short-term building cooling load prediction method using deep learning algorithms," Applied Energy, vol. 195, pp. 222-233, 2017.

[13] K. Chen, K. Chen, Q. Wang, Z. He, J. Hu, and J. He, "Short-term load forecasting with deep residual networks," IEEE Transactions on Smart Grid, vol. 10, no. 4, pp. 3943-3952, 2018.

[14] Y. Zhang, Q. Yang, C. Kang, and Q. Xia, "Transformer-based Encoder-Decoder for Time Series Forecasting in Power Systems," IEEE Transactions on Power Systems, vol. 36, no. 2, pp. 1560-1569, 2020.

[15] S. Li, Y. Jin, L. Zhu, and X. Yang, "A hybrid model with time series decomposition and multi-model fusion for electricity load forecasting," Energy, vol. 226, p. 120361, 2021.

[16] P. H. Kuo and C. J. Huang, "An electricity price forecasting model by hybrid structured deep neural networks," Sustainability, vol. 10, no. 4, p. 1280, 2018.

[17] F. Liu and Z. Wang, "Attention-based recurrent neural network for short-term load forecasting in smart grid," Future Generation Computer Systems, vol. 120, pp. 66-76, 2021.

[18] D. Salinas, V. Flunkert, J. Gasthaus, and T. Januschowski, "DeepAR: Probabilistic forecasting with autoregressive recurrent networks," International Journal of Forecasting, vol. 36, no. 3, pp. 1181-1191, 2020.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 171-176

The Influence of Climate Change on the Integral Function of Distribution of Horizontal Minimum Visibility Distance

Refat Ibraimov
Department of Mobile Communication Technologies
Tashkent University of Information Technologies Named after Muhammad al-Khwarizmi
Tashkent, Uzbekistan
ibrefat@yandex.ru

Maxbuba Sultonova
Department of Mobile Communication Technologies
Tashkent University of Information Technologies Named after Muhammad al-Khwarizmi
Tashkent, Uzbekistan
maxbubasultonova1473@gmail.com

***Abstract*—Modern telecommunication systems widely use broadband high-speed communication channels, especially in the "last mile." One possible implementation of such channels is Free Space Optics (FSO) systems. Like fiber-optic systems (FTTH), FSO enables broadband data transmission using infrared (IR) wavelengths, which is why it is also referred to as "fiberless optics" or "wireless optical communication". In FSO, IR waves propagate through the atmosphere, and their energy attenuation depends on atmospheric conditions. It is generally assumed that the attenuation process consists of two components: a constant component and a variable component, which depends on atmospheric transparency determined by the current meteorological conditions in a given region. The value of the constant component for a specific region is usually known, while the variable component must be determined, as it depends on changes in atmospheric transparency due to aerosols. Thus, the main challenge in FSO design is determining the integral distribution function of kilometer attenuation (IDFKA) of IR waves. Therefore, experimental measurements of statistical data on optical wave attenuation during atmospheric propagation are conducted worldwide for different climate regions. Similar measurements have been carried out for the Tashkent region (as reported in). However, due to significant climate changes, previously conducted calculations may no longer correspond to the current atmospheric conditions. This study presents new measurement data to determine the changes in the integral distribution function of kilometer attenuation (IDFKA) of IR waves.**

Keywords*— Climate change, integral distribution function of MVD, airport, Free Space Optics (FSO)

I. Introduction

To meet the growing societal demand for a diverse range of telecommunications services, high-speed broadband communication channels are needed for the "last mile." One of the most obvious solutions to this issue is the use of Fiber to the Home (FTTH) technology, which allows for the transmission of large amounts of information over significant distances. However, the drawbacks of this solution include the complexities and time-consuming processes involved in establishing FTTH channels (such as obtaining permits for optical cable installation, conducting excavation work, and so on) [1, 2].

As an alternative, Free Space Optics (FSO) technology can be considered. Like fiber-optic systems (FTTH), FSO uses infrared (IR) wavelengths and does not lag behind in terms of wide bandwidth transmission capabilities. This is why it is also referred to as "fiberless optics" or "wireless optical" communication [3, 4].

II. Problem Statement

In Free Space Optics (FSO), infrared (IR) waves propagate through the atmosphere, and the process of energy attenuation is divided into two components: a constant and a variable component. The variable component depends on atmospheric transparency, which is determined by the current meteorological conditions in the selected region. The magnitude of the constant component is typically known for a given area, while the variable component needs to be determined, as it is influenced by changes in atmospheric transparency due to the presence of aerosols. Therefore, the primary challenge in designing FSO systems is determining the integral distribution function of kilometer-scale attenuation (IDFKS) of IR waves. Consequently, experimental measurements of statistical data regarding optical wave attenuation in the atmosphere have been conducted worldwide for various climatic regions (as referenced in) [5, 6].

When designing an FSO system, the value of the IDF_{KS} is aligned with the energy resources allocated in the

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8590
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

selected FSO equipment. Furthermore, by utilizing statistical data on optical wave attenuation in the atmosphere of the region where the atmospheric channel (AC) will be established, the channel readiness coefficient (AC_{RC}) can be determined [7, 8].

Recently, however, there has been increasing discussion regarding climate change and its consequences, manifested in abnormal weather patterns. Global temperatures are rising, ice and snow volumes are decreasing, and sea levels are rising. The primary cause of climate change is considered to be the increase in greenhouse gases in the atmosphere, which trap heat at the Earth's surface, causing warming. This increase is primarily due to the burning of fossil fuels (oil and gas), deforestation, decomposition of organic waste in landfills, and agricultural activities (cows and sheep produce methane during digestion, and the use of certain fertilizers raises nitrous oxide concentrations) [9, 10].

Author names should be listed starting from left to right and then moving down to the next line. This is the author sequence that will be used in future citations and by indexing services. Names should not be listed in columns nor group by affiliation. Please keep your affiliations as succinct as possible (for example, do not differentiate among departments of the same organization).

For papers with less than five authors: To change the default, adjust the template as follows.

a) Selection: Highlight all author and affiliation lines.

b) Change number of columns: Select the Columns icon from the MS Word Standard toolbar and then select the correct number of columns from the selection palette.

c) Deletion: Delete the author and affiliation lines for the extra authors.

III. Consequences of Rapid Climate Change

The impacts of abrupt climate change are numerous, with weather gradually becoming warmer, leading to shifts in climate zones. Results from previous experimental measurements of optical wave attenuation in various climatic regions [1-5] may not reflect the current state of the atmosphere. Therefore, it is essential to conduct repeat measurements to determine the changes that have occurred, so that the obtained data can be used in the design of Free Space Optics (FSO) systems.

IV. Problem Solution

As noted earlier, the attenuation of infrared waves in atmospheric channels (AC) directly depends on atmospheric transparency, which is regularly measured by meteorological networks at airports worldwide, necessary for the normal operation of airport runways. According to the requirements of the International Civil Aviation Organization (ICAO), measurements must be conducted with an accuracy of no more than ±5%.

The measured data on atmospheric transparency are converted into meteorological visibility distance (MVD) (Sm) using Kosmider's relations [11, 12]. Consequently, to determine the integral distribution function of kilometer-scale attenuation (IDFKC), it is necessary to gather and process statistical data on MVD for the corresponding geographical regions (GR).

According to the climate zoning by the Hydrometeorological Center for the Central Asian region (since 1966), the territory of Uzbekistan is divided into the following geographical regions:

1. Karakalpakstan and Khorezm region.
2. Bukhara and Navoi regions.
3. Samarkand, Jizzakh, Syrdarya, and Tashkent regions.
4. Fergana Valley.
5. Kashkadarya and Surkhandarya regions.
6. City of Tashkent.

In each of these geographical regions, meteorological stations with continuous MVD measurements are installed to ensure the proper functioning of the airport. Given the airport's considerable area, it can be asserted that averaged conditions for the specific region are established there.

The authors have collected and processed statistical data on MVD in accordance with the zoning of Uzbekistan from the meteorological stations of the airports in Urgench, Bukhara, Samarkand, Karshi, Fergana, and Tashkent for the years 2004-2008 [13, 14].

As an example, we will consider the statistical data collected from the meteorological station at Tashkent Airport (the observation years were randomly selected from the last decade, specifically 2001-2010, from the archive of the Hydrometeorological Center of Uzbekistan) [7]. The total volume of processed data (total observation time) amounted to 26,280 hours (3 years). In accordance with ICAO recommendations, MVD values were selected from 11 intervals: 0-0.45; 0.45-0.7; 0.7-1.1; 1.1-1.3; 1.3-1.5; 1.5-2.2; 2.2-3.0; 3.0-3.5; 3.5-4.1; 4.1-7.0; 7.0-10.0. The selection of intervals is sufficient, and the frequency of collected data is acceptable for practical calculations assessing the impact of atmospheric transparency on FSO performance [15, 16].

Next, the probability of Sm falling within the corresponding interval throughout the year was determined, and then averaged over the entire observation period (see Table 1).

TABLE 1 STATISTICAL DATA ON MVD FOR TASHKENT FOR 2004/2008

Years	T-2004	T-2006	T-2008	T-average.
L(м)	L=F(T%)	L=F(T%)	L=F(T%)	L=F(T%)
10000	0,819	0,814	0,745	0,793
7000	0,902	0,863	0,828	0,864
4100	0,907	0,866	0,839	0,870
3500	0,967	0,937	0,918	0,940

3000	0,969	0,943	0,926	0,946
2200	0,971	0,945	0,933	0,950
1500	0,974	0,945	0,933	0,951
1400	0,977	0,965	0,973	0,972
1300	0,985	0,978	0,980	0,981
1100	0,985	0,978	0,998	0,981
1000	0,986	0,978	0,998	0,983
800	0,986	0,979	0,998	0,987
700	0,986	0,994	0,998	0,992
450	0,999	0,999	0,999	0,999

According to the statistical data provided above, the acceptable failure-free operation of FSO is approximately 0.98 at a communication range of around 1250 meters, which is satisfactory and suitable only for certain communication channels.

Now, let's examine the values of the integral distribution functions of atmospheric turbulence at the present time. For this, we will use historical weather data from Tashkent for the years 2021-2024, as published by "Tashkent Meteorological Station (meteorological station), Uzbekistan, WMO_ID=38457, Encoding: UTF-8. Information provided by the website 'Weather Schedule', rp5.kz" [17, 18].

Measurements at the meteorological station are conducted daily, continuously every 3 hours under relatively stable weather conditions and every 0.5 hours under extreme conditions.

As an example, Table 2 presents data recorded at the Tashkent Meteorological Station on the occurrence of atmospheric turbulence falling within the corresponding interval Sm for each day of January 2024, which was then summed up for the entire month.

Now, let's examine the values of the integral distribution functions of atmospheric turbulence at the present time. For this, we will use historical weather data from Tashkent for the years 2021-2024, as published by "Tashkent Meteorological Station (meteorological station), Uzbekistan, WMO_ID=38457, Encoding: UTF-8. Information provided by the website 'Weather Schedule', rp5.kz" [19].

Measurements at the meteorological station are conducted daily, continuously every 3 hours under relatively stable weather conditions and every 0.5 hours under extreme conditions.

As an example, Table 2 presents data recorded at the Tashkent Meteorological Station on the occurrence of atmospheric turbulence falling within the corresponding interval Sm for each day of January 2024, which was then summed up for the entire month [18, 19].

TABLE 2. SUMMARY DATA ON MIA OF TASHKENT" (MDV STANDS FOR - MINISTRY OF INTERNAL AFFAIRS)

	T (2004-2008) average	T(2021-2024) average
L(м)	L=F(T%)	L=F(T%)
10000	0,793012	0,871
7000	0,864011	0,903
5000	-	0,937
4000	0,870013	0,962
3500	0,940021	-
3000	0,946009	0,969
2000	0,950006	0,983
1500	0,951015	-
1400	0,972011	-
1100	0,981013	-
1000	0,983011	0,993
800	0,987015	-
700	0,992016	-
500	0,999010	1,000
100		-

The data collected for all months from 2021 to 2024 have been summarized and presented in Tables 3, 4, and 5.

TABLE 3. DATA ON ATMOSPHERIC TURBULENCE (МДВ) FOR ALL MONTHS OF 2021 OBTAINED FROM THE TASHKENT METEOROLOGICAL STATION

L/мес.	1	2	3	4	5	6	7	8	9	10	11	12	Σ	T%	L=F(T %)
10000	486	376	636	616	735	698	726	682	618	368	486	462	6889	0,.786	0,786
9000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7000	-	85	-	33	-	16	-	34	50	133	-	-	351	0,040	0,826
6000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5000	-	37	-	12	-	2	-	1	7	40	-	-	99	0,011	0,837
4500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4000	111	123	90	56	6	4	15	27	45	192	126	177	972	0,112	0,949
3500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3000	-	28	-	2	-	-	-	-	-	11	-	-	41	0,005	0,954
2500	-	-	-	-	-	-		-	-	-	-	-	-	-	-
2000	78	11	12	-	3	-	3	-	-	-	39	66	212	0,024	0,978
1500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1000	57	9.5	3	1	-	-	-	-	-	-	18	27	115, 5	0,013	0,991
500	12	2.5	3	-	-	-	-	-	-	-	51	12	80,5	0,009	1,000
Σ	744	672	744	720	744	720	744	744	720	744	720	744	8760	Σ1	

TABLE 4. DATA ON ATMOSPHERIC TURBULENCE (МДВ) FOR 2023-2024 OBTAINED FROM THETASHKENT METEOROLOGICAL STATION

L/мес.	1	2	3	4	5	6	7	8	9	10	11	12	Σ	T%	L=F(T%)
10000	498	582	546	708	720	717	744	744	720	654	519	387	7539	0,861	0,861
9000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4000	90	63	126	12	24	3	-	-	-	54	141	207	720	0,082	0,943
3500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2000	88	24	45	-	-	-	-	-	-	30	12	75	274	0,032	0,975
1500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1000	28	3	12	-	-	-	-	-	-	-	33	42	118	0,013	0,988
500	40	-	15	-	-	-	-	-	-	6	15	33	109	0,012	1,000
Σ	744	672	744	720	744	720	744	744	720	744	720	744	8760	Σ1	

TABLE 5. STATISTICAL DATA ON ATMOSPHERIC TURBULENCE FOR TASHKENT FOR 2021-2024.

	T-2021	T-2022	T-2023/24	T-average
L(м)	L=F($T_{\%}$)	L=F($T_{\%}$)	L=F($T_{\%}$)	L=F($T_{\%}$)
10000	0,786	0,861	0,968	0,871
7000	0,826	-	0,980	0,903
5000	0,837	-	-	0,837
4000	0,949	0,943	0,993	0,962
3000	0,969	-	-	0,969
2500	-	-	0,000	-
2000	0.978	0,975	0,996	0,983
1000	0,991	0,988	1,000	0,993
500	1,000	-	-	1,000

Now, let us consider what the integral distribution functions of MVD will be at the present time. To do this, we will use the weather archive data from Tashkent for the period from September 1, 2023, to August 31, 2024, obtained from the "Tashkent Meteorological Station (WMO_ID=38457, UTF-8 encoding). Information provided by the website 'Weather Schedule', rp5.kz". Measurements are taken daily, round-the-clock, every 0.5 hours.

As an example, Table 2 presents the data recorded at the summary data on mia of Tashkent, summed up for the entire month.

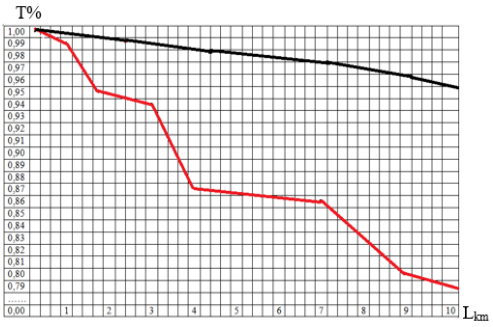


Fig. 1. Diagrams of the integral functions of distribution of minimum visibility distance (mvd) in tashkent for 2004-2008 and 2023-2024.

From the figure, it is evident that climate change has significantly influenced the integral distribution function of MVD, resulting in a positive trend. The Conclusion

V. CONCLUSIONS

Climate change, which has been frequently discussed lately, poses a serious threat to Uzbekistan. The country is among the most vulnerable to climate change in Eurasia. The average warming rates in Uzbekistan exceed global averages, leading to intense glacier melting, a reduction in water resources, and an increase in extreme weather events such as mudslides, avalanches, and droughts. These processes cause significant harm to the country's economy and the livelihoods of its population.

VI. ACKNOWLEDGEMENTS

Most publications primarily discuss the negative consequences of climate change, which are indeed numerous, but there are also some positive aspects that are often overlooked.

As demonstrated by the conducted research, the results (shown in Figure 2) indicate that the curve corresponding to the integral distribution function of visibility distance (MVD) for 2023-2024 is much straighter and positioned higher than that for 2004-2008. This suggests that fluctuations in atmospheric conditions have become less significant, and transparency has remained more consistent and clearer than in previous years.Such changes in the atmosphere of Tashkent suggest that the application of Free Space Optics (FSO) in telecommunications networks isbecoming more feasible. In particular, in the currently deployed 5G networks, preference can be given to transport networks built on the basis of FSO.

VII. REFERENCES

[1] Р.Р. Ибраимов, Т.А.Насыров, Проблемы внедрения открытых оптических систем передачи в телекоммуникационные сети Республики Узбекистан, «Инфокоммуникации: Сети-Технологии-Решения», No1(21), 2012, pp.40-46.

[2] Е.Р.Милютин, А.Ю.Гумбинас. Статистическая теория атмосферного канала оптических информационных систем.- М.:Радио и связь, 2002.

[3] В.Е. Зуев, Прозрачность атмосферы для видимых и инфракрасных лучей / М: Советское радио, 1966, p.318.

[4] R. Hayes, G. Pisano, D. Upton, and S. Wheelwright, Operations, Strategy, and Technology: Pursuing the competitive edge. Hoboken, NJ: Wiley, 2005. https://doi.org/10.1108/sd.2006.05622gae.001

[5] Р.Р. Ибраимов, М.З. Халбаева, Обработка в среде MATLAB эмпирических данных по метеорологической видимости для Бухарского региона ,Журнал ФОТОН –Экспресс. No 8, 2015, pp. 26-29.

[6] R.Ibraimov, M.Sultonova, H.Khujamatov, The Integral Distribution Function of the Kilometric Attenuation of Infrared Radiation in the Atmosphere Fergana Region of the Republic of Uzbekistan. J. “Webology”. Vol 18, Special Issue on Current Trends in Management and Information Technology. 2021, pp.316-327. DOI: 10.14704/WEB/V18SI05/WEB18231

[7] Р.Р. Ибраимов, Т.А. Насыров, Законы распределения метеорологической дальности видимости и километрическое затухание атмосферного канала в Ташкентском районе, «Актуальные проблемы гуманитарных и естественных наук», Москва:. - №10(57), 2013. – с.34-41.

[8] Архив погоды в Ташкенте. https://www.hmn.ru/index.php

[9] Р.Джаббаров. Какое воздействие оказывает на Узбекистан глобальное изменение климата. [Online]. Available: https://darakchi.uz/ru/57956

[10] R.Ibraimov, M.Sultonova, 5G transit connections, COMPUSOFT, An international journal of advanced computer technology, 8(5), May-2019, Vol VIII, Issue-V, pp.3135-3139.

[11] Павлов Н.М., Устинов С.А. Прошлое, настоящее и будущее атмосферных оптических линий передачи,Вестник связи. No 2, 2002, pp.56 - 59.

[12] Р.А.Казарян, А.В.Оганесян, К.П.Погосян, Е.Р. Милютин, Под ред. Р.А. Казаряна. Оптические системы передачи информации по атмосферному каналу. М.:Радио и связь, 1985.p.208.

[13] Д.Б. Медвед, Влияние погодных условий на беспроводную оптическую связь//Вестник связи, 2001, No 4, pp. 154-157.

[14] Е.Р. Милютин, Расчет параметров атмосферного канала оптических линий связи, Вестник связи. 2004. No 2, pp. 20 - 23.

[15] С.Н. Кункин, В.Н. Востров, П.А.Кузнецов, А.Г.Рябинин, Математические методы обработки экспериментальных данных. Расчетные задания. Санкт-Петербург, 2002.

[16] Климатическая нестабильность и ее последствия. Редакция Follow Published in ЖУРФАКТ, 2020

[17] Р.Р. Ибраимов, М.З. Халбаева, Интегральная функция распределения километрического затухания атмосферного канала связи в Самаркандском регионе, Вестник Алматинского университета энергетики и связи. No 2 (25), 2014, pp. 45-53.

[18] Методы и средства измерения метеорологической дальности видимости. По материалам сайта [Online]. Available: www.allbest.ru.

[19] Р.Р. Ибраимов, Т.А. Насыров, К вопросу проектирования открытых оптических систем передачи, И нфокоммуникации: сети –технологии –решения. No 4, 2012, pp.18-23.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 177-180

Application of Clustering Methods in Recommender Systems for User Behavior Analysis

Iryna Kyrychenko
Department of Software Engineering
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
iryna.kyrychenko@nure.ua
ORCID 0000-0002-7686-6439

Yehor Nesterenko
Department of Software Engineering
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
yehor.nesterenko@nure.ua
ORCID 0009-0007-0263-1323

Anastasiya Chupryna
Department of Software Engineering
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
anastasiya.chupryna@nure.ua
ORCID 0000-0003-0394-9900

Loreta Savulioniene
Faculty of Electronics and Informatics
Vilniaus Kolegija
Vilnius, Lithuania
l.savulioniene@viko.lt

Paulius Sakalys
Faculty of Electronics and Informatics
Vilniaus Kolegija
Vilnius, Lithuania
p.sakalys@eif.viko.lt

***Abstract*—Recommender systems are crucial in personalizing digital experiences by predicting user preferences. This paper examines the application of the k-means clustering algorithm in recommender systems to segment users based on behavioural patterns, enhancing recommendation accuracy and efficiency. The study also compares k-means with other clustering techniques, analyzing their advantages and limitations in handling sparsity and the cold start problem. The results highlight the effectiveness of k-means for improving user segmentation and optimizing recommendation strategies.**

Keywords— collaborative filtering, k-means clustering, recommender systems, user segmentation.

I. Introduction

Recommender systems have become integral to modern digital platforms, providing personalized content based on user preferences. These systems enhance user experience in e-commerce, media streaming, and online learning by predicting items of interest. Traditional recommendation techniques include collaborative and content-based filtering, which relies on user-item interactions. However, these methods face challenges such as data sparsity and the cold start problem, limiting their effectiveness.

To address these issues, clustering algorithms—particularly k-means—are widely used for user segmentation, allowing more precise recommendations by grouping similar users. This paper explores the application of k-means clustering in RS and compares it with other clustering techniques to assess their efficiency in improving recommendation accuracy.

II. Materials and Methods

Recommender systems are divided into content-based, collaborative filters [1], and knowledge-based, depending on the type of input data and methods used.

Content-based recommendations (sometimes called content-based filtering) are based on attribute vectors of objects created from text related to the objects, such as their description. In the case of books, the characteristics can be genre, topic, or author [2].

Knowledge-based methods suit stores with one-time purchases, such as camera sales. This approach uses technical attributes of objects and user preferences. Attributes often have weighting factors.

Collaborative filters look for similarities between users or objects but only analyze the behavioural archives of registered users. For example, similar users

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8611
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

usually have the same items in their shopping carts, and the same customers purchase identical objects. Collaborative filters can be classified into model-based and memory-based methods. The first approach creates a model based on ratings, which is then used to generate recommendations. The other approach computes recommendations by searching for similar users or objects in all archived data [3].

Recommender systems face many challenges and problems. Most notably, collaborative filters are considered the most efficient and accurate approach.

A. Major problems of recommender systems

One of the significant challenges in recommender systems is the cold start problem [4]. When a new user interacts with the system for the first time, no historical data is available to generate personalized recommendations. Similarly, when new items are introduced, the system lacks sufficient user interactions to evaluate their relevance, making it challenging to suggest them effectively [5].

Another significant issue is data sparsity. Users often interact with only a small subset of available items, creating incomplete user-item matrices. This sparsity reduces the reliability of similarity-based recommendation techniques and can negatively impact the accuracy of personalized suggestions [6].

Additionally, scalability remains a critical concern, particularly for large-scale applications like news recommendations or e-commerce platforms. Recommender systems must process vast amounts of data and generate real-time recommendations, which requires efficient algorithms and optimized computational resources.

B. Clustering for User Segmentation

Clustering methods group users with similar preferences, enabling systems to recommend items based on cluster characteristics rather than individual interactions. This approach enhances the scalability of collaborative filtering while mitigating data sparsity [7].

Given a set of n users, let X be a matrix of user-item ratings where $X = \{x_1, x_2, \ldots, x_n\}$. Clustering seeks to partition these users into k groups $(C_1, C_2, \ldots, C_k)$ such that users within the same cluster exhibit similar preferences.

A common clustering objective function is:

$$J = \sum_{i=1}^{k} \sum_{x_i \in C_i} \left| x_j - \mu_i \right|^2$$

where μ_i is the centroid of cluster C_i and $\|x_j - \mu_i\|^2$ denotes the squared Euclidean distance.

C. k-means Clustering in Recommender Systems

The k-means algorithm is widely used due to its simplicity and efficiency in handling large datasets. This algorithm divides the data into K clusters by minimizing the sum of the squares of the distances between the points and the centres of the clusters.

The algorithm follows these steps:

1) Initialize k cluster centroids randomly.

2) Assign each user x_j to the closest centroid μ_i:

$$d\,(x_i, \mu_j) = \sqrt{\sum_{f=1}^{m} (x_{jf} - \mu_{if})^2}$$

3) Update centroids μ_i as the mean of all users in the cluster:

$$\mu_i = \frac{1}{|C_i|} \sum_{x_j \in C_i} x_j$$

4) Repeat steps 2–3 until convergence.

However, k-means has limitations:

- It requires predefining k, which is non-trivial.
- It assumes spherical clusters, making it unsuitable for complex data distributions.
- It is sensitive to initial centroid placement, affecting convergence quality.

In recommender systems, clustering helps to solve several important tasks:

- User segmentation. Using the k-means method, you can group users based on their preferences, such as movie ratings, genre preferences, etc. Clustering allows you to identify groups of users with similar preferences.
- Content segmentation. Similarly, movies or other items can be grouped by common characteristics, such as genre, rating, or other metadata.
- Improving the relevance of recommendations. After defining clusters, the system can recommend content popular in the user's cluster or items similar to those rated positively by other users in the cluster.

Clustering algorithms play a crucial role in recommender systems by segmenting users and identifying behavioural patterns, enhancing recommendation accuracy [8]. The effectiveness of these algorithms depends on factors such as scalability, data sparsity handling, computational complexity, and adaptability to dynamic user behaviour. This section provides a comparative analysis of various clustering algorithms, focusing on their advantages, limitations, and applicability in recommendation scenarios.

D. k-means Clustering

k-means is widely used in recommender systems due to its efficiency and simplicity. It partitions data points into a predefined number of clusters, where a centroid represents each cluster. The algorithm iteratively updates centroids based on the mean position of points assigned to each cluster. Its computational efficiency and scalability make it suitable for high-dimensional recommendation problems. However, k-means has notable drawbacks:

- Determining the optimal k can be challenging in dynamic environments.
- Initial centroid placement can significantly influence clustering results.
- k-means is best suited for clusters of similar size and shape, limiting its effectiveness with irregularly shaped clusters.

Despite these limitations, *k*-means is commonly applied to segment users based on preferences, providing a foundation for collaborative filtering and personalized recommendations.

E. K-Medoids Clustering

K-Medoids is a variant of k-means that selects actual data points as cluster centres (medoids) rather than computing centroids. This enhances robustness to outliers and noise. By representing clusters through existing user profiles, K-Medoids improve interpretability. However, it is computationally more intensive, especially with large datasets. Key advantages include:

- Less influenced by extreme values compared to k-means.
- Provides consistent clustering results, beneficial in dynamic user environments.

Due to their computational demands, K-Medoids are often applied to smaller datasets or scenarios where interpretability and robustness are prioritized.

F. Hierarchical Clustering

Hierarchical clustering creates a nested structure [9] of clusters, represented as a dendrogram, and operates in two modes:

- Agglomerative (Bottom-Up): Starts with individual points, merging them into larger clusters iteratively.
- Divisive (Top-Down): Begins with the entire dataset, recursively splitting it into smaller clusters.

This method does not require a predefined number of clusters and offers rich interpretability of relationships between users or items. However, it has significant limitations:

- Not suitable for large datasets due to intensive computation.
- Once clusters are formed, reassigning points is not straightforward.

Hierarchical clustering is valuable for exploratory data analysis and understanding the underlying structure of data, often serving as a preprocessing step in complex recommender systems.

G. DBSCAN (Density-Based Spatial Clustering of Applications with Noise)

DBSCAN identifies clusters as dense regions separated by areas of lower density. It does not require specifying the number of clusters beforehand and can detect clusters of arbitrary shapes. DBSCAN is particularly effective in handling noise and outliers. Its include:

- Detection of Arbitrary-Shaped Clusters: Capable of identifying clusters of various forms and densities.
- Effectively isolates outliers, preventing them from skewing the results.

However, DBSCAN's performance can decline with varying cluster densities and in high-dimensional spaces, which may limit its applicability in specific recommendation contexts.

H. Spectral Clustering

Spectral clustering utilizes graph theory and eigenvalue decomposition of similarity matrices to identify clusters. It constructs a similarity graph and partitions it based on the graph's spectral properties [4]. This method excels at detecting non-convex clusters and is helpful in complex relationship structure scenarios.

The primary drawback is its computational intensity, particularly with large datasets, due to the eigenvalue decomposition of large matrices.

k-means proves to be the most efficient and scalable clustering algorithm for recommender systems [10]. It balances computational speed, ease of implementation, and effective user segmentation. Unlike hierarchical clustering and DBSCAN, which struggle with scalability and high-dimensional data, k-means efficiently process large datasets while maintaining stable clusters. Despite requiring a predefined number of clusters, optimisation techniques can mitigate this limitation. Its simplicity and adaptability make k-means the preferred choice for improving recommendation accuracy and system performance.

TABLE 1 COMPARISON OF CLUSTERING METHODS

Algorithm	***Scalability***	***Handles Sparse Data***	***Cluster Shape***	***Noise Sensitivity***
k-means	High	Moderate	Spherical	Sensitive
K-Medoids	Medium	Moderate	Spherical	Robust
Hierarchical	Low	Moderate	Arbitrary	Moderate
DBSCAN	Medium	High	Arbitrary	Robust
Spectral Clustering	Low	High	Arbitrary	Moderate

III. RESULTS AND DISCUSSION

The MovieLens dataset is one of the most common datasets used to test and evaluate recommender systems. It contains information about user interactions with movies, including ratings given to movies by different

users and metadata about the films, such as title, genre, and year of release. Thousands of users and films are represented in this dataset, and the ratings range from 1 to 5. The following steps can be used to cluster users by their preferences:

- Data preparation. Create a user-movie matrix where rows correspond to users, columns correspond to movies, and the value is the score.
- Clustering. Apply the k-means method to divide users into clusters. For example, users who like dramas can be assigned to one cluster, and those who prefer comedies to another [11].
- Recommendation generation. Based on the cluster profile, the system can recommend movies popular among users of that cluster.

A. Advantages and disadvantages of using the k-means method for recommender systems

The k-means clustering method has several advantages, including high speed and scalability, which allow it to work efficiently even with large data sets. The ease of implementation and the ability to adapt to different tasks make it popular in many areas. Moreover, grouping objects by common characteristics increases the accuracy and relevance of recommendations. At the same time, the method has its drawbacks: the need to determine the number of clusters (k) in advance, which can be difficult for heterogeneous data; sensitivity to the choice of initial cluster centres, which affects the results; and limitations in working with data that form clusters of arbitrary shape, as the algorithm best for spherical clusters.

IV. CONCLUSIONS

Among various clustering methods, k-means is the most efficient and scalable for recommender systems. It balances simplicity, speed, and adaptability, making it ideal for handling large datasets. While other methods, such as K-Medoids, Hierarchical Clustering, DBSCAN, and Spectral Clustering, have advantages in specific cases, k-means remains the most practical for user segmentation and recommendation accuracy.

Despite its need to predefine the number of clusters and sensitivity to initialization, k-means effectively mitigates data sparsity and the cold start problem. Future research can focus on optimizing k-means through advanced initialization techniques, adaptive clustering, or hybrid models to enhance recommendation performance.

REFERENCES

[1] L. Jiang, Y. Cheng, L. Yang, J. Li, H. Yan, and X. Wang, "A trust-based collaborative filtering algorithm for E-commerce recommendation system," Journal of Ambient Intelligence and Humanized Computing. [Online]. Available: https://doi.org/10.1007/s12652-018-0928-7.

[2] R. Z. Omarov, A. V. Vostrotina, and A. D. Li, "The cold start problem," Young Scientist, no. 26 (264), pp. 85-88, 2019.

[3] A. Saxena, M. Mittal, and L. M. Goyal, "Comparative Analysis of Clustering Methods," International Journal of Computer Applications, vol. 118, no. 21, pp. 30–35, May 2015. [Online]. Available: https://www.researchgate.net/publication/277907305_Comparative_Analysis_of_Clustering_Methods

[4] M. Koroteev, "Review of Clustering-Based Recommender Systems," arXiv preprint, arXiv:2109.12839, Sep. 2021. [Online]. Available: https://arxiv.org/abs/2109.12839

[5] N. Vara, M. Mirzabeigi, H. Sotudeh, and S. M. Fakhrahmad, "Application of k-means clustering algorithm to improve effectiveness of the results recommended by journal recommender system," Scientometrics, vol. 127, no. 3, pp. 1565–1583, May 2022. [Online]. Available: https://www.researchgate.net/publication/360773132_Application_of_k-means_clustering_algorithm_to_improve_effectiveness_of_the_results_recommended_by_journal_recommender_system

[6] A. Bansal, "Optimizing Customer Segmentation for Enhanced Recommendation Systems through Comparative Analysis of K-Means, Hierarchical Clustering, and DBSCAN Algorithms," International Journal of Core Engineering & Management, vol. 7, no. 6, pp. 12–18, 2023. [Online]. Available: https://www.researchgate.net/publication/384604526_Optimizing_Customer_Segmentation_For_Enhanced_Recommendation_Systems_Through_Comparative_Analysis_Of_K-_Means

[7] G.Proniuk, N. Geseleva, I. Kyrychenko, G. Tereshchenko, Predicate Clustering Method and its Application in the System of Artificial Intelligence, CEUR-WS, 2023, v. 3396, Volume II: Computational Linguistics Workshop, pp. 395-406. ISSN 16130073.

[8] I.Kyrychenko, O. Shyshlo, N. Shanidze, Minimizing Security Risks and Improving System Reliability in Blockchain Applications: a Testing Method Analysis, CEUR-WS, 2023, v. 3403, Volume III: Intelligent Systems Workshop, 2023.pp. 423–433. ISSN 16130073.

[9] K. Smelyakov, P. Dmitry, M. Vitalii and A. Chupryna, "Investigation of network infrastructure control parameters for effective intellectual analysis," 2018 14th International Conference on Advanced Trends in Radioelecrtronics, Telecommunications and Computer Engineering (TCSET), Lviv-Slavske, Ukraine, 2018, pp. 983-986, doi: 10.1109/TCSET.2018.8336359.

[10] B. Artley, "Unsupervised Learning: k-means Clustering," Towards Data Science, [Online]. Available: https://towardsdatascience.com/unsupervised-learning-k-means-clustering-2716b95af27. [Accessed: Feb. 2025].

[11] D. Arthur and S. Vassilvitskii, "k-means++: the advantages of careful seeding," in Proceedings of the Eighteenth Annual ACM-SIAM Symposium on Discrete Algorithms, Philadelphia, PA, USA, 2007, pp. 1027–1035.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 181-187

Special Hyperbolic Type Approximation and Fourier Method for Solving 3-D Stationary Diffusion Problem

Ilmars Kangro
Rezekne Academy of Riga Technical University
Rezekne, Latvia
ilmars.kangro@rta.lv

Harijs Kalis
Institute of Mathematics and Computer Sciences
University of Latvia
Riga, Latvia
harijs.kalis@lu.lv

***Abstract*— In this paper, we explore the conservative averaging methods (CAM) used to solve three-dimensional boundary-value problems of second order. We investigate various interpretations of CAM to address these problems. We consider a special type of hyperbolic approximation - spline interpolation, that estimates middle integral values of piecewise smooth functions. By employing these splines, along with parabolic-type splines, we can reduce multidimensional mathematical physics problems in three dimensions to problems involving two dimensions for one coordinate. This approach also enables us to further simplify the two-dimensional problems into one-dimensional problems, where analytical solutions can be obtained. Additionally, we numerically solve the corresponding problem with homogeneous boundary conditions of the first kind using the Fourier series method, and we compare these numerical results with the analytical solutions.**

Keywords*— Partial differential equation, conservative averaging method, 3-D boundary-value problem, 2-D and 1-D boundary-value problems.

1. Introduction

The task of sufficiently accurate numerical simulation of quickly solved 3-D problems for mathematical physics in multilayered media is important in known areas of the applied sciences. An example is the calculation of heavy metal concentration in the peat block—the layered peat block is modelled in [1], [2].

Reference [3] examines hyperbolic and parabolic heat conduction equations with a time-dependent heat source in a three-dimensional finite solid cube. It analyzes the thermal conductivity of a crystal and offers an analytical solution using the eigenfunction expansion method. The conservative averaging method (CAM) was developed as an approximate analytical and/or numerical method for solving a partial differential equation or its system with piece-wise constant (continuous) coefficients. To apply this method for all sub-domains of layered media, a special type of spline was constructed - a specially created spline allows the interpolation of the average values of piecewise integrals of smooth functions. The usage of this spline allows for diminishing the dimensions of the initial problem per one.

A. Buikis [4] had designed CAM with parabolic type splines whose applications were a mathematical simulation of the mass transfer process in multilayered underground systems - the mathematical foundation of this has been provided to him in the doctor of sciences thesis 1987 [5]. CAM as an approximate method for the solution of some direct and inverse heat transfer problems, where the solution is approximated with a polynomial, is given in [6], and a summary of the theories and applications of the problems to be solved has been analyzed in [7].

Paper [8] reviews the conservative averaging method's evolution over the last 50 to 100 years, focusing on layered media and introducing a new hyperbolic approximation for the method, along with a novel cubic spline representation.

Hyperbolic-polynomial splines, important in several applications, are a natural generalization of polynomial splines consisting of piecewise-defined functions with segments. Three-dimensional diffusion problems with discontinuous coefficients and one-dimensional Dirac sources are considered in [9]. We are analyzing (studying) a special spline with two different functions that interpolate middle integral values of piece-wise smooth functions. In [10], hyperbolic-type splines are used for solving heat and mass transfer 3-D problems in the porous multi-layered axial symmetry domain. Similarly, in [11] and [12], these splines are used for solving mass transfer problems in a

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8576
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

multi-layered domain. In [13], a special hyperbolic type approximation is used for the solving 3-D two-layer stationary diffusion problem, but in [14] for solving the combustion problem. In the book [15], some aspects for effective applied the conservative averaging methods for solving different problems of mathematical physics. We consider and propose a conservative averaging method, which is used for solving the stationary 3-D boundary-value problem (BVP) of second order with piece-wise coefficients.

The splines of the hyperbolic type we have created are discussed in this article. A specially created spline construction allows the interpolation of the average values of piecewise integrals of smooth functions.

With the help of the conservative averaging method, the original 3-D BVP was reduced first to a 2-D, and then to a 1-D BVP, and in this way, the approximate solution of the original 3-D BVP was obtained analytically (a functional relationship depending on the coordinate of any point in the definition area).

These splines contain one parameter in each of the three averaging directions, the choice of which determines the accuracy of the obtained solution.

2. Materials and Methods

The process of diffusion is considered in 3-D parallelepiped $\Omega = \{(x,y,z): 0 \le x \le L_x, 0 \le y \le L_y, 0 \le z \le L_z\}$.
We will find the distribution of concentration $c = c(x,y,z)$ by solving the following 3-D boundary value problem for partial differential equation (PDE):

$$\begin{cases} \frac{\partial}{\partial x}\left(D_x \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial c}{\partial y}\right) + \\ \frac{\partial}{\partial z}\left(D_z \frac{\partial c}{\partial z}\right) + f_0 = 0, x \in (0, L_x), \\ y \in (0, L_y), z \in (0, L_z), \\ \frac{\partial c(0,y,z)}{\partial x} = \frac{\partial c(x,0,z)}{\partial y} = \frac{\partial c(x,y,0)}{\partial z} = 0, \\ D_x \frac{\partial c(L_x,y,z)}{\partial x} + \alpha_x (c(L_x,y,z) - c_{ax}) = 0, \\ D_y \frac{\partial c(x,L_y,z)}{\partial y} + \alpha_y (c(x,L_y,z) - c_{ay}) = 0, \\ D_z \frac{\partial c(x,y,L_z)}{\partial z} + \alpha_z (c(x,y,L_z) - c_{az}) = 0, \end{cases} \quad \text{(BVP1)}$$

where f_0 is the fixed source function, D_x, D_y, D_z are the constant coefficients, $\alpha_x, \alpha_y, \alpha_z$ are the constant mass transfer coefficients, c_{az}, c_{ay}, c_{ax} are the given concentration on the boundary.

A. The CAM with the hyperbolic type integral spline approximation in z-direction

Similarly, in [11] for solving (BVP1) we consider respect to the z-direction the CAM

$$c(x,y,z) = c_z(x,y) + m_z(x,y) f_{z1} + e_z(x,y) f_{z2} \quad (1)$$

$$f_{z1} = \frac{0.5 L_z \sinh(a_z(z-0.5L_z))}{\sinh(0.5 a_z L_z)}, \quad (2)$$

$$f_{z2} = \frac{\cosh(a_z(z-0.5L_z)) - A_{0z}}{8 \sinh^2(0.25 a_z L_z)}, \quad (3)$$

where $A_{0z} = \frac{\sinh(0.5 a_z L_z)}{0.5 a_z L_z}$, (4)

$c_z(x,y) = \frac{1}{L_z}\int_0^{L_z} c(x,y,z)dz$, (5) is the averaged value and a_z is fixed initial parameter (unknown).
We can see that the parameters a_z tend to zero then the limit is the integral parabolic spline from [4]. The unknown function $m_z(x,y), e_z(x,y)$ are determined from boundary conditions by $z = 0, z = L_z$: $d_z m_z - k_z e_z = 0$ (6), $m_z = p_z e_z$ (7),
$p_z = k_z / d_z$ (8), $d_z = 0.5 a_z L_z \coth(0.5 a_z L_z)$ (9),
$k_z = 0.25 a_z \coth(0.25 a_z L_z)$ (10),
$D_z(d_z m_z + k_z e_z) + \alpha_z(c_z + 0.5 m_z L_z + b_z e_z - c_{az}) = 0$ (11),
where $b_z = \frac{\cosh(0.5 a_z L_z) - A_{0z}}{8 \sinh^2(0.25 a_z L_z)}$. (12)
Therefore $e_z(x,y) = \frac{c_{az} - c_z(x,y)}{g_z}$, (13)
$g_z = b_z + 0.5 p_z L_z + 2 k_z D_z / \alpha_z$. (14)
The boundary value 2-D problem is in the following form:

$$\begin{cases} \frac{\partial}{\partial x}\left(D_x \frac{\partial c_z(x,y)}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial c_z(x,y)}{\partial y}\right) \\ + a_{0z}^2 (c_{az} - c_z(x,y)) + f_0 = 0, \\ \frac{\partial c_z(0,y)}{\partial x} = \frac{\partial c_z(x,0)}{\partial y} = 0, \\ D_x \frac{\partial c_z(L_x,y)}{\partial x} + \alpha_x (c_z(L_x,y) - c_{ax}) = 0, \\ D_y \frac{\partial c_z(x,L_y)}{\partial y} + \alpha_y (c_z(x,L_y) - c_{ay}) = 0, \end{cases} \quad \text{(BVP2)}$$

where $a_{0z}^2 = \frac{2 D_z k_z}{L_z g_z}$. (15)

B. The CAM with the hyperbolic type integral spline approximation in y-direction

For solving (BVP2) we are applying respect to y-direction of the CAM:
$c_z(x,y) = c_y(x) + m_y(x) f_{y1} + e_y(x) f_{y2}$ (16) - approximate solution with two functions

$$f_{y1} = \frac{0.5 L_y \sinh(a_y(y-0.5L_y))}{\sinh(0.5 a_y L_y)}, \quad (17)$$

$$f_{y2} = \frac{\cosh(a_y(y-0.5L_y)) - A_{0y}}{8 \sinh^2(0.25 a_y L_y)}, \quad (18)$$

where $A_{0y} = \frac{\sinh(0.5 a_y L_y)}{0.5 a_y L_y}$, (19)

$a_y = a_{0z}\sqrt{1/D_y}$. (20)

Similarly, as in the previous case - "the CAM in x - direction" we determine the unknown functions $m_y(x), e_y(x)$ from boundary conditions by $y = 0, y = L_y$ and we have

$e_y(x) = \frac{c_{ay} - c_y(x)}{g_y}$, (21)

$g_y = b_y + 0.5p_yL_y + 2k_yD_y/\alpha_y$, (22)

$m_y(x) = p_ye_y(x), p_y = k_y/d_y$, (23)

$d_y = 0.5a_yL_y\,coth(0.5a_yL_y)$, (24)

$k_y = 0.25a_y\,coth(0.25a_yL_y)$, (25)

$b_y = \frac{cosh(0.5a_yL_y) - A_{0y}}{8\,sinh^2(0.25a_yL_y)}$. (26)

Then we obtain the boundary value 1-D problem is in the following form

$$\begin{cases} \frac{\partial}{\partial x}\left(D_x\frac{\partial c_y(x)}{\partial x}\right) + a_{0y}^2\left(c_{ay} - c_y(x)\right) \\ +a_{0z}^2\left(c_{az} - c_y(x)\right) + f_0 = 0, \\ \frac{\partial c_y(0)}{\partial x} = 0, D_x\frac{\partial c_y(L_x)}{\partial x} + \alpha_x\left(c_y(L_x) - c_{ax}\right) = 0, \end{cases} \quad \text{(BVP3)}$$

where $a_{0y}^2 = \frac{2D_yk_y}{L_yg_y}$. (27)

C. The CAM with the hyperbolic type integral spline approximation in x-direction

For solving (BVP3) we are applying respect to x -direction the CAM:

$c_y(x) = c_x + m_xf_{x1} + e_xf_{x2}$ (28)- approximate solution with two functions

$f_{x1} = \frac{0.5L_x\,sinh(a_x(x - 0.5L_x))}{sinh(0.5a_xL_x)}$, (29)

$f_{x2} = \frac{\cosh(a_x(x - 0.5L_x)) - A_{0x}}{8\sinh^2(0.25a_xL_x)}$, (30)

where $A_{0x} = \frac{sinh(0.5a_xL_x)}{0.5a_xL_x}$, (31)

$c_x = \frac{1}{L_x}\int_0^{L_x} c_y(x)dx$ (32) is the average integrals value, the parameter a_x we choose in the following form

$a_x = \sqrt{(a_{0z}^2 + a_{0y}^2)/D_x}$. (33)

Similarly, to the previously discussed cases of the CAM, we determine the unknown constants m_x, e_x from boundary conditions by $y = 0, y = L_y$ and we have

$e_x = \frac{c_{ax} - c_x}{g_x}$, (34)

$g_x = b_x + 0.5p_xL_x + 2k_xD_x/\alpha_x$, (35)

$m_x = p_xe_x$ (36), $p_x = k_x/d_x$ (37),

$d_x = 0.5a_xL_x\coth(0.5a_xL_x)$, (38)

$k_x = 0.25a_x\coth(0.25a_xL_x)$, (39)

$b_x = \frac{cosh(0.5a_xL_x) - A_{0x}}{8\,sinh^2(0.25a_xL_x)}$. (40)

Solving boundary value problem (BVP3) we obtain a linear algebraic equation

$a_{0y}^2(c_{ay} - c_x) + a_{0z}^2(c_{az} - c_x) + a_{0x}^2(c_{ax} - c_x) +$

$+f_0 = 0$ (41)

or $c_x = \frac{f_0 + a_{0y}^2c_{ay} + a_{0z}^2c_{az} + a_{0x}^2c_{ax}}{a_{0y}^2 + a_{0z}^2 + a_{0x}^2}$, (42)

$a_{0x}^2 = \frac{2D_xk_x}{L_xg_x}$. (43)

3. Results and Discussion

In the previous chapter, it was obtained that the created splines contain one parameter in each of the three averaging directions, the choice of which determines the accuracy of the obtained solution.

In this chapter, a method was created to improve the accuracy of the obtained solution.

Accuracy can be improved by using different orientations of the averaging method, that is, by varying the averaging direction z, y and x in the dimensionality reduction process (3-D →2-D→1-D), thus obtaining the best parameter values that correspond to the optimal solution of the boundary value problem being solved.

The boundary value problem studied in the publication was solved, also using the Fourier method for homogeneous boundary conditions (BCs) of the first kind, and the numerical solutions obtained by both methods (the averaging method and the Fourier method) were compared.

A. The CAM with the hyperbolic type integral spline approximation in y -direction and z-direction

This chapter (*A.*) is studying the calculation of the parameters required for the conservative averaging method (CAM) using the direction change method in the process of implementing the CAM.

a) Calculation of a_y by applying averaging in y-direction

The approximate solution of the present stage of CAM is in the form:

$c(x, y, z) = c_y(x, z) + m_y(x, z)f_{y1} +$

$+e_y(x, z)f_{y2}$, (44)

where $c_y(x, z) = \frac{1}{L_y}\int_0^{L_y} c(x, y, z)dy$ (45) is the averaged value, functions f_{y1}, f_{y2} (46) are given in the section 2. *B.* Parameter a_y is in the form $a_y = a_{0z}\sqrt{1/D_y}$ (48), where $a_{0z}^2 = \frac{2D_zk_z}{L_zg_z}$ (49).

The k_z and g_z functions depend on the previous value of a_z in the iteration process. Therefore, the a_z value for this parameter must be defined as the starting value for the iteration process.

b) Calculation of a_z by applying averaging in z-direction

The approximate solution of the present stage of CAM is in the form:

$c_y(x,z) = c_z(x) + m_z(x)f_{z1} + e_z(x)f_{z2}$, (50)

where $c_z(x) = \frac{1}{L_z}\int_0^{L_z} c_y(x,z)dz$ (51) is the averaged value, functions f_{z1}, f_{z2} (52) are given in section *A*.

Parameter a_z is in the form $a_z = a_{0y}\sqrt{1/D_z}$ (53) where $a_{0y}^2 = \frac{2D_y k_y}{L_y g_y}$ (54).

The k_y and g_y functions depend on the a_y parameter value when averaging in y-direction (see *a)*).

This results in the new value of the a_z parameter in the iteration process.

c) Calculation of parameter $\boldsymbol{a_x}$

Parameter a_x is calculated using precalculated parameter values a_{0z}^2 and a_{0y}^2:

$a_x = \sqrt{(a_{0z}^2 + a_{0y}^2)/D_x}$. (55)

The calculated values of a_z, a_y, a_x (see *a)*, *b)* and *c)*) correspond to one step in the iteration process.

The process continues by repeating *a)*, *b)* and *c)* using the parameter values calculated in the previous step.

The iteration process is completed when the maximum difference between the two step corresponding parameter values, taken from the absolute value, does not exceed the predefined accuracy.

Values of the iteration process results - calculated parameters a_z, a_y, a_x should be used for the application of CAM to solve the boundary value problem (BVP1) studied in the present publication (see Chapter 2).

B. The Fourier method for homogenous boundary conditions of first kind

We use the Fourier method to solve the boundary value problem (BVP) under question and to compare it with conservative averaging method (CAM) with the aim to assess the efficiency of the CAM.

For solving (BVP1) (see Chapter 2) we consider the extended domain

$\Omega_1 = \{(x_1,y_1,z_1): 0 \le x_1 \le 2L_x, 0 \le y_1 \le 2L_y, 0 \le z_1 \le 2L_z\}$

where $x_1 = x + L_x \in [L_x, 2L_x]$,

$y_1 = y + L_y \in [Ly, 2L_y], z_1 = z + L_z \in [L_z, 2L_z]$ for $x \in [-L_x, L_x], y \in [-L_y, L_y], z \in [-L_z, L_z]$.

We have homogenous boundary conditions (BCs) of first kind with

$\alpha_z = \alpha_y = \alpha_x = \infty, c_{az} = c_{ay} = c_{ax} = 0$. (56)

Then for the partial differential equation of (BVP1) (see Chapter 2) we have following BCs (without symmetrically BCs for $x = y = z = 0$):

$c(x_1, y_1, 2L_z) = c(x_1, 2L_y, z_1) = c(2L_x, y_1, z_1) = c(x_1, y_1, 0) = c(x_1, 0, z_1) = c(0, y_1, z_1) = 0$ (57)

and the solution of the (BVP1) in the series form is:

$c(x_1,y_1,z_1) = \sum_{i,j,k}^{\infty} A_{i,j,k}W_{i,j,k}(x_1,y_1,z_1)$, (58)

$f_0 = \sum_{i,j,k}^{\infty} B_{i,j,k}W_{i,j,k}$, (59)

where

$B_{i,j,k} = f_0 \int_0^{2L_x}\int_0^{2L_y}\int_0^{2L_z} W_{i,j,k}(x_1,y_1,z_1)dx_1dy_1dz_1 = \frac{64f_0\sqrt{L_xL_yL_z}}{\pi^3(2i-1)(2j-1)(2k-1)}$, (60)

$W_{i,j,k}(x_1,y_1,z_1) = \sqrt{\frac{1}{L_xL_yL_z}}\sin\frac{i\pi x_1}{2L_x}\sin\frac{j\pi y_1}{2L_y}\sin\frac{k\pi z_1}{2L_z}$ (61)

are the orthonormed eigenfunctions $(i,j,k = \overline{1,\infty})$ with the corresponding eigenvalues

$\mu_{i,j,k} = \left(\frac{i\pi}{2L_x}\frac{j\pi}{2L_y}\frac{k\pi}{2L_z}\right)^2$. (62)

Therefore

$A_{i,j,k} = -C_0\sqrt{L_xL_yL_z}(-1)^{i+j+k}(a_{i,j,k})^{-1}$, (63)

$a_{i,j,k} = (2i-1)(2j-1)(2k-1)(a_i + a_j + a_k)$, (64)

$a_i = D_x((2i-1)/L_x)^2$, (65)

$a_j = D_y((2j-1)/L_y)^2$, (66)

$a_k = D_z((2k-1)/L_z)^2$, (67)

$C_0 = \frac{256f_0}{\pi^5}$. (68)

We apply the Fourier series solution, performing averaging in different directions.

For averaging in xyz-direction by $z = L_z$ we have $c_{xyz} = \frac{1}{L_xL_yL_z}\int_{L_x}^{2L_x}\int_{L_y}^{2L_y}\int_{L_z}^{2L_z} c(x_1,y_1,z_1)dx_1dy_1dz_1$ (69)

and the discrete form of the solution is $c_{xyz} = \frac{8C_0}{\pi^3}\sum_{i,j,k}^{\infty}(b_{i,j,k})^{-1}$, $b_{i,j,k} = (2i-1)^2(2j-1)^2(2k-1)^2(a_i + a_j + a_k)$. (70)

For averaging in yz-direction by $x = L_x$ we have $c_{yz} = \frac{1}{L_yL_z}\int_{L_y}^{2L_y}\int_{L_z}^{2L_z} c(L_x,y_1,z_1)dy_1dz_1$ (71) and the discrete form of the solution is

$c_{yz} = -\frac{4C_0}{\pi^2}\sum_{i,j,k}^{\infty}(-1)^i(c_{i,j,k})^{-1}$, (71)

$c_{i,j,k} = (2i-1)(2j-1)^2(2k-1)^2(a_i + a_j + a_k)$. (72)

For averaging in z-direction by $x = L_x, y = L_y$ we have $c_z = \frac{1}{L_z}\int_{L_z}^{2L_z} c(L_x,L_y,z_1)dz_1$ (73) and the discrete form of the solution is

$c_z = \frac{2C_0}{\pi}\sum_{i,j,k}^{\infty}(-1)^{i+j}(d_{i,j,k})^{-1}$, (74)

$d_{i,j,k} = (2i-1)(2j-1)(2k-1)^2(a_i + a_j + a_k)$. (75)

The maximal value M_F is calculated as follows: $M_F = c(L_x,L_y,L_z) = -C_0\sum_{i,j,k}^{\infty}(-1)^{i+j+k}(a_{i,j,k})^{-1}$. (76)

Example 1.

We consider the (BVP1) (see Chapter 2) with parameters $f_0 = 1, L_z = 1, L_x = 1, L_y = 1, D_z = 10^{-3}, D_x = D_y = 3.10^{-4}$, $\alpha_z = \alpha_y = \alpha_x = \infty$, $c_{az} = c_{ay} = c_{ax} = 0$. For initial value $a_z = 1$ we obtain with the iteration process using 5 iterations (*It*) the following parameter values $a_z = 1.1898, a_y = 3.3027, a_x = 3.9530$ for applying the CAM, difference (*konv*) (maximum difference between the two step corresponding parameter

values, taken from the absolute value) is defined 10^{-6} (see Fig. 1, Table 1).

TABLE 1 ITERATION PROCESS RESULTS

Iteration steps	Parameters		
	a_z	a_y	a_x
1.	1.0000	3.2632	3.9158
2.	1.1856	3.3018	3.9521
3.	1.1897	3.3027	3.9530
4.	1.1898	3.3027	3.9530

Table 1 shows the first four iteration steps for coefficient values, written with four decimal places. The results of the fourth and fifth steps do not differ from the results of the third iteration step for the number of decimal places considered.

The maximal values (M) and averaged values (A) of the solution were compared, obtained by the Fourier method and by the spline method (hyperbolic, parabolic approximation):

1. Maximal values M ($M_F = 403.63$ for Fourier method with 10 series sum $M_H = 399.44$ for hyperbolic approximation, $M_P = 703.125$ for parabolic approximation);
2. Averaged values A for the following averaging directions:

a) xyz -direction ($Axyz_H = 159.39$ for hyperbolic approximation, $Axyz_F = 154.40$ for Fourier method, $A_P = 208.33$ for parabolic approximation);
b) yz -direction ($Ayz_H = 205.13$ for hyperbolic approximation, $Ayz_F = 203.37$ for Fourier method);
c) z -direction ($Az_H = 272.27$ for hyperbolic approximation, $Az_F = 271.96$ for Fourier method),
($a_x = a_y = a_z = 0.0001$ for parabolic spline).

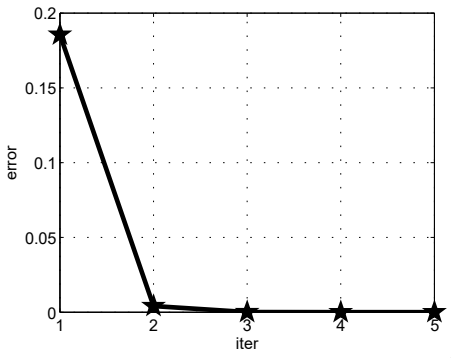


Fig. 1. Iteration process for a_z, error for *konv*=10^{-6}, $It = 5$.

In the Fig. 2 - Fig. 4 there are represented the hyperbolic and parabolic spline solutions $c(x, y, 0)$ and Fourier method's solutions $c(x_1, y_1, L_z)$.

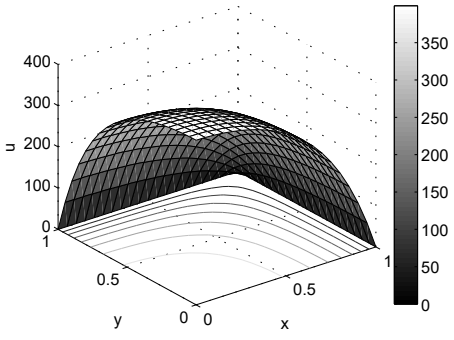


Fig. 2. Solution $u = c(x, y, 0)$ with hyperbolic approximation, $Max_H = 399.44$, $A_H = 159.39$.

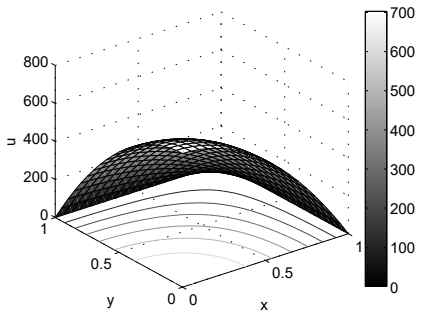


Fig. 3. Solution $u = c(x, y, 0)$ with parabolic approximation, $Max_P = 703.125, A_p = 208.33$.

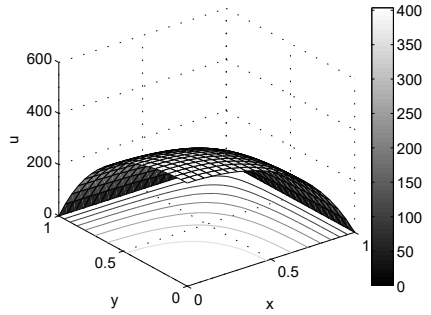


Fig. 4. Solution $u = c(x, y, 0)$ with Fourier approximation, $Max_F = 403.63, A_F = 154.40$.

To assess the accuracy of the results of the studying method, a relative error was used concerning another method (conditionally, more accurate).

Then the relative error of the results for the hyperbolic spline method, calculated relative to the result of the Fourier method, was approximately 1% for the value $M$and 3% for the value A (comparing the results of Fig. 2 and Fig. 4).

If $\alpha_x = \alpha_y = \alpha_z = 1$ (the case of the third kind of boundary conditions), then for hyperbolic splines we have obtained $M_H = 676.02, Axyz_H = 173.17$.
The maximal values (M) and averaged values (A) of the solution were compared also in the case of the third-kind of boundary conditions obtained by the spline method (hyperbolic, parabolic approximation) for BVP parameters $L_x = L_y = 1, L_z = 1, c_{ax} = c_{ay} = c_{az} = 0$, $\alpha_x = 1, \alpha_y = 20, \alpha_z = 300, D_x = 10^{-1}, D_y = 10^{-2}, D_z = 10^{-3}$ and for spline function's parameters $a_y = 0.6200, a_x = 0.2932, \alpha_z = 300$, thus obtained the result: $M_H = 800.78$, $Axyz_H = 204.15$, $M_P = 911.59$, $A_P = 213.87$.
Then the relative error of the results for the parabolic spline method, calculated relative to the result of the hyperbolic spline method, was 14% for the value M and 5% for the value A.

Example 2.
We consider the (BVP1) (see Chapter 2) with parameters $f_0 = 2, L_z = 1, L_x = 2, L_y = 2, D_z = 10^{-3}$, $D_x = 10^{-3}$, $D_x = 3.10^{-4}$, $D_y = 3.10^{-5}$, $\alpha_z = \alpha_y = \alpha_x = \infty$, $c_{az} = c_{ay} = c_{ax} = 0$. For the initial value $a_z = 1$ we obtain with the iteration process using 5 iterations the following parameter values $a_z = 0.3983, a_y = 10.0525, a_x = 3.2610$ for applying the CAM.
For comparing the maximal (M) and averaged (A) solution's values obtained by the Fourier method and by the spline method (hyperbolic approximation) the following results were calculated:
1. Maximal values M ($M_F = 992.16$ for Fourier method with 20 series sum, $M_F = 992.17$ for Fourier method with 40 series sum, $M_F = 1004.14$ for Fourier method with 10 series sum, $M_H = 984.08$ for hyperbolic approximation);
2. Averaged values A for the following averaging directions:
a) xyz -direction ($Axyz_H = 530.78$ for hyperbolic approximation, $Axyz_F = 528.05$ for Fourier method);
b) yz -direction ($Ayz_H = 625.06$ for hyperbolic approximation, $Ayz_F = 626.06$ for Fourier method);
c) z -direction ($Az_H = 657.78$ for hyperbolic approximation, $Az_F = 661.45$ for Fourier method).
3. $M_P = 2078.52$, A_P=615.86 for parabolic approximation.
There are represented the hyperbolic and Fourier methods solutions $c(x, y, 0)$ (see Fig. 5 and Fig. 6).

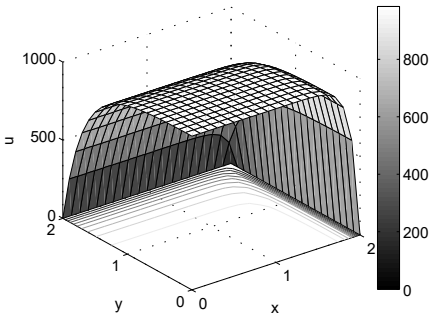


Fig. 5. Solution $u = c(x, y, 0)$ with hyperbolic approximation, $Max_H = 984.08, A_H = 530.78$.

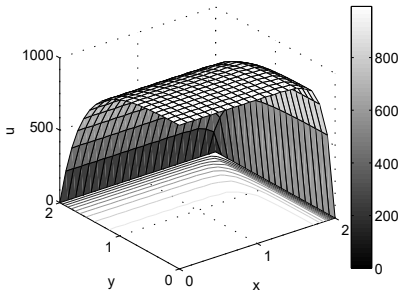


Fig. 6. Solution $u = c(x, y, 0)$ with Fourier approximation, $Max_F = 992.17, A_F = 523.05$.

In this case, the comparison results (Fig. 5 and Fig. 6) are as follows - the relative error of the results for the hyperbolic spline method, calculated concerning the result of the Fourier method, was approximately 1% for the value $M$and 2% for the value A .
Similar to the previously discussed cases, here too, the relative error obtained with the hyperbolic spline method concerning the result of the Fourier method does not exceed 3%.

4. CONCLUSIONS

1. Being based on the conservative averaging method (CAM), the special hyperbolic type splines with 2 fixed functions with unknown parameters for solving 3-D stationary diffusion boundary value problem (BVP) have been created.
2. It is characteristic that for the successful solution of the above-mentioned BVP, it is necessary to find the unknown parameters in the fixed functions, included in the splines. Therefore, in addition to the developed general scheme of the conservative averaging method (for example, averaging in the z ->y->x directions), it was necessary to create a special method for calculating the unknown parameters of spline functions. The developed method is based on varying the averaging directions, which allows a calculation of the necessary parameter values to obtain the optimal solution to the boundary value problem.
It should also be noted that varying the directions can be successfully applied to other types of splines, such as

exponential and parabolic, in solving boundary value problems.

3. To assess the accuracy of the results of the method under study, the relative error was used regarding another method (conditionally more accurate), for example, the relative error of the results of the hyperbolic spline method regarding the results of the Fourier method was calculated. In the case of first-kind boundary conditions (BCs), the relative error was calculated regarding the results of the Fourier method, but for the third kind BCs (comparing hyperbolic and parabolic spline) - regarding the results of the hyperbolic spline solutions.

In numerical experiments solving the studied boundary value problem, it was found that the relative error of the results for the hyperbolic spline method, calculated relative to the result of the Fourier method,
did not exceed approximately 1% for the maximal value M and 3% for the averaged value A - therefore, it is a completely acceptable result for engineering calculations.

4. It is also worth noting the excellent capabilities of the MATLAB software in solving the studied boundary value problem with the Fourier method in defining mass transfer coefficients and further using them as the operational algorithms. For the theoretical values $\alpha_z = \alpha_y = \alpha_x = \infty$ choosing $\alpha_z = \alpha_y = \alpha_x = 10^9$ in the corresponding practical solution, we obtain a solution to the boundary value problem that is completely correct for the theoretical framework and useful in practice.

5. The Solution of the studied boundary value problem obtained by the CAM in the analytical form allows for a better understanding and interpretation of the solution of the studied 3-D BVP alongside other possible methods of obtaining the solution only numerically.

REFERENCES

[1] E. Teirumnieka, E. Teirumnieks, I. Kangro, H. Kalis, A. Gedroics. The mathematical modeling of Ca and Fe distribution in peat layers. Proceed. Of the 8-th int. scienti_c practical conference "Environment. Technology. Resources." Rezekne higher education institution, June 20-22, 2 2011, 40-47.

[2] I. Kangro, H. Kalis, A. Gedroics, E. Teirumnieka, E. Teirumnieks. On mathematical modelling of metals distributions in peat layers. Mathematical Modelling and Analysis, 19:4 2014, 568-588.

[3] M. R. Talaee and V. Sarafrazi, Analytical solution for three-dimensional hyperbolic heat conduction equation with time-dependent and distributed heat source. Journal of Mechanics, DOI: 10.1017/jmech.2016.42, 2016, pp.1-11.

[4] A. Buikis, The analysis of schemes for the modelling same processes of filtration in the underground. Riga, Acta Universitatis Latviensis, 592, 1994, 25-32 (in Latvian).

[5] A. Buikis, Modelling filtration processes in layered porous media by the conservative averaging method. Dr. Thesis, Kazan, 1987 (in Rusian).

[6] A. Buikis, Conservative averaging as an approximate method for solution of some direct and inverse heat transfer problems. Advanced Computational Methods in Heat Transfer, WIT Transaction on Engineering Sciences, vol.53 2006, 311-320.

[7] A. Buikis, Conservative Averaging Method: Theory and Applications. Abstracts of MMA2015, May 26-29, Sigulda, Latvia, 2015, pp. 2.

[8] A. Buikis, The conservative averaging method development in the petroleum science. Journal of Scientific and Engineering Research, 2017, 4(4):176-197.

[9] E. Bejaoui and F. Ben Belgacem, Treatment of 3D diffusion problems with discontinuous coefficients and Dirac curvilinear sources, Appl. Numer. Math. 207, 2025, pp. 400–413.

[10] H. Kalis, A. Buikis, A. Aboltins, I. Kangro. Special Splines of Hyperbolic Type for the Solutions of Heat and Mass Transfer 3-D Problems in Porous Multi-Layered Axial Symmetry Domain. Mathematical Modelling and Analysis, 22:4 2017, 425-440.

[11] H. Kalis, A. Buikis and I. Kangro, Special splines of exponential type for the solutions of mass transfer problems in multi-layer domains. Mathematical Modelling and Analysis, 21:4 2016, 450-465.

[12] A. Buikis, H. Kalis and I. Kangro, Special hyperbolic type spline for mass transfer problems in multi-layer 3-D domains. Proc. of 3-rd int. conf. on applied, numerical and computational mathematics (ICANCM 15). Sliema, Malta, 2015, 25-34.

[13] I. Kangro, H. Kalis, E. Teirumnieka, E. Teirumnieks. Special Hyperbolic type approximation for solving of 3-D two-layer stationary diffusion problem. Proc. of the 12th int. scienti_c practical conference Environment. Technology. Resources., Rezekne Academy of Technologies, June 20-22, 2019, 95-100.

[14] A. Aboltins, I. Kangro and H. Kalis, Conservative averaging methods for solving some nonlinear heat transfer problems related to combustion. Proc. Of the 19th int. conf. Engineering for Rural Development, May 20-22, 2020, Jelgava, 2020, 1698-1705.

[15] H. Kalis and I. Kangro, Effective Finite Difference and Conservative Averaging Methods for Solving Problems of sMathematical Physics. Monography, Rēzekne: Rēzeknes Tehnoloģiju akadēmija, 2021.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 189-195

National Strategies for Digitization of Higher Education: a Comparison Between Latvia and Lithuania

Saranya Kanna Baskar
Department of Business Management
Biznesa augstskola Turība
Rīga, Latvia
saranyakannan85@gmail.com

Velga Vēvere
Department of Business Management
Biznesa augstskola Turība
Rīga, Latvia
velga.vevere@gmail.com

***Abstract*— Digitization has impacted both countries and shown extensive potential. However, there are differences in both countries in contexts like culture, cognition, tradition, and economic performance among the two countries. The present research has thus developed a comparative scenario of the efforts taken by Latvia and Lithuania to promote and upgrade their higher education sector. This research has covered peer-reviewed data and comparative scenario of the strategic focus of the strategic focus of national strategies implemented for the digitization of Higher Education, the E-learning structure, the rate of digital and other such aspects in Latvia and Lithuania. The research found that in comparing national strategies for the digitization of higher education between Latvia and Lithuania, both countries demonstrate a commitment to advancing digital education but through distinct approaches. While Lithuania has adopted a more centralized, policy-driven strategy with clearly defined goals for digital transformation; Latvia has taken a more decentralized path, allowing individual institutions more autonomy in their digital initiatives. The research highlights that while both Latvia and Lithuania are devoted to digitizing higher education, their strategies differ in focus and execution. Latvia's all-inclusive and well-funded method may lead to instant and broad-based digital incorporation. On the other hand, Lithuania's directed approaches could cause in more comprehensive and need-specific results.**

Keywords*— *Digitization, Higher Education, Latvia, Lithuania, Higher Education Strategies

I. Introduction

Lithuania and Latvia are neighbouring countries and strong allies who have cooperation in all the bilateral contracts. Digitization has impacted both countries and shown extensive potential [1]. However, there are differences in both countries in contexts like culture, cognition, tradition, and economic performance among the two countries [2].

The study intends to develop a comparative scenario of the efforts taken by the two case countries, namely Latvia and Lithuania to promote and upgrade their higher education sector and the corresponding national strategies implemented for the purpose. Therefore, the study will cover peer-reviewed data and a comparative scenario of the strategic focus of the strategic focus of national strategies implemented for the digitization of Higher Education, the E-learning structure, the rate of digital and other such aspects in each of these countries. The specific contents of this comparative study have been discussed in the present research.

Strategic Focus is the main component of the strategic framework of a country or organization which indicates that there is clarity in the mission and vision. Moreover, the clarity in mission and vision is well-articulated in the strategy taken by the country or the organization [8], [9]. A strategic focus is very important in the process of digitization of higher education because it gives the organizations, countries or stakeholders direction a roadmap on how the goal can be achieved and the barriers that come along in the path can be overcome [10], [11]. Thus, the application of this understanding of the importance of strategic focus in higher education shows that the Baltic States comprising of countries such as Estonia, Latvia, and Lithuania have considered it as their goal to enable digitization in their higher education sector. The small size, demography and flexibility of each of these countries present a conducive environment for innovation [12]. A comparative study on the strategic focus of digitization initiatives in Latvia indicates that the country prioritizes regular assessment of the digital competencies of its students so that the loopholes can be identified and holistic education can be provided to them. The country also gives the first priority to safety parameters of digital competency development of the students so that students can learn how to use the digital

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8597
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

resources and platforms safely [13], [14]. Then the development of their communication and collaboration skills is prioritized. Latvia also gives importance to the deployment of hybrid teaching-learning as part of the curriculum of digital competence so that it benefits the hybrid audience [13]. The distinctive aspect of the digitization initiative of Lithuania is that its focus is on the development of digital competency among students right from the primary and secondary school levels. Simultaneously, the country makes an effort to promote adult digital competency.

TABLE 1 STATUS OF DIGITALIZATION OF HIGHER EDUCATION IN LATVIA AND LITHUANIA

Latvia		
Latvia has implemented extensive strategies to advance the digitization of higher education, emphasizing digital skills development and infrastructure improvements as part of the "Digital Transformation Guidelines for 2021-2027."		
Digital Skills Goals	• 70% of citizens with at least basic digital skills by 2027. • 45% of citizens achieving above-basic digital skills. • 3% of employed individuals working as ICT specialists	[3]
Funding and Investment	• €203 million allocated for digital skills activities, supported by national and European funding sources	[3]
COVID-19 Remote Learning Transition	• During the pandemic, approximately 23% of students in the fall semester of 2020 believed they achieved all study results via remote learning. • This increased to 34.8% in the spring semester of 2021,	[4]
LITHUANIA		
Index of Readiness for Digital Lifelong Learning	Lithuania ranks 11th among EU-27 countries with an index score of 0.623 stating its moderate readiness for digital education, institutions and policies, and the availability of digital learning	[5]
ICT Infrastructure and Training	It developed EdTech solutions in schools, the development of teacher competencies in digital education, and the training of 21,600 individuals by 2026 to acquire digital skills.	[6]
European Horizon Projects	As of 2024, Lithuania has secured €13 million in funding for 29 projects under the Horizon program (focusing on research and innovation in digitalization)	[7]

Through a unified model of Lifelong Learning System, Lithuania also promotes digitization initiatives for all learners, irrespective of their ages [15]. These focal areas are grossly missing in the digitization drive of Latvia. Nonetheless, to that of Latvia, and Lithuania also have a platform for regular assessment of the digital competencies of the students [13], [15] Another commonality between the strategic focus of the digitization initiative of both Latvia and Lithuania. The latter considers it as a core principle to teach the safe use of digital technologies as part of its digital competency development drive [15].

The major flaw in the strategic focus is Latvia is that it lacks a clear explanation of the allocation of sufficient funds for investment in digitalization. Similarly, there is dearth of availability of simultaneous training and development of academic and administrative staff. The country also fails to mention clear objectives of the digital competency development of the students in light of global education standards [14]. Unlike Latvia, Lithuania also has detailed strategies and roadmaps for promoting digitization. Along with these, the country also gets financial support from European Union Structural Funds for Lithuania for developing three major components of its digitization framework, namely, digital public services, digital access and skills, and digital infrastructure [16].

There are certain similarities in the strategic focus of both Latvia and Lithuania in terms if the development of the digital competency framework of their respective countries as well. For instance, there is a gross lack of any effort to develop a micro-credentials ecosystem where efforts will be made towards upskilling the digital competencies of the staff with proper training. There is least attention towards the development of strategies for retaining high-level digitally competent professionals [15].

II. MATERIAL AND METHODS

A. Comparison of E-Learning Infrastructure

The E-Learning Infrastructure can be understood as the total of all the components that are necessary for achieving success in digitization initiatives. Even though there are no definite ways to define the components of E-Learning Infrastructure, e-learning systems, communication applications, internet services, and electronic devices are roughly some of its vital components [17]. E-learning infrastructure is an important component of digitization in education because it plays a crucial role in improving both the quality of education and cognitive competence of the learners through the use of technologies like Learning Management Systems (LMS), electronic devices, communication applications, and internet accessibility [18]. Based on this understanding, the assessment of the E-learning infrastructure of Latvia shows that Latvia has to follow a formal framework in the sector of higher education for being a part of the European Union. One of these is the Strategic Framework for European cooperation in education and training. The purpose of this framework is to allow the exchange of best

practices in education policy, gather and disseminate knowledge and advance educational policies for initiating educational policy and reforms, both at the national and regional levels [19]. Therefore, being a part of the country European Union, Latvia also follows objectives like 'Lifelong learning' and 'Mobility a reality' as part of its E-learning initiative. Additionally, Latvia also uses digital tools for establishing social ties between teachers and students [20]. In complying with the guidelines of the EU, Latvia has widened the scope of its E-learning framework. Now, in addition to the acquisition of ICT basic skills, the framework aims to develop interactive e-resources for facilitating effective E-learning for learners of different ages. The framework also intends to develop a holistic information and knowledge society. Therefore, it integrates ICT applications in learning, teaching and dispersal of education at different levels of education (formal, non-formal and informal) [21]. However, among the bottleneck areas in the E-Learning Framework of Latvia are regional disparities in accessing and using e-Learning resources and a lack of adequate support for promoting E-Learning among adults so that they can manage their daily chores and work simultaneously [22], [23]. Thus, a distinctive feature of the E-Learning framework of Latvia is that it mainly intends to spread digital competency among adults who have not been exposed to digital skill development yet.

When compared with the E-Learning framework of Lithuania, it will be seen that the focus of this framework is mostly to encourage distance learning [24]. Secondly, both the framework of higher studies E-Learning of Lithuania is guided by the Law on Higher Education and Research of the country itself [25]. The framework does not have any connection with the guidelines of the EU which is the case for the E-Learning framework of Latvia. Another important aspect of the E-learning framework of Lithuania is that the country is making several endeavours consistently to spread its access to all the interested learners irrespective of their regional differences. This shows that the regional disparity regarding access to upgraded and digitized higher education is not a problem for Lithuania as the country promotes distance education [26]. Moreover, Lithuanian scholars constantly monitor the quality of distance education and conduct research to upgrade its frameworks [27]. On the contrary, the E-Learning framework of Latvia lacks these supportive facilities which make it difficult for adult learners to balance their education with work, life responsibilities and daily chores [22].

Even though there are differences in the E-Learning frameworks of Latvia and Lithuania, a common feature could be found in the frameworks of these case countries. Both countries integrate lots of ICT tools for knowledge gathering and dispersal and the creation of effective virtual learning environments. For instance, while the E-Learning framework of Lithuania comprises tools such as WebCT virtual learning environment, ViPS video lecturing system, the E-Learning framework of Latvia integrates tools like interactive whiteboards, computers, multimedia projectors and digital gauges [26], [28].

B. Comparison of Digital Literacy

Digital literacy is the ability of average individuals of a country to understand and use digital technology effectively in their daily life activities. It is the amalgam of specific knowledge, skills and dispositions that are integral to using digital media effectively [29]. Digital literacy is important because it develops the acumen of individuals to learn, change and adapt to the fast evolving digital world so that they become capable of mining and processing meaningful information in such a way that the knowledge can be used for solving practical problems [30]. Lithuania and Latvia are among the countries that are trying to spread the reach of digital literacy throughout the country too. The scenario of Latvia in particular suggests that in 2022, the basic digital literacy rate of the country was 50.8%. Since Latvia follows the EU guidelines of digitization competency, the statistics were 4.8% below the EU average of digital skills expected from the people of a country. In 2023, the basic digital competency in Latvia decreased further and exhibited only 45.3% of the total population of the country. The basic digital skills of the Latvian population fell further and demonstrated 32.5% of the total population [31]. The majority of the Latvian population is moderate level internet users [32]. Moreover, their average internet use and digital skills are not similar to that of the neighbouring countries of Latvia with similar GDPs like Estonia and Lithuania [33].

A focused comparison of the digital literacy of the case country Lithuania suggests that this neighbouring country of Lithuania has 93% digital competency [33]. This shows that a quarter of the population of Latvia lacks basic digital skills like reading, counting and interpreting digital data [33]. A statistical database by the Ministry of the Economy and Innovation of the Republic of Lithuania, [34] from 2023 further shows that in Lithuania basic digital literacy is highest among people of age groups 16 to 24 years old. 81.28% of this group has digital literacy. This is followed by the age group of 25-34 years with 78.41% digital literacy. The digital literacy is lowest in the Lithuanian population belonging to the age group of 65 to 74 years whose competency represents only 15.15% of the population [34]. Thus, a comparative study of the digital literacy of Latvia and Lithuania shows that the average population of Lithuania has higher digital literacy as compared to that of Latvia.

Following table presents a comparison between Latvia, Lithuania and EU average on basic digital literacy-

TABLE 2 BASIC DIGITAL LITERACY- LATVIA VS LITHUANIA VS EU AVERAGE

Category	Latvia	Lithuania	EU Average
People with Basic Digital Skills (Age 16–74)	45%	52.90%	55.60%
ICT Specialists in Workforce	2.80%	4.90%	4.80%

Sources: [35][36]

Following table presents a comparison between Latvia, Lithuania and EU average on digital skill development-

TABLE 3 DIGITAL SKILL DEVELOPMENT- LATVIA VS LITHUANIA VS EU AVERAGE

Matric	Latvia	Lithuania	EU Average
Basic Digital Skills (% of population)	48%	50%	54%
Above Basic Digital Skills (% of population)	24%	28%	26%
ICT Specialists (% of total employment)	2.80%	3.70%	4.60%
ICT Graduates (% of all graduates)	3.20%	5.10%	3.90%
Adults in ICT Training (% of population 25–64)	8%	9%	11%
Use of Internet for Online Learning (% of internet users)	22%	24%	27%
Participation in Digital Up skilling (Last 3 months)	17%	21%	23%

Source: [35], [37]

It can be inferred from the above table that Lithuania slightly outperforms Latvia. But EU average outperforms both the countries.

Further, the table below presents the availability of online courses- Latvia vs Lithuania-

TABLE 4 AVAILABILITY OF ONLINE COURSES-- LATVIA VS LITHUANIA

Metric	Latvia	Lithuania
Share of internet users engaging in online learning activities (2022)	27.78%	32.17%
Adult participation in lifelong learning (2022)	9.70%	27.40%

Sources: [38], [39]

It can be inferred from the above table that Lithuania outperforms Latvia when it comes to online course users. Also, the adult population participation in using online courses is also higher than Latvia.

III. RESULTS AND DISCUSSIONS

A. Distance Learning

Distance learning is a form of teaching-learning session in which there is no physical classroom. There is no need for the learners to be physically present in any traditional form of classroom to undergo any course [40]. Technology plays a crucial role in facilitating distance learning because educators and learners are spatially separated from each other in this format of learning. So, they depend upon digital technology and multimedia for setting up distance learning classrooms [41]-. Distance learning has been chosen as a factor for comparison between the case countries because it breaks the formal barriers of higher education and gives greater scopes to the learners for pursuing further education [42]. In Latvia, only 10% of all off-site students were undergoing distance education courses in 2010-2011. Again, the Latvia's Sustainable Development Strategy 2030 was taken around 2012 to include universities for training programs fully based on distance education. During that time, five universities, ten institutions of higher education and three colleges were already running courses through distance education. In addition, a private institution was offering studies exclusively through the mode of distance education [43]. According to the report of the Ministry of Education and Science, there had been a drastic rise in distance education in 2020 with an average growth of 20% of such institutions. Distance education has been taken up at the secondary level has been taken up by many schools in Latvia over the past few years post COVID situation. The number of showing interest in distance education has also increased by 30% in the post COVID years [44]. In the case of adult education, Education Development Strategy of Latvia considers distance learning mode as ideal [45]. However, the country is a strong supporter of the importance of physical institutions specifically in the case of school level education [44]. A comparative scenario of distance education in Lithuania shows that Lithuania also has a long history of distance education. The top universities in the country such as Kaunas University of Technology, Lithuanian University of Health Sciences, LCC International University, Kazimieras Simonavicius University, Vilnius University and Mykolas Romeris University have at least one distance learning program for their students. These institutions have around 700 to 1500 student enrolment [46]. Mykolas Romeris University (MRU), which is the leading institution of Lithuania has around 7500 students enrolled in their distance learning courses [47]. A major inference drawn from the data presented so far is that even though distance learning is encouraged in both countries is encouraged, Lithuania has a stronger foundation with a much higher percentage of student enrolment in various distance learning technical courses than Latvia.

B. Research And Innovation

While research is the systematic process of generating new knowledge, innovation is improvising this new knowledge and making it appropriate for solving practical problems [48]. Research and innovation are important for measuring the level of progress of any educational institute or any education system and assessing their compatibility with global standards [49], [50]. Assessment of the level of research and innovation in the educational sector of Latvia shows that the country has developed the STDI policy for the year 2021-2027 to develop a new base and generate new knowledge for the development of high-quality research based educational system that would lead to creative and skilful society. The policy also aimed to develop sustainable human capital for the country [51]. Since 2011, there has been 221% increase in invesment in Research and Development. The majority of R&D projects in the country take place in

higher educational institutions and research institutes. Currently, there are 62 registered research institutions in the country. 22 of these institutes are publicly owned and funded by the Latvian government. The niche areas of R&D in Latvia are Biomedicine and pharmaceuticals, Smart materials and photonics, Information and communication technologies and Agriculture and life sciences [52]. Nonetheless, even though there are earnest efforts of Latvia to promote research and development, R&D in the higher education system in particular remains connected with the EU funding cycles. Hence, longer-term R&D planning becomes difficult. Therefore, the role of the Latvian government becomes vital here in boosting overall investment in R&D in the higher education sector to enable the innovation capacity of the private institutions [53]. On the contrary, in Lithuania, the investment in R&D activities for fostering technological development is very low. Contrary to Latvia where the effort of Latvian government is seen, the growth of investments in R&D in private sector of Lithuania is also very low [54]. The reason is, 54.9% of the investment in R&D is EU funded and meant for the business sector. Moreover, as the EU funding is mostly aimed at fostering income scopes, the least attention is given to innovation. Therefore, the technological development policies taken in Lithuania fail to ensure a breakthrough in innovation [54]. The Lithuanian government also makes up only 1% of their GDP in R&D in the sectors of education and technology [55]. These aspects make the pace of R&D very slow in Lithuania as compared to Latvia.

C. International Collaboration

International Collaboration must be understood as a form of strategic cross-border partnership between countries so that both parties mutually benefit [56]. In the educational sector, international collaboration brings innovation through the flow of new knowledge. This enhances the academic quality of the educational institutes and gives them global recognition [57]. Lithuania actively collaborates with international organizations like NATO and the EU to promote human rights and democracy. The country also collaborated with Latvia and Estonia to secure their positions in the face of the risks presented by Russia [58]. The country also encourages international collaborations with other countries and welcomes students from abroad to study in Lithuanian academic institutions. This strengthens the health of the Lithuanian tertiary education sector [59]. While Latvia already maintains international collaboration with Lithuania to maintain its safety against Russia [58]The country's universities also actively engage in international collaboration to facilitate international identification, enable information and knowledge exchanges, and strengthen their good reputation. It has active bilateral partnership agreements with 233 universities located in 53 countries and regions of the world. Latvia has recently signed 1020 international agreements with 447 institutions under 33 European programmes. Additionally, Latvia has signed and 38 Inter-institutional agreements with 17 partner countries to improve its educational sector [60]. Thus, while efforts to establish international collaboration can be noticed in the case of both countries, Latvia has a more proactive approach whereby it consistently enters into regular bilateral partnership agreements. In the case of Lithuania, there is more interest for internationalization to promote qualitative improvement of the educational sector.

Overall, both countries are facing many challenges when it comes to digitalization of higher education. Following table summarizes these challenges-

TABLE 5 CHALLENGES OF DIGITALIZATION OF HIGHER EDUCATION- LATVIA VS LITHUANIA VS EU AVERAGE

Metric	Latvia	Lithuania	EU Average
Basic Digital Skills (% of population aged 16–74)	45.30%	52.90%	55.60%
Above Basic Digital Skills (% of population aged 16–74)	24%	23%	26%
ICT Specialists (% of total employment)	4.40%	4.90%	4.80%
Enterprises Providing ICT Training to Employees	15%	Data not specified	22%
5G Coverage in Populated Areas	53.10%	98.90%	89.30%
Adoption of Cloud Computing by Enterprises	Increased by 14.3% in 2023	33.6% of enterprises use cloud services, below EU average of 38.9%	38.90%
Adoption of Artificial Intelligence (AI) by Enterprises	Data not specified	4.9% of enterprises use AI, below EU average of 8%	8%

Sources: [61]–[63]

IV. CONCLUSION

A comparative scenario of the higher education sector of Lithuania and Latvia was provided to understand the need and significance of digitization in them. The research conducted a comparative study and found distinctive differences between Latvia and Lithuania in the infrastructure, funding, focus and other aspects. It was found that fund allocation in higher education is not clearly mentioned in Latvia whereas Lithuania has a clear guideline in this aspect. In Latvia, fund allocation in higher education often lacks clear and transparent guidelines, making it challenging to track how resources are dispersed across institutions and programs. By contrast, Lithuania has developed a more structured

approach to funding higher education. Lithuania's funding model includes clear distribution guidelines and often includes a mix of state funding, competitive grants, and performance-based financing. This structure is intended to support funding with strategic intentions like quality developments, research results, and institutional effectiveness.

In Latvia, the lack of consistent guidelines can lead to discrepancies in how organizations receive and exploit their funds, possibly affecting the quality and attractiveness of their higher education system. The Lithuanian model might offer Latvia a outline for generating a more transparent and performance-oriented funding system, helping stakeholders through clear standards and answerability

Again, Lithuania promotes digital competency from the school level, but the focus of Latvia is on adult digital competency development. However, Latvia is proactive in terms of international collaborations to boost the educational sector. Further, Latvia makes considerable investment in R&D in the higher education sector.

In comparing national strategies for the digitization of higher education between Latvia and Lithuania, both countries demonstrate a commitment to advancing digital education but through distinct approaches.

The present research will serve as a comprehensive literature on understanding different digital education models of Latvia and Lithuania. This research will facilitate the stakeholders in understanding government policies impact higher education digitization in both the countries. Finally, it can help both countries to get insights on the scope to improve their higher education systems.

V. REFERENCES

[1] N. Germanas and G. Jegermanis, "Strategic commitment and choices for Latvia and Lithuania in the age of disruptionn and great power rivalry," 2024.

[2] J. Antwi, "What does a comparison between Latvia, Lithuania, Kazakhstan and Kyrgyzstan tell about the cognition and institutions as social capital in the extended market order?," 2010.

[3] M. Jākobsone, "Latvian - Education Development Guidelines 2021-2027," 2022. [Online]. Available: https://eprasmes.lv/wp-content/uploads/2022/02/Latvijas-Izglitibas-attsitibas-pamatnostadnes-2021-2027.pdf.

[4] L. Daniela and H. Selcuk, "Digitalization Of Higher Education And Response To Covid-19 Pandemic In Latvia," *Human, Technol. Qual. Educ.*, 2022, doi: 10.22364/htqe.2022.18.

[5] OECD, "Country Digital Education Ecosystems and Governance A Companion to Digital Education Outlook 2023," 2023. doi: 10.1787/906134d4-en.

[6] Ministry of Economy and Inovation, "Lithuania - National Digital Decade strategic roadmap," 2024. [Online]. Available: https://eimin.lrv.lt/media/viesa/saugykla/2024/5/wzspkh-PiZI.pdf.

[7] Times Higher Education, "European Commission: KTU attracts the most research funding in Lithuania," *Times Higher Education*, 2024. https://www.timeshighereducation.com/research/kaunas-university-technology/european-commission-ktu-attracts-most-research-funding-lithuania.

[8] A. S. Khalifa, "Strategy: restoring the lost meaning," *J. Strateg. Manag.*, vol. 13, no. 1, pp. 128–143, Feb. 2020, doi: 10.1108/JSMA-09-2019-0158/FULL/XML.

[9] B. J. Debicki, E. R. Ramirez-Solis, and L. M. Baños-Monroy, V. I. Gutierrez-Patrón, "The impact of strategic focus on relational capital: A comparative study of family and non-family firms," *J. Bus. Res.*, vol. 119, pp. 585-598., 2020.

[10] M. Habib, "Digital transformation strategy for developing higher education in conflict-affected societies," *Soc. Sci. Humanit. Open*, vol. 8, no. 1, p. 100627, Jan. 2023, doi: 10.1016/J.SSAHO.2023.100627.

[11] M. A. Mohamed Hashim, I. Tlemsani, and R. Matthews, "Higher education strategy in digital transformation," *Educ. Inf. Technol.*, vol. 27, no. 3, pp. 3171–3195, Apr. 2022, doi: 10.1007/S10639-021-10739-1/FIGURES/6.

[12] L. Bolt, "Digital development in the Baltic States," *The Baltic Times*, Dec. 2023.

[13] LBTU, "Extensive digitalization initiatives have been implemented in higher education," 2023.

[14] L. Daniela and D. Ivsiņa, "Human, Technologies and Quality of Education - On a Pathway Towards the Digitalisation of Higher Education: The Case of Latvia," 2022.

[15] A. Krasavina, "Lithuania - National Digital Decade strategic roadmap," 2024.

[16] L. Zilioniene, "Lithuania's Digital Transformation Journey: A short story," 2024.

[17] A. Garad, A. M. Al-Ansi, and I. N. Qamari, "THE ROLE OF E-LEARNING INFRASTRUCTURE AND COGNITIVE COMPETENCE IN DISTANCE LEARNING EFFECTIVENESS DURING THE COVID-19 PANDEMIC," *J. Cakrawala Pendidik.*, vol. 40, no. 1, pp. 81–91, Feb. 2021, doi: 10.21831/cp.v40i1.33474.

[18] A. Garad, A. M. Al-Ansi, and I. N. Qamari, "The role of e-learning infrastructure and cognitive competence in distance learning effectiveness during the covid-19 pandemic," *J. Cakrawala Pendidik.*, vol. 40, no. 1, 2021.

[19] European Commission, "Strategic Framework," 2024.

[20] R. Nacheva and A. Jansone, "Multi-layered Higher Education E-Learning Framework," *Balt. J. Mod. Comput.*, vol. 9, no. 3, 2021.

[21] I. Maslo, "e-Learning for Lifelong Learning in Latvia," in *e-Learning for Lifelong Learning*, T. Lee, R. Birzina, J. L. Gervacio, S. Jones, M. Fadzil, L. Abdol Latif, and J. M. Pawlowski, Eds. Korea National Open University Press, 2012.

[22] K. Osis, S. Cakula, A. Kapenieks, and G. Zarifis, "Lifelong Learning Strategy Framework for the Vidzeme Region," 2015.

[23] B. Žmuk, F. H. Qureshi, S. Khawaja, B. Žmuk, F. H. Qureshi, and S. Khawaja, "Inequality in E-Learning in European Union Countries: Role of Gender, Education and Urban Development," *Interdiscip. Descr. Complex Syst. INDECS*, vol. 21, no. 5, pp. 441–457, Sep. 2023, doi: 10.7906/indecs.21.5.2.

[24] A. Targamadzè and G. Cibulskis, "Development of Modern e-Learning Services for Lithuanian Distance Education Network LieDM," *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, vol. 4226 LNCS, pp. 299–309, 2006, doi:

10.1007/11915355_28.

[25] European Commission, "Higher education," 2024.

[26] A. Targamadzė and G. Cibulskis, "Development of modern e-learning services for Lithuanian distance education network LieDM," 2006.

[27] R. Lauzackas, A. Rackauskaite, and D. Jaskauskaite, "Master Study Programmes Orientation and Curricula Inconsistency in Lithuanian Universities," *Qual. High. Educ.*, vol. 1, 2001.

[28] E. Agency, "INFORMATION AND COMMUNICATION TECHNOLOGY (ICT) FOR INCLUSION," 2024.

[29] L. Pangrazio, A. L. Godhe, and A. G. L. Ledesma, "What is digital literacy? A comparative review of publications across three language contexts," *E-learning Digit. Media*, vol. 17, no. 6, 2020.

[30] Charles Sturt University, "Digital Literacies GLO: Why is Digital Literacy important?," 2024.

[31] European Commission, "Latvia 2024 Digital Decade Country Report," 2024.

[32] OECD, "Fostering the digital transformation among people, firms and government," in *Going Digital In Latvia*, OECD Publishing, 2024.

[33] A. Broks, "Digital illiteracy looming over Latvia: here's how progressive IT companies can help," 2021.

[34] Ministry of the Economy and Innovation of the Republic of Lithuania, "EIMIN: an opportunity for digitally excluded people to improve their digital skills," Vilnius, Lithuania, 2024.

[35] A. Krasavina, "Lithuania: a snapshot of digital skills," *Digital Skills and Jobs Plateform*, 2024. https://digital-skills-jobs.europa.eu/en/latest/briefs/lithuania-snapshot-digital-skills.

[36] Latvian Public Media, "Room for improvement of Latvia's digital skills," *Latvian Public Media*, 2024. https://eng.lsm.lv/article/society/education/23.02.2024-room-for-improvement-of-latvias-digital-skills.a544072/.

[37] European Commissionion, "Digital Economy and Society Index (DESI) 2022," *European Commissionion*, 2022. https://digital-strategy.ec.europa.eu/en/policies/desi.

[38] Statista, "Share of internet users in Latvia that used online learning material, participated in online courses, or other forms of online learning from 2015 to 2022," *Statista*, 2023. https://www.statista.com/statistics/1237132/share-internet-users-learning-material-courses-online-learning-latvia/.

[39] Latvia Public Media, "Around 10% of Latvian adults are learning," *Latvia Public Media*, 2023. https://eng.lsm.lv/article/society/education/12.06.2023-around-10-of-latvian-adults-are-learning.a511482/.

[40] A. Higgins, "Paradigms, distance learning, education, and philosophy," *J. Open, Flex. Distance Learn.*, vol. 24, no. 2, pp. 4–14, 2020.

[41] J. V. Hasanova, K. A. Najafova, and G. A. Karimova, "Digital Technology Development: Distance Education," in *2nd International Scientific and Practical Conference "Modern Management Trends and the Digital Economy: from Regional Development to Global Economic Growth"(MTDE 2020)*, May 2020, pp. 401–404, doi: 10.2991/AEBMR.K.200502.066.

[42] A. Sahoo, "IMPORTANCE OF DISTANCE EDUCATION IN INDIA," *Int. J. Dev. Res.*, vol. 14, no. 1, 2024.

[43] D. Vasilevska, "Distance Education in Higher Education in Latvia.," 2012.

[44] P. Devica, "Interest in online schools on the rise in Latvia," *LSM.lv*, Nov. 2020.

[45] O. Pozdnyakova and A. Pozdnyakov, "Adult Students' Problems in the Distance Learning," *Procedia Eng.*, vol. 178, pp. 243–248, Jan. 2017, doi: 10.1016/J.PROENG.2017.01.105.

[46] Studyportals, "The Ultimate Guide to Studying in Latvia in 2025," *Studyportals*, 2024. .

[47] Studyportals, "Mykolas Romeris University," *Studyportals*, 2024. .

[48] V. L. Stéphan, U. Joaquin, K. Soumyajit, and J. Gwénaël, *Educational research and innovation measuring innovation in education 2019 what has changed in the classroom?: What has changed in the classroom?* OECD Publishing, 2019.

[49] A. Iqbal, F. Latif, F. Marimon, U. F. Sahibzada, and S. Hussain, "From knowledge management to organizational performance: Modelling the mediating role of innovation and intellectual capital in higher education," *J. Enterp. Inf. Manag.*, vol. 32, no. 1, pp. 36–59, Jan. 2019, doi: 10.1108/JEIM-04-2018-0083/FULL/XML.

[50] B. Tracey and K. Florian, *Educational Research and Innovation Governing Education in a Complex World*. OECD Publishing, 2016.

[51] Ministry of Education and Science, "ANALYTICAL REVIEW OF THE LATVIAN SMART SPECIALISATION STRATEGY (RIS3): The progress of Latvian science," 2023.

[52] Mission Latvia, "Research in Latvia," 2024.

[53] EU, "Specific Support to Latvia II: Summary article," 2020.

[54] M. Valuzis, "Overview of promoting technology-based innovations and investments in Lithuania," *Appl. Technol. Innov.*, vol. 11, no. 1, pp. 47–52, Jan. 2015.

[55] G. Kelly and É. Edmondson, "Science and Innovation in Lithuania: Pushing the research boat out," *Science Business Publishing Ltd.*, Jul. 2014.

[56] E. R. Rabelo-Silva, V. Monteiro Mantovani, L. López Pedraza, P. C. Cardoso, C. Takao Lopes, and T. H. Herdman, "International Collaboration and New Research Evidence on Nanda International Terminology," *Int. J. Nurs. Knowl.*, vol. 32, no. 2, pp. 103–107, Apr. 2021, doi: 10.1111/2047-3095.12300.

[57] D. C. Finger *et al.*, "The Importance of International Collaboration to Enhance Education for Environmental Citizenship," *Sustainability*, vol. 13, no. 18, 2021.

[58] Brand Lithuania Team, "International Cooperation," 2024.

[59] OECD, "Tertiary education in Lithuania," in *Education in Lithuania*, Paris: OECD Publishing, 2017.

[60] University of Latvia, "International cooperation," 2024.

[61] European Commission, "Lithuania 2024 Digital Decade Country Report," *European Commission*, 2024. https://digital-strategy.ec.europa.eu/en/factpages/lithuania-2024-digital-decade-country-report.

[62] A. Krasavina, "Expert discussion on the future of digital skills in Latvia," *Digital Skills and Job Platforms*, 2023. https://digital-skills-jobs.europa.eu/en/latest/news/expert-discussion-future-digital-skills-latvia.

[63] European Commission, "Latvia 2024 Digital Decade Country Report," *European Commission*, 2024. https://digital-strategy.ec.europa.eu/en/factpages/latvia-2024-digital-decade-country-report.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference, 2025. Volume II, 197-203

Innovative Approaches to the Organization of Distance Learning with the Use of Digital Technologies in Domestic and International Educational Practices

Svitlana Kizim
Department of Innovative and Information Technologies in Education
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
skizim2012@gmail.com

Oksana Voloshyna
Department of Pedagogy and Educational Management
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
woloshina5555@gmail.com

Liudmyla Bondarchuk
Department of Management and Administration Vinnytsia Institute of Trade and Economics of State University of Trade and Economics
Vinnytsia, Ukraine
l.bondarchuk@vtei.edu.ua

Mykyta Sapohov
Department of Innovative and Information Technologies in Education
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
sopogov@ukr.net

Tetiana Melnychuk
Department of *Culture, Methods of Teaching History and Special Historical Disciplines*
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
tmelnychuk@gmail.com

***Abstract*- Distance learning using digital technologies has become a vital necessity in Ukraine in the context of pandemic and war. Such a transition took place in a short period of time and has now become a significant innovation in the educational space of Ukraine. Foreign experience in implementing distance learning has been analyzed, which allows taking into account the individual abilities, needs, temperament, and employment of students who have the opportunity to master the educational program in any sequence and pace, and interact with participants in the educational process through the use of distance learning platforms. The principles of open education are outlined (mobility of students and teachers; equal access to educational systems; ensuring quality education; structuring and implementation of educational services). The characteristics of blended learning models that are actively implemented in foreign and domestic educational institutions (Rotation Model, Flex Model, A La Carte Model, Enriched Virtual Model) are presented. The didactic capabilities of the main distance learning platforms (Moodle, Edmodo, iSpring, WebTutor, Google Classroom) are revealed. The interconnected structural elements of distance learning platforms in a blended learning environment are summarized and graphically presented. The features of the practical application of distance learning platforms in blended learning at the Mykhailo Kotsiubynskyi Vinnytsia State Pedagogical University are analyzed according to its main components in the process of professional training of education seekers in the specialties 015.39 Professional Education (Digital Technologies), 011 Educational and Pedagogical Sciences, 073 Management. The results of a survey of education seekers and teachers are presented. in order to assess the effectiveness of the use of distance learning technology in studying educational material, organizing independent work, communication and interaction of all participants in the educational process. The main platforms for providing distance learning at the university are described and graphically presented, the main criteria for selecting distance learning sites by scientific and pedagogical workers, types of static data when working with distance platforms, types of activities of participants in the educational process using distance learning platforms, types of reproduction of the results of education seekers using distance learning platforms. The main aspects of the practical experience of implementing blended learning in professional training of specialists at the pedagogical university are summarized. The main directions of innovative approaches to the use and implementation of**

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8605
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

structural elements remote platforms in the conditions of blended learning in the process of professional training of specialists are determined, namely: access to educational content: interaction with the teacher; interaction between students; evaluation and feedback.

Keywords- blended learning, digital technologies, distance learning platforms, professional training of future teachers.

I. INTRODUCTION

The current education and science system is undergoing profound digital changes and needs to align with global trends in digital development to ensure the successful realization of every individual in a globalized society. The increasing speed of information flow and constant updating of information bring professional training of specialists closer to the conditions of high-tech production. Accordingly, improving the quality of their professional training, and upgrading qualifications without leaving the workplace in a short period of time with minimal costs requires the effective implementation of distance learning technologies in the professional training of 21st-century professionals.

The use of distance learning technologies has become particularly relevant in the context of the pandemic and the war in Ukraine. Under such conditions, the education system in Ukraine found itself in a fundamentally new situation when the entire educational process was transferred to a small format using distance technologies. Changes have occurred at all levels of the country's education system, as evidenced by the domestic experience. Educational institutions did not have a preparatory stage for such a massive transition to a distance format since teaching and learning in uncertain conditions was necessary. This transition took place in a short period of time and is now an essential innovation in the educational space of Ukraine.

It should be noted that in global practice, distance learning using digital technologies and electronic educational resources is an integral component of quality professional training. The world experience of implementing distance learning technologies can be characterized by the following directions: organizing distance learning in the Internet space; active implementation of mobile and cloud technologies in the educational process, the use of open educational platforms, and more.

In the process of utilizing distance learning technologies in educational institutions, the principles of open education are implemented, namely:

- The principle of mobility for learners and instructors - ensuring mobility for participants of the educational process, including international mobility.
- The principle of equal access to educational systems - providing equal opportunities for education within open systems for all individuals who have the desire and need to learn throughout their lives.
- The principle of providing quality education - ensuring that open systems deliver education of such quality that meets the individual educational needs and societal demands for general and professional levels of preparation.
- The principle of structuring and implementing educational services - facilitating market mechanisms for the formation of qualitative and quantitative training, retraining, and upgrading of learners at different levels of education [1] – [3].

Taking these principles into account, distance learning technologies become an essential component of the educational process in educational institutions. The adaptability and modularity of distance learning elements allow participants in the educational process to implement a wide range of educational services according to chosen forms, methods, and types of learning.

II. MATERIALS AND METHODS

The purpose of the article is to provide theoretical justification and practical implementation of distance learning technologies in the process of professional training of specialists

In the context of our research, the classification of blended learning models proposed by online education researchers X. Steiker and M. Hori is important [4], [5]. This classification has found its implementation in both foreign and domestic educational institutions for professional training of specialists (tabl.1):

TABLE 1 BLENDED LEARNING MODELS AND CHARACTERISTICS

Blended Learning Models	Characteristics
Rotation Model	Based on the principle of cyclic change in learning location (rotation), where learners follow a specific schedule, moving from one form of instruction ("station") to another. One of these stations always involves online learning, while others may involve group work, project-based tasks, individual assignments with the teacher, and more.
Flex Model	Combines online learning with traditional classroom instruction, taking into account the learners' or instructor's potential to provide maximum flexibility in learning. Learners receive instruction in designated classrooms with assigned teachers and other consultants. Each learner has a personalized learning plan that includes group activities, project work, individual consultations, and more.
A La Carte Model	Relies entirely on online learning. In this model, the teacher serves as an online instructor. Learners may participate in the learning process either in a physical classroom or from home.
Enriched Virtual Model	Traditional classroom instruction is complemented with online elements. In this model, the traditional instruction ("lecturing" of materials) takes place through in-person classroom sessions, while learners engage in the remaining part of the course online. One instructor delivers both traditional and online instruction.

Implementing blended learning in vocational training involves learners acquiring a portion of the educational content through traditional instructional methods, while the remaining content is obtained using distance learning platforms.

Let's analyze the most common distance learning platforms used for organizing blended learning in educational institutions, taking into account the perspectives of both international and domestic practitioner instructors and researchers [7] – [8] (tabl.2).

TABLE 2 PLATFORM NAME AND CHARACTERISTICS

Platform name	Characteristics
Moodle	Moodle is a free and open-source learning management system. It is installed on a server and supports over 100 languages and more than 1500 plugins. Moodle is suitable for educational institutions, training centers, and corporate training. It allows uploading presentations, images, videos, audio, and text files. Moodle can be customized to generate reports based on specific goals, such as analyzing learners' performance, tracking their study time, platform engagement, test errors, and more. Features of the Moodle platform: • Configuration through plugins.The functionality and design of Moodle can be modified using plugins, which can be freely downloaded from the internet or created by users themselves; • Open-code system. Development can be done by anyone. Typically, users develop plugins and share them on the internet for general access; • Integration with other services. Moodle can be easily integrated with other platforms such as WordPress or webinar platforms like Zoom.
Edmodo	Edmodo - a specialized web service that requires installation. Edmodo positions itself as a social network for learning or the "Facebook for education" - it functions based on the principles of social educational networks. The teacher creates a group (an online course) with a unique link and code, which need to be shared with other participants in the educational process. The group can have various educational elements such as posts (in the form of quizzes or files), tests, assignments, and surveys. Content from other services can be imported, such as news feeds from the educational institution's website, YouTube videos, or content from other services. Features of the Edmodo platform: • Free to use. • Ad-free. • Simple registration process. • Users are divided into three groups: educators, learners, and parents (each group has its separate registration and access code).
iSpring	iSpring - a platform oriented towards the corporate training sector. It allows users to start working immediately after registration. It supports various types of learning materials, webinars, detailed statistics, and a course editor that enables quick creation of courses and quizzes using office documents and videos. It includes the iSpring Learn learning portal and the iSpring Suite course builder. The platform is designed for the rapid launch of online learning. Presentations, images, videos, and audio files can also be uploaded to the platform. Features of the iSpring platform: • Course builder: With this tool, users can create educational content such as courses, tests, interactive simulations, and screencasts. • Unlimited storage: Users can upload an unlimited number of files as there is no storage limit. • Integration with other services: iSpring Learn easily integrates with other client systems through an open API, for example, events and corporate portals. • Quick platform launch.
WebTutor	WebTutor – an online learning system with modules for personnel management and evaluation that allows not only organizing training but also managing all HR processes: assessing the level of competency formation, automating recruitment and initial staff training, and so on. This complex system with extensive capabilities enables obtaining statistics on any data directions and presenting them in the form of graphs or tables. Features of the WebTutor platform: • Configuration through modules. WebTutor offers modules - separate programs with functionality (for example, distance learning modules, personnel selection, chatbots). In total, the platform has 12 modules. • Integration with other systems. WebTutor can be integrated with the client's IT infrastructure systems: 1C, Oracle EBS, SAP HR, and others. • Course Builder. WebSoft has the CourseLab course builder, which allows creating educational content.
Google Classroom	Google Classroom is an application designed specifically for education, available to all owners of a personal Google account. Features of the Google Classroom platform: • Allows creating educational courses. • Enables sharing educational materials. • Facilitates the creation of assignments. • Provides the ability to assess knowledge acquisition and track the performance progress of each student. • Offers a wide range of tools for work, including videos, images, and simulators. • Ensures confidentiality and protection of personal information of participants in the educational process. • Can be accessed and used with educational content from mobile devices (smartphones, iPhones, tablets) based on Android and iOS. Developers provide extensions for Chrome and the ability to download apps from the Google Play Store and iTunes.

Generalization of the processed scientific literature allowed us to schematically represent the main elements of distance learning platforms that are capable of providing high-quality professional training for specialists (Fig. 1).

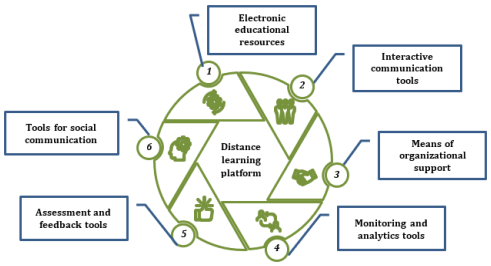


Fig. 1. Interrelated Structural Elements of Distance Learning Platforms in Blended Learning Environments

Let's characterize the interrelated elements of distance learning platforms in blended learning environments, as presented in Fig. 1:

- The distance learning platform is the central element that provides access to educational content, assignments, tests, and other resources, allowing interaction among all participants in the educational process.

- Electronic educational resources include e-textbooks, presentations, video lessons, audio recordings, and other materials that facilitate effective learning and independent study of the educational content.
- Interactive communication tools provide participants in the educational process with the ability to interact with each other through forums, chats, video conferences, and email.
- Organizational support tools include class schedules, course information, materials for self-study, and technical support for students and instructors.
- Monitoring and analytics tools display data on student activity, performance, and progress, enabling analysis of results and continuous improvement of the educational process.
- Assessment and feedback tools allow for electronic tests, assignments, and other forms of evaluation through the distance learning system.
- Social support tools provide feedback and support in particularly important life situations influenced by the conditions of uncertainty in Ukraine.

The identified elements of distance learning platforms contribute to the effective organization of the educational process and facilitate active interaction between instructors and learners during their professional training.

The question of using and implementing distance learning technologies and platforms in blended learning environments requires a thorough study. During our research, we employed theoretical methods such as analysis and synthesis of scientific sources, regulatory documents, theoretical literature, and electronic sources of information related to the issue of using and implementing distance learning technologies and platforms in professional training. We also utilized empirical methods, including observations and surveys. Additionally, we employed methods of mathematical data analysis.

The processing of the obtained data was carried out using software packages such as SPSS and Microsoft Excel.

The issue of implementing distance learning technologies in the context of blended learning was studied during the professional training of education seekers specializing in 015.39 Professional Education (Digital Technologies), 011 Educational and Pedagogical Sciences, and 073 Management. A survey was conducted to assess the utilization of distance learning technologies and platforms for quality professional training, including the study of educational materials, organization of independent work, communication, and interaction among all participants in the educational process.

During the study of the university-wide discipline "Computer-Oriented Learning Technologies" and the implementation of the project "Transformation of the Teacher Digital Competence Formation System: Innovative European Approaches" (Project: 101085799 - TSDigComp - ERASMUS-JMO-2022-HEI-TCH-RSCH, Grant Agreement No. 101085799 - TSDigComp), a survey was conducted among education seekers and academic staff of Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University regarding the use of distance learning technologies and platforms in professional training of specialists.

The survey was anonymous and covered 124 education seekers and 45 academic staff members. The survey questions addressed the organization and interaction of participants in the educational process in the context of utilizing distance learning technologies and platforms to ensure quality professional training in the face of uncertainty in Ukraine.

III. RESULTS AND DISCUSSIONS

In the process of professional training of specialists, the use of distance platforms in the conditions of blended learning can be represented by several variants of " blending:

- a combination of the eye form and the remote form;
- a combination of various formats of professional training in classroom conditions (main face-to-face training using distance learning technologies and various forms of working with electronic resources, online courses, etc.);
- a combination of independent study of educational content and work in the classroom;
- mixing the main educational content according to the traditional method (textbooks and educational materials) with external materials (electronic resources) [9], [10].

Currently, the most popular practice in Ukraine is the practice of combining face-to-face with remote.

The survey results show that the LMS Moodle platform (24%) is the most popular for organizing blended learning in higher education institutions, 22% use the Classroom platform, 2% use the iSpring Online platform, 1% use the LMS Edmodo platform, and the Meet 8 platform is used for communication %, own system using messengers 2%, Zoom platform 14% and Microsoft Teams 8% were used for video recording of educational content and its distribution for education seekers, 23% of respondents were composing platforms (Fig. 2).

When choosing platforms for the organization of blended learning, it is important to carefully consider the content of the educational component and the requirements for the competencies that the future specialist should possess in the process of studying it in accordance with the educational and professional training program for those seeking education. Under such conditions, the key point is to consider the educational content that the student can master independently with the help of electronic educational resources, and that requires constructive explanation within the classroom. The analysis of the questionnaire allowed us to identify the most common criteria for choosing distance learning platforms that

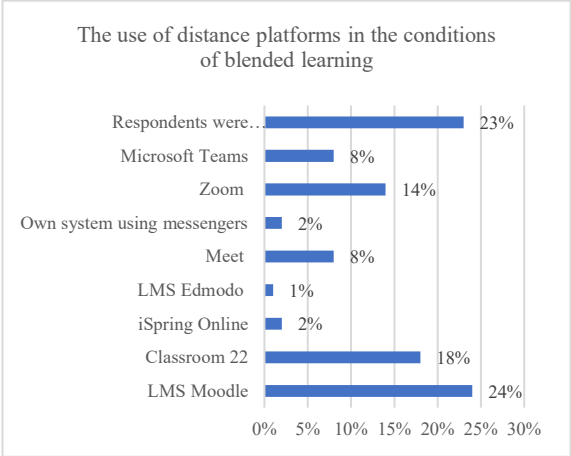


Fig. 2. Diagram showing the choice of distance learning platforms by scientific and pedagogical workers for the organization of professional training of specialists in conditions of blended learning.

correspond to the quality and effectiveness of blended learning, namely, 6% consider the registration of education seekers when working with a distance platform, 12% choose free access to learning within the distance platform, the breadth of coverage 10% of participants in the educational process pay attention, 18% choose the convenience of work and the system, 14% choose mobility, 12% choose the implementation of an individual approach when working with a remote platform, 10% pay attention to interactive interaction, 9% integrate online services, compose 2 or more criteria of 19% of participants in the educational process (Fig. 3).

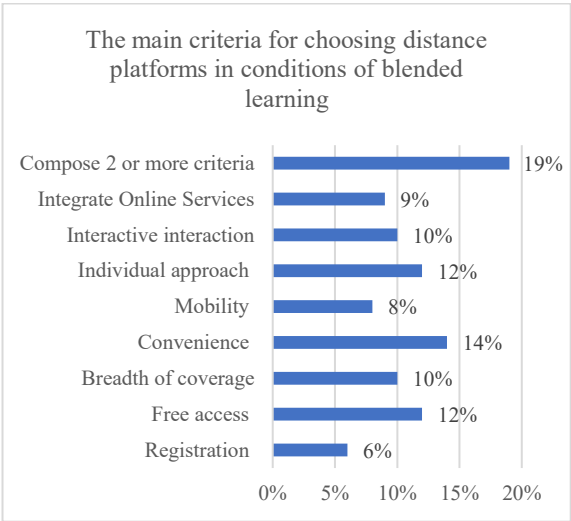


Fig. 3. Diagram showing the main criteria for the selection by scientific and pedagogical workers of remote platforms for the organization of professional training of specialists in the conditions of blended education

When working with distance learning platforms, it is important to prepare the educational content and adapt it to the goal of the educational discipline within the educational and professional training program for those seeking education. Increasing the information saturation of educational content is achieved by using visualization to represent static and dynamic, real and abstract objects, holistic presentation of algorithms, processes, phenomena, reproduction of connections, etc.

As a result of the questionnaire, we determined that the visualization of materials for filling distance learning platforms in the conditions of blended learning are represented by the most common types of files: text 6%, hypertext 4%, images 7%, audio, video 12%, video 4%, tables 9%, program files, scripts 11%, archives 5%, combine 2 or more types of data 42% of respondents (Fig. 4).

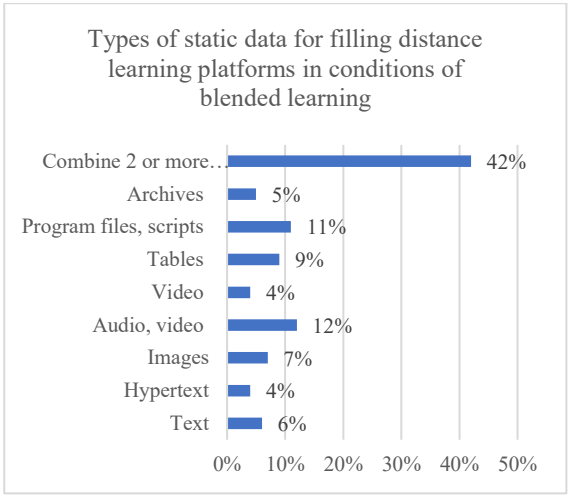


Fig. 4. Diagram showing the types of static data when working with distance learning platforms for the organization of professional training of specialists in the conditions of blended learning

The effectiveness of training using distance learning platforms depends on the interest and activity of all participants in the training process. The most common types of activity when working with distance learning platforms for students are tasks 15%, surveys 12%, chats 10%, video chats 7%, forums 8%, quizzes 12%, testing 10%, correspondence 4%, compose 2 and more types of activity by 22% of respondents (Fig. 5).

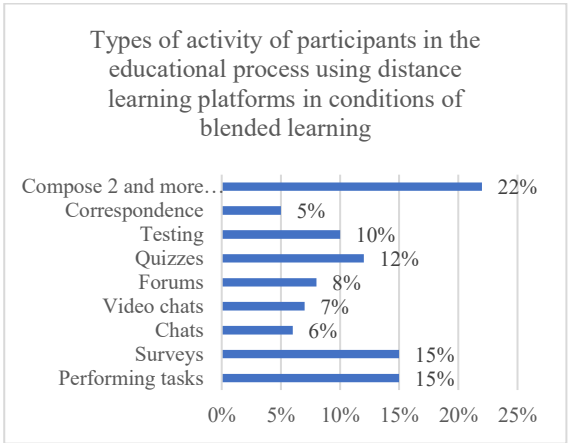


Fig. 5. Diagram showing the types of activity of participants in the educational process using distance learning platforms for the organization of professional training of specialists under the conditions of blended learning

The training process and its completion are accompanied by the automatic generation of data that reflects the intermediate and final results of professional training. The results can be presented in the form of a grade or points for completing tasks, the origin of tests, performance information, performance journals, report cards, electronic scorebooks, etc. The most common types of learning outcomes using distance platforms are grades and scores 15%, performance journals 12%, report cards 10%, scorebooks 7%, awards 8%, prizes 12%, statuses 10%, emoticons 5%, comments 4%, 17% of respondents compose 2 or more types of results evaluation (Fig. 6).

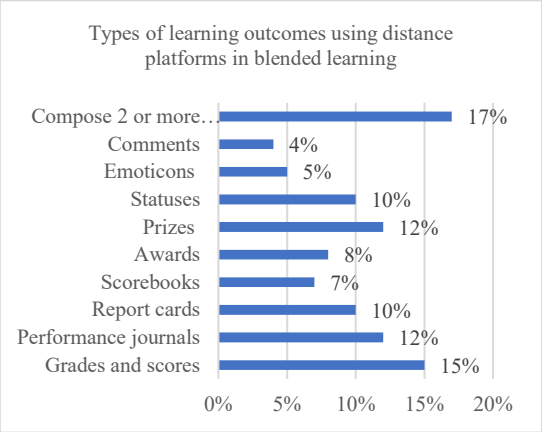


Fig. 6. Diagram showing the types of reproduction of the results of education seekers using distance learning platforms for the organization of professional training of specialists in conditions of blended learning

During the survey, the respondents noted the advantages of using and implementing structural elements and platforms of distance learning in the conditions of blended learning in the professional training of specialists, which provide:

- effectiveness - the level of achievement of goals and the quality indicator of educational activity - 22%;
- universality - possibility to use in any institution of higher education - 28%;
- optimality - organization of rational use of human, time, and technical resources - 18%;
- flexibility - the possibility of adjusting the training organization depending on specific conditions - 32%.

Regarding the shortcomings and problems of the use and implementation of structural elements and platforms of distance learning in conditions of blended learning in the professional training of specialists, the respondents singled out:

- student identification – 24%;
- establishing communication skills, working in a team – 36%;
- development of structural elements for filling distance learning platforms – 18%;
- composition of structural elements for filling distance learning platforms - 12%;
- centralized technical and methodological support in the process of using and implementing structural elements and platforms of distance learning in conditions of blended learning in educational institutions - 10%.

Taking into account the analysis of the results of the survey and the results of the theoretical provisions of our research, we will single out innovative approaches to the use and implementation of structural elements and platforms of distance learning in conditions of blended learning in the professional training of specialists:

- Access to educational content: students can access e-textbooks, lecture notes, video lessons and other educational resources through the distance learning platform, which allows them to study the material at a time and pace convenient for them, self-study and self-development, adapt the educational process to their needs and opportunities.
- Interaction with the teacher: students can communicate with teachers using e-mail, forums or chats. They can ask questions, receive explanations and consultations, which contributes to effective learning, understanding of educational content and cooperation between teachers and students.
- Interaction between students: distance learning platforms provide opportunities for communication and collaboration between students. They can discuss learning topics, support group projects, and share experiences through forums, chats, or virtual groups.
- Assessment and feedback: students can take and pass various forms of assessment through the distance learning platform. Teachers can evaluate work, provide feedback, and assign grades, which facilitates objective assessment of student performance.

Under such conditions, we believe that our proposed innovative approaches to the use and implementation of structural elements and platforms of distance learning in conditions of blended learning in the professional training of specialists, on the one hand, contribute to the independent educational activity of the student, increase the level of their professional training, and on the other hand, encourage teacher to constantly search for effective technologies, forms and methods for quality organization of professional training of education seekers in accordance with the challenges of a globalized society.

IV. CONCLUSIONS

We analyzed the quality of the organization of the use and implementation of structural elements and platforms of distance learning in conditions of blended learning at the Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University according to its main components. Blended education in an educational institution is characterized by the following quality indicators: the content of education aimed at training qualified specialists; introduction of new innovative educational technologies into curricula, educational programs, methodical and organizational support.

We believe that under such conditions, distance education will not completely replace classical education, however, most likely, there will be a transition to blended

learning, in which digitalization of education will be manifested in various formats. In our opinion, there will be a transition from rigid standardization of the educational process to various forms of informal education, implementation of individual educational trajectories, network education. Rethinking the requirements for teachers, reassessing their status and the value of work, adapting educational programs to modern realities: full or partial online training, leading teachers from other educational institutions are invited; systematic support for the activities of teachers and students of higher education is carried out.

It should be noted that the transition to blended learning using structural elements and distance learning platforms helps the participants of the educational process to outline new opportunities and gain new positive experience. And this will certainly benefit institutions of higher education, because the software of various online educational platforms has been improved. Accumulated experience shows that remote technologies will become an integral part of modern educational programs. It is only necessary to find the optimal balance of traditional and distance learning formats.

References

[1] N. Dmitrenko, O. Voloshyna, S. Kizim, K. Mnyshenko, and S. Nahorniak. Smart Education in the Prospective Teachers' Training. CEUR Workshop Proceedings this link is disabled ю 3364, 2023, pp. 38–53 https://doi.org/cte.NUM.

[2] O. Voloshyna, T. Melnychuk, M. Sapohov, N. Burlaka, and A. Khilya. The potential of developing and creating online applications for teacher training. Environment. Technology. Resources. Rezekne, Latvia Proceedings of the 15th International Scientific and Practical Conference. Volume II, pp. 525-529, 2024, https://doi.org/10.17770/etr2024vol2.8086.

[3] A. Yarovyi, A. Yarovyi, S. Kizim, and V. Ozeranskyi, Innovative Trends in the Field of Modern Artificial Intelligence Methodology, ETR, vol. 2, pp. 132–137, Jun. 2024, doi: 10.17770/etr2024vol2.8065.

[4] M. Aker, M. and L.J. Pentyn Herrera. Smart literacy learning in the twenty-first century: Facilitating pbsl pedagogic collaborative clouds. Singapore: Springer Singapore, 2020, pp.429–445. Available from: https://doi.org/10.1007/978-981-15-0618-5_25.

[5] I.K. Suartama, P. Setyosari, U. Sulthoni. Development of an Instructional Design Model for Mobile Blended Learning in Higher Education, iJET 14(16), 2019, pp. 4–21. DOI: https://doi.org/10.3991/ijet.v14i16.10633.

[6] T. Karakose, R. Yirci, and S. Papadakis. Examining the associations between covid 19-related psychological distress, social media addiction, covid-19-related burnout, and depression among school principals and teachers through structural equation modeling. International journal of environmental research and public health, 19(4). 2022. https://doi.org/10.3390/ijerph19041951.

[7] O. Rohotchenko, T. Zuziak, S. Kizim, S. Rohotchenko, and O. Shynin. Information and Communications Technology in the Professional Training of Future Professionals in the Field of Culture and Art. Postmodern Openings. 12(3), 2021, pp. 134-153. https://doi.org/10.18662/po/12.3/332

[8] N. Dmitrenko, Y. Koliadych, L. Melnyk, and O. Voloshyna. The Use of ICT in Learning ESP by Pre-Service Teachers of Mathematics in the Wartime (O uso de tecnologias de informação e comunicação no estudo do inglês para fins específicos por futuros professores de matemática em tempos de Guerra). Texto Livre, Belo Horizonte-MG, v. 17, 2024. pp. 47-58, DOI: 10.1590/1983-3652.2024.47588.

[9] N. Lazarenko, A. Kolomiiets, V. Bilous, S. Zahorodnii, I. Gromov, O. Zhovnych, and N. Ivanichkina. Institutional Repositories as a Global Dissemination Tool of Educational and Scientific Information. Encounters in Theory and History of Education / Rencontres en Théorie et Histoire de l'Éducation / Encuentros en Teoría e Historia de la Educación, 23, 2022, pp. 241–258. https://doi.org/10.24908/encounters.v23i0.15230.

[10] S.A. Wichadee. Development of the Blended Learning Model Using Edmodo for Maximizing Students' Oral Proficiency and Motivation, iJET 12(2), 2017, pp. 137–154. DOI: https://doi.org/10.3991/ijet.v12i02.6324.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 205-212

Organization of Adaptive Training Using Artificial Intelligence Technologies in the Context of War

Svitlana Kizim
Department of Innovative and Information Technologies in Education
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
skizim2012@gmail.com

Oksana Voloshyna
Department of Pedagogy and Educational Management
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
woloshina5555@gmail.com

Irina Sarancha
Department of Psychology and Social Work
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
isarancha@gmail.com

Svitlana Nahorniak
Department of Pedagogy and Educational Management
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
svitlanamnagor@gmail.com

Olena Stoliarenko
Department of Pedagogy and Educational Management
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
olena-best@ukr.net

***Abstract*— Digital transformation of spheres of human life involves the development and implementation of artificial intelligence technologies, particularly in the educational system. The article covers the potential of organising adaptive learning in the context of the war in Ukraine. It determines the theoretical foundation, defines the essence of artificial intelligence technologies, and presents their classification and areas of application. It determines the advantages of using artificial intelligence technologies in the organisation of the educational process of a higher education institution. The platforms and specialised software using artificial intelligence technologies that ensure the organisation of adaptive learning are characterised. It is noted that the most optimal platform for the use of artificial intelligence, particularly chat-bots, is Telegram, which creates not only a platform for communication and posting diverse information, but also serves as a means of organising an individual educational trajectory and allows one to upload files and exchange educational content. JavaScript language is used for implementing Telegram educational chat-bot's multi-functionality. The article theoretically grounds and presents the algorithm for the application of artificial intelligence, in particular, a chat-bot, in the conditions in the context of adaptive learning in the pedagogical institution of higher education. It highlights the features of using chat bot for studying the discipline "Engineering and Computer Graphics". The chat-bot is implemented on the Node.JS platform, using the Node-Telegram-Bot-API library. The results of a pedagogical experiment are presented, which included a survey on the effectiveness of using artificial intelligence, in particular Telegram, to organize adaptive learning among students and teachers. The results of the survey among students showed that the use of telegrambot is appropriate in the process of professional training, as it provides quick access to various types of information through the integration of web applications, intelligent systems and access to intelligent artificial intelligence systems. Teachers noted that in the process of using telegrambots, direct contact with students decreased, they noted that the chatbot's reaction was not always correct, low Internet connection speed, insufficient digital skills of teachers to create adaptive digital environments, IT security problems, and uncertainty in using modern digital standards. A comparison of the survey data of students and teachers shows that telegrambots are in demand among students and require the development of digital skills of teachers in creating and implementing adaptive digital environments using artificial intelligence technologies.**

Keywords*— *adaptive learning, artificial intelligence technologies, educational chat-bot, students of the pedagogical university.

I. Introduction

The development of technologies and the pace of their spread affect all spheres of human life. The educational environment is not an exception, as the digital space contributes to the globalization of science and education. According to the analytical company International Data Corporation (IDC), the amount of information is growing exponentially and by 2025 its volume will have increased

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8606
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

10 times in comparison with 2016, and will exceed 163 zettabytes [1]. This is the result of the ability of computer systems to process information at high speed.

The introduction of electronic educational resources and information and communication technologies into the education system is due to the need for successful integration into the global educational space, increasing the competitiveness of higher education institutions at the international level, and the formation of a new paradigmatic status of the educational institution. The demand for using the potential of digital technologies, in particular artificial intelligence methods, is reflected in the emergence of numerous online courses, visual control programs, and distance learning. This has become vitally necessary in Ukraine in the context of the COVID -19 pandemic and full-scale war.

Considering the requirements of the modern educational space, the education system requires the organization of adaptive learning using adaptive digital environments that are able to meet the interests and needs of the participants in the educational process. The importance of adaptive learning, as the coronavirus epidemic and the war in Ukraine have shown, is beyond doubt, as its role is recognized by the vast majority of both scholars and educators.

II. Materials And Methods

The purpose of our research is to determine the features of the organization of adaptive training using artificial intelligence technologies in the context of war.

To achieve the research goal, a set of theoretical and empirical methods. Theoretical methods. was applied: theoretical methods - analysis, systematization, generalization of the works of domestic and foreign researchers, experts, own pedagogical experience and the experience of the project team Transformation of the Teacher Digital Competence Formation System : Innovative European Approaches (Project: 101085799 – TSDigComp – ERASMUS-JMO-2022-HEI-TCH-RSCH (Grant Agreement No. 101085799 – TSDigComp) regarding creation and use of an adaptive digital environment for those seeking education in war conditions and determining the content of adaptive learning models using digital technologies, in particular artificial intelligence; identification of factors that determine the effectiveness of an adaptive digital environment, in particular a chatbot. Empirical methods: questionnaires and interviews with the students of specialty 015.39 Vocational education (Digital technologies), project participants Transformation of the Teacher Digital Competence Formation System : Innovative European Approaches and teachers of Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University regarding the effectiveness of using an adaptive digital environment, in particular, Telegram in the process of studying the academic discipline "Engineering and Computer Graphics" and within the framework of the project implementation Transformation of the Teacher Digital Competence Formation System : Innovative European Approaches.

Surveys and interviews were conducted in September 2024.

III. Results And Discussion

In modern research, scientists describe adaptive learning as a technology and as a process.For example, P. Kerr described adaptive learning as an educational technology, the purpose of which is to create "automated, dynamic and interactive content" [2] . J.M. Lowendal and colleagues defined adaptive learning as a process that "... dynamically adjusts the way educational content is presented to learners based on their responses to proposed tasks or based on their preferences (for example, visual presentation of content)" [3]. Scientists emphasize that adaptive learning contributes to obtaining a unique learning experience taking into account the individual characteristics of students, improves the learning process, and contributes to the formation of professional competencies of future specialists.

The analysis of scientific studies [4]–[6] made it possible to **conclude** that there are differences in the focus of adaptive learning analysis. Researchers consider it appropriate to take into account the following characteristics of students when developing an adaptive system:

- basic knowledge and fundamental knowledge in the discipline being studied;
- cognitive styles, or thinking styles, which are ways of engaging in cognitive activity;
- learning styles – habitual approaches based on the individual characteristics of studentst;
- metacognitive knowledge – awareness of personal cognitive processes in relation to the capabilities of others;
- student preferences;
- student behaviour (e.g., viewing videos, answering test tasks, etc.);
- student profile - personal data of the student (gender, age, etc.);
- student abilities – psychological traits that determine success in the learning process (acquired knowledge, developed abilities, skills);
- student interests – the motivation to learn something new [7], [8].

One of the trends in modern didactics is the development of adaptive educational technologies for teaching various disciplines.

In 2021, the Concept of the Development of Artificial Intelligence in Ukraine until 2030 was approved. The document states the need for "...implementation of artificial intelligence technologies in the field of education, economy, public administration, cyber security , defense and other areas to ensure Ukraine's long-term competitiveness in the international market." [9] In 2022,

during the war, in the context of the Recovery Plan of Ukraine, the "Education 4.0: Ukrainian Dawn" programme was presented, which is a concept of education that involves the use of the latest technologies to improve the educational process and prepare students for life in a digital society and is based on the principles of flexibility, customization, collaboration and advanced learning. The purpose of education 4.0 is not only to prepare students for the digital economy and robotization of labor, but also to prepare citizens for life in the modern world who can think critically and creatively, develop life and professional self-improvement skills.

Scientists identify three main models of adaptive learning: the student model, the content model, and the learning model. A student model is the provision of information about an individual student that is necessary for an adaptive system. The model includes information provided directly by students (for example, personal data), information about academic performance, topics of the discipline that the student has already studied, watching videos, studying additional materials, etc. The system uses this information to predict the behavior of the student and adapt it to his or her individual needs [8].

Methods of adaptation of learning material based on the student model are quite popular, as it is believed that an adaptive system can be effective only if it is able to adapt to the needs of students [10].

The content model is based on its characteristics and searche for relevant learning resources that meet the needs and preferences of users [8].

A learning model, also known as a pedagogical model, helps adapt the educational process based on the learner's model and provides a basis for making decisions about what content to provide to the student (taking into account speed, format, sequencing of materials, etc.).

The popularization of modern adaptive learning and the implementation of the suggested adaptive learning models is connected with the development of digital technologies, in particular with artificial intelligence. It is one of the important tools that provides access to various educational resources, promotes individualization \ training.

Therefore, the organization of adaptive learning requires the development of modern digital environments using artificial intelligence. In our study, we will consider an adaptive digital environment as a system that basically uses algorithms with elements of artificial intelligence and machine learning to implement adaptive learning models, taking into account the needs of the student, the features of the content and the learning model.

Analysis of literature [11] – [14] allowed us to classify technologies and practices of using AI in education and identify their main characteristics (*table)*

In our research, we consider chatbots to be one of the ways to organize adaptive learning using artificial intelligence. From the point of view of modern scientific realities, the work of a teacher and a student is compared to the personalization of learning, which is based on the creation of electronic courses, considering the individual characteristics of students, in particular their psychological characteristics, the level of initial knowledge, individual goals and educational tasks. Compared to classic digital environments, the chatbot offers the following features: reduced workload, shorther learning time due to a carefully selected information block; increased target audience as a result of attracting students with different levels of training; saving traffic during online education, using effective control tools, etc.

TABLE 1 PLATFORM NAME AND CHARACTERISTICS OF TECHNOLOGIES AND PRACTICES OF AI APPLICATION IN THE FIELD OF EDUCATION

Technologies and practices	**Characteristics**
Language technologies recognition, processing and generation of human speech	The computer recognizes speech and processes it. It can present the identified patterns and results of the analysis with the help of speech that is accessible for perception
Technologies for personalisation learning, adaptive training	Features of artificial neural networks are considered. They find regularities in masses of information and use them to project individual educational trajectories. Training is adjusted to the level, individual characteristics and goals of the students
Virtual assistants	Use information from the Internet, as well as information selected by the user, for forecasting purposes, for example, predicting an individual study schedule
Proctoring	Used to identify students during distance learning (for example, during an exam), tracks redundant and atypical elements (people, sounds), opening new tabs, eye movements, etc.
Interval technologies (intermediate) education	The app tracks the learning material studied, the periods of learning interruptions. Based on the information, it predicts which sections the students have not mastered sufficiently. Then they are recommended for revision
Automatic assessment	A specialized computer program based on AI that simulates the behavior of a teacher who assigns grades. It can evaluate and analyze the learning outcomes of education seekers
Smart campus	A type of chatbot for answering typical students' questions. For example, the schedule of classes, availability of places in dormitories, location of classrooms, availability of educational content, etc
Gamification	Application of computer games and simulators in education
Chatbots	The program simulates a live conversation with the user.

In the process of adaptive learning, chatbots do not require the direct participation of the teacher, because they are based on the interaction of education seekers and the adaptive digital environment.

A pedagogical experiment was conducted to obtain experimental data in the process of designing and creating

an adaptive digital environment, in particular a telegram bot for the implementation of adaptive learning models taking into account the needs of students, content and learning model. In the process of studying the disciplines of the professional cycle for students of the specialty 015.39 Vocational education (Digital technologies) and project participants Transformation of the Teacher Digital Competence Formation System : Innovative European Approaches (Project: 101085799 – TSDigComp – ERASMUS-JMO-2022-HEI-TCH-RSCH at Vinnytsia State Pedagogical University named after Mykhailo Kotsiubynskyi, a survey was conducted regarding the organization of adaptive learning using Telegram . The survey was anonymous, the sample of respondents is not representative. Coverage of respondents – 52. Questionnaire questions related to the effectiveness of using artificial intelligence, in particular Telegram in the conditions of implementation of adaptive learning models meet the needs of students.

The development, implementation and use of AI products and programs in the educational space of Ukraine has significantly increased and accelerated in the conditions of the coronavirus and war. For some time, the educational process was completely transferred to a distance format, and this could not be done without achievements in the IT sphere. We would like to note that since February 2023, GPT chat has become free in Ukraine.

In the conditions of the coronavirus, UNESCO experts developed a universal classification of tools for the organization of distance learning with the use of AI, namely: digital resources for psychosocial support of all subjects of the educational process; digital learning management system (Google Classroom, Moodle, Blackboard , Canvas , etc.); educational programs for mobile gadgets; open online courses; services for self-study; digital readers (books); programs for the joint work of all participants of the educational process online (Telegram, Skype, Zoom, WebEx , etc.); tools for creating digital educational content.

The question remains whether students can improve their results when the educational system is adapted to their needs. According to P. Johannes and A. Lagerstorm [15], this issue can be best addressed by the joint efforts of scientists , educators and developers of adaptive digital environments.

Based on the data of "AIN.UA" - a Ukrainian online publication about IT business, startups, technologies and entrepreneurship. The mass media covers everything that happens in the Ukrainian Internet: deals and startup launches, success and failure stories, journalistic investigations and author's columns are published (Fig. 1).

Therefore, in our research, we will present an algorithm for creating an adaptive digital environment, in particular, a Telegram bot into which Google is integrated Classroom API and artificial intelligence system.

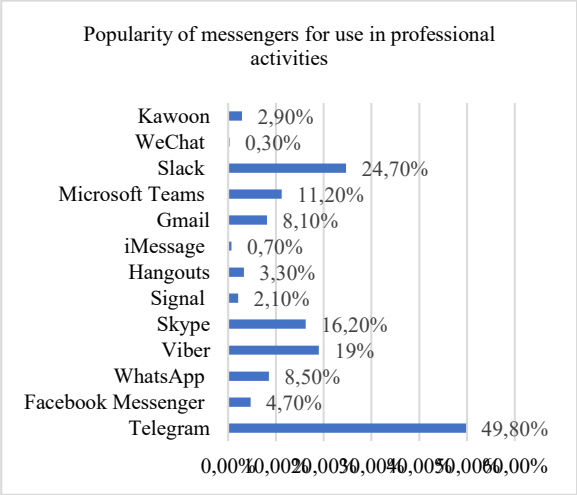


Fig. 1 Diagram showing the popularity of messengers for professional use

Telegram is an open-source cross-platform messenger with IP telephony features that allows you to exchange text, voice and video messages, photos and files in many formats. As of March 2021, official clients for Telegram include:

- Mobile applications for Android and iOS / iPadOS;
- Desktop applications for Windows, Linux and macOS;
- Web application.

Using the Telegram messenger, users get not only a platform for communication, but also many other features, thanks to which the messenger has gained great popularityю

Creating a Telegram bot using node js , node-js-telegram-api, and nest js is a difficult but rewarding task. A Telegram bot is a program that can interact with the users through the popular Telegram messaging platform. Node js is a JavaScript runtime that allows developers to build scalable and efficient web applications. Node-js-telegram-api is a library that simplifies communication between node js and Telegram Bot API. Nest js is a framework that provides a modular and flexible architecture for building node applications.

Here are the stages of the telegram bot creation algorithm:

1. Register a new bot in Telegram using the BotFather service. This will provide us a unique token that can be used to authenticate our bot and access the Telegram Bot API .

2. Create a new JavaScript project and install the necessary dependencies, such as node-js-telegram-api and nest js .

3. Create the main module that will load our nest application js and initialise our Telegram bot. We can use the Telegram bot class from node-js-telegram-api to instantiate our bot and pass it the token we received from

BotFather . Next, we set up some event listeners to handle the different types of messages and commands that our telegram bot will receive from the users.

4. Create a service module that will contain the business logic for Telegram. This module defines the methods that the Telegram bot will use to perform various tasks such as sending messages, receiving data, processing commands, etc.

5. Create a controller module that will manage the Telegram bot's routes. This module defines the endpoints that the Telegrambot uses to communicate with the Telegram Bot API. Decorators from NestJS are useful for mapping these endpoints to methods from the service module. At this stage, we use middleware functions to inspect and analyze incoming requests from Telegram (Fig. 2).

```
    const access_token = await
this.authService.getAuth({
      telegram_id: +body.telegram_id,
    });
    const classroom = google.classroom({
      version: 'v1',
    });
    const course = await
classroom.courses.courseWork.get({
      access_token,
      courseId: '596489149759',
      id: body.id,
    });
    console.log(course.data);
    return course.data;
  }
}
```

Fig. 2. View of the telegram bot for training for the students majoring in 015.39 Vocational Education (Digital Technologies)

Considering the practical experience of the teachers of Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University, the Google Classroom learning management system is quite common in wartime, which organizes the educational process in distance learning.

However, in times of war, access to the Internet faces significant problems. The students are not always able to visit Google Classroom and complete the assigned tasks in time. In uch circumstances , the telegrambot we have created saves traffic due to the absence of a redundant graphic interface. A comfortable work speed for the participants of the educational process can be achieved even with a lower speed of the Internet connection.

The telegrambot we have created allows us to integrate Google Classroom in some academic disciplines in the context of the organization of adaptive training for the students of Vinnytsia Mykhailo Kotsyubynskyi State Pedagogical University. This approach will allow you to synchronize with the educational process, adapt to the progress of the participants of the educational process, independently adjust and study the educational content in real time.

To integrate Google Classroom in the Telegram bot, we need to use Google Classroom API, which is a RESTful web service that allows developers to manage courses, assignments, students, teachers, and other resources on Google Classroom.

Here is the algorithm for integrating Google Classroom into a Telegram bot :

1. Activate the Google API Classroom in our Google project Cloud Platform and get the API key and client ID. We also need to set up the OAuth 2.0 consent screen and configure the areas that Telegram bots will ask the users when they allow it to access their Google Classroom data .

2. Create a new service module that will handle communication between Telegrambot and the Google API Classroom . This module will define the methods that the Telegrambot will use to perform various tasks, such as creating courses, to-do lists, grading submissions, and more. The googleapis or axios libraries are useful for making HTTP requests to the Google API Classroom .

3. Change the main module and add logic for OAuth 2.0 flow processing. To do this, we need to create an authorization URL that redirects users to a Google login page where they can give Telegrambot permission to access their Google data Classroom .

4. Create an endpoint that will receive an authorization code from Google and exchange it for access tokens and updates. The passport or oauth2orize libraries are useful at this stage to simplify this process.

5. Modify the controller module, add some commands and messages that will allow users to interact with Google Classroom via Telegram .

6. Create the classroom command that will offer users to authorize the telegram bot . If they haven't already done it, it will then display a menu of options to manage their courses and assignments. In this case, create messages that notify users of new assignments, submissions, grades, etc. (Fig. 3).

```
    const access_token = await
this.authService.getAuth({
      telegram_id: +body.telegram_id,
    });
    const classroom = google.classroom({
      version: 'v1',
    });
    const course = await
classroom.courses.courseWork.get({
      access_token,
      courseId: '596489149759',
      id: body.id,
    });
    console.log(course.data);
    return course.data;
  }
}
```

Fig. 3 Access to Google in Telegram Classroom from the academic discipline "Engineering and Computer Graphics"

In order to integrate artificial intelligence systems into Telegrambot , we need to use certain machine learning or natural language processing techniques that will improve the functionality and operation of Telegrambot .

We will offer possible scenarios for the integration of

artificial intelligence systems:

- Use natural language understanding (NLU) to analyze user input and extract intent and essence from it. This will allow us to understand what the user wants. For this, the dialogflow or wit.ai libraries are useful , which allow you to create an NLU model for the telegrambot and train it with sample utterances and intentions.
- Use natural language generation (NLG) to generate natural and engaging responses for our users. This will allow us to personalize their messages and make them more conversational. The gpt-3 or openai-api libraries are useful , providing text generation based on specific input or context.
- Use machine learning to analyze user feedback and behavior to further adapt Telegram to the learners' needs. In this case, the tensorflow or pytorch libraries are useful for building a machine learning model in telegrambot and training with data and metrics (Fig. 4).

```
    const access_token = await
this.authService.getAuth({
      telegram_id: +body.telegram_id,
    });
    const classroom = google.classroom({
      version: 'v1',
    });
    const course = await
classroom.courses.courseWork.get({
      access_token,
      courseId: '596489149759',
      id: body.id,
    });
    console.log(course.data);
    return course.data;
  }
}
```

Fig. 4. Telegram bot access to the Open artificial intelligence system Chat - GPT AI Bot v3.0.2 in the process of studying the educational discipline "Engineering and Computer Graphics"

It should be noted that we have tested Telegrambot , which integrates Google Classroom API and artificial intelligence system in the process of studying the educational discipline "Engineering and Computer Graphics" of the specialty 015.39 Professional education (Digital technologies) and project participants Transformation of the Teacher Digital Competence Formation System : Innovative European Approaches (Project: 101085799 – TSDigComp – ERASMUS-JMO - 2022-HEI-TCH-RSCH at Mykhailo Kotsiubynskyi Vinnytsia State Pedagogical University.

As part of these activities, a pedagogical experiment was conducted, which included a survey on the effectivenes of using artificial intelligence, in particular, Telegram for the organization of adaptive training of the students.

The analysis of the results of the questionnaire during the pedagogical experiment made it possible to highlight the possibilities that indicate the appropriateness of using Telegram for the organization of adaptive learning: saving time for studying the discipline - 8%, correctness of the material - 6%, instant communication - 10%, accessibility of learning - 5%, simple interface - 7%, ease of use - 15%, integration of web applications and intelligent systems - 21%, access to intelligent artificial intelligence systems - 25%, difficulty in use - 2%, lack of gadgets - 0%, limited access to the Internet - 1 % (Fig. 5).

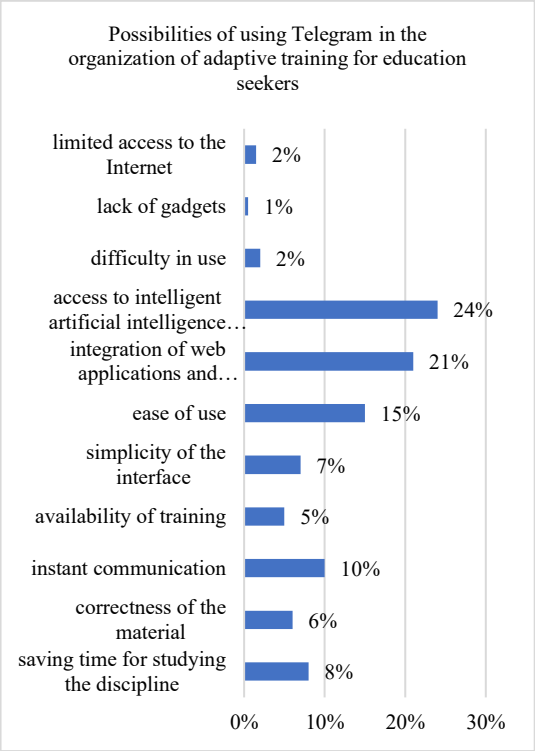


Fig. 5. A diagram demonstrating the possibilities of using Telegram in the organization of adaptive training for students

The results of the survey among the students showed that the use of telegrambot is appropriate in the process of professional training of students, as it provides quick access to various types of information through the integration of web applications , intelligent systems and access to intelligent systems of artificial intelligence. Under such conditions, artificial intelligence technologies, in particular, telegrambot, can increase the accessibility of education and contribute to the improvement of the quality of professional training of the students.

The opinion of the teachers of Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University is important regarding the creation and implementation of adaptive digital environments using artificial intelligence technologies, in particular telegrambots . As part of the study, a survey of teachers was conducted in order to determine the features of using adaptive digital environments, in particular telegrambots in the organization of adaptive learning (Fig. 6).

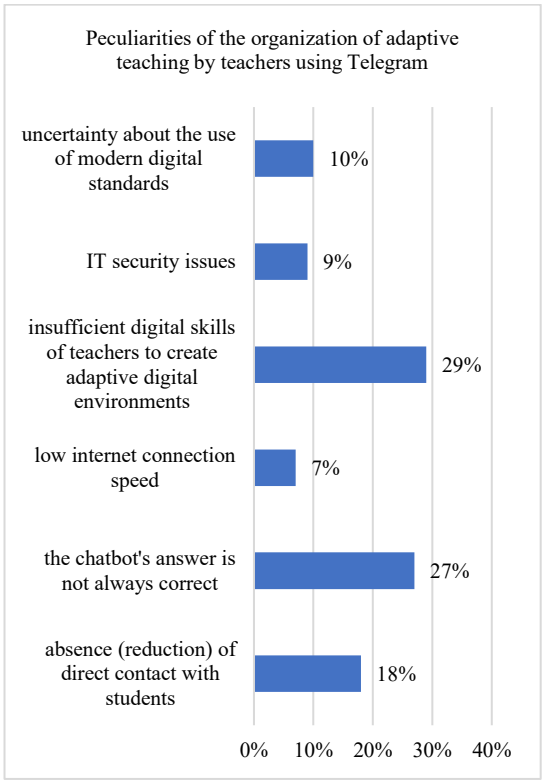


Fig. 6 Diagram showing the peculiarities of the organization of adaptive learning by teachers using Telegrambot

The teachers' survey allowed us to identify the specifics of using of artificial intelligence technologies, in particular telegrambots , and to obtain the following data: lack (reduction) of direct contact with students - 18%, not always correct response of the chatbot - 27%, low speed of Internet connection - 7%, insufficient digital skills of teachers to create adaptive digital environments - 29%, IT security issues - 9%, uncertainty about the use of modern digital standards - 10%.

A comparison of survey data from students and teachers regarding the use of artificial intelligence technologies, in particular telegrambots , for the organization of adaptive learning shows that telegrambots are in demand among the students and require the development of digital skills of teachers regarding the creation and implementation of adaptive digital environments using artificial intelligence technologies, in particular telegram bots.

IV. Conclusions

The implementation of adaptive digital environments using artificial intelligence technologies is rapidly developing and requires a constant search for innovative approaches to their creation and use in the process of professional training of students. The implementation of adaptive digital environments using artificial intelligence technologies, in particular telegrambots , ensure flexibility, openness to modifications, accessibility in the conditions of the organization of adaptive learning through individualization, personalization, a person-oriented approach to learning. The analysis of scientific sources allowed us to generalize that Telegram not only creates a platform for communication and allows you to post diverse information, but is also a means of organizing an individual learning trajectory, allows you to upload files and exchange educational content.

The results of the pedagogical experiment proved that for students, using telegrambot is appropriate in the process of professional training, as it provides quick access to various types of information through the integration of web applications, intelligent systems and access to intelligent artificial intelligence systems. Teachers noted that in the process of using telegram bots, direct contact with students decreased, they noted that the chat bot's reaction was not always correct, the low speed of the Internet connection, insufficient digital skills of teachers to create adaptive digital environments, IT security problems, and uncertainty in the use of modern digital standards.

A comparison of survey data from students and teachers shows that Telegram bots are in demand among students and require the development of teachers' digital skills in creating and implementing adaptive digital environments using artificial intelligence technologies.

Given this, we consider it relevant and promising to study the theoretical foundations of design, the creation of adaptive digital environments using artificial intelligence technologies, in particular telegrambots based on web technologies , as well as the development of methods for their use in the professional training of education seekers, in particular in war conditions . Since adaptive digital environments based on artificial intelligence technologies, in particular, telegrambots will become a driving force for the development of digital pedagogy to expand the possibilities of active learning.

IV. REFERENCES

[1] B. Tripathy, Internet of Things (IoT): TeChnologies, AppliCations, Challenges and Solutions. Florida: CRC Press, 2017.

[2] P. Kerr, Adaptive learning. ETL Journal. Vol. 70, no. 1, 2016, pp. 88—93. DOI:10.1093/elt/ccv055

[3] J.M. Lowendahl, T.L.B. Thayer and G. Morgan, Top 10 strategic technologies impacting higher education in 2016 Gartner Research, [Online]. Available: URL: https://www.academia.edu/29441505/Top_10_Strategic_Technologies_Impacting_in Higher_Education_ [Accessed: Aug. 25 ,2024].

[4] N. Dmitrenko, O. Voloshyna, S. Kizim, K. Mnyshenko and S. Nahorniak, . Smart Education in the Prospective Teachers' Training. CEUR Workshop Proceedingsthis link is disabled, 3364, 2023, pp. 38–53 https://doi.org/10.55056/cte.568

[5] O. Voloshyna, T. Melnychuk, M. Sapohov, N. Burlaka and A. Khilya, The potential of developing and creating online applications for teacher training. Environment. Technology. Resources. Rezekne, Latvia Proceedings of the 15th International Scientific and Practical Conference. Volume II, pp. 525-529, 2024, https://doi.org/10.17770/etr2024vol2.8086

[6] A. Yarovyi, A. Yarovyi, S. Kizim and V. Ozeranskyi, Innovative Trends in the Field of Modern Artificial Intelligence

Methodology, ETR, vol. 2, pp. 132–137, Jun. 2024, doi: 10.17770/etr2024vol2.8065.

[7] T.K.F. Chiu and I.A.C. Mok, Learner expertise and mathematics different order thinking skills in multimedia learning. Computers & Education. Vol. 107, 2017, pp.147—164. DOI:10.1016/j.compedu.2017.01.008

[8] F. Martin and D. Markant, Adaptive learning modules. In M.E. David, M.J. Amey (eds.). The SAGE encyclopedia of higher education. London: Sage, 2020, pp. 2-4 DOI:10.4135/9781529714395.n31

[9] Kabinet ministriv Ukrainy. Rozporiadzhennia vid 2 hrudnia 2020 r. № 1556-r «Pro skhvalennia Kontseptsii rozvytku shtuchnoho intelektu v Ukraini» [Cabinet of Ministers of Ukraine. Order dated December 2, 2020 No. 1556-r "On the approval of the Concept of the development of artificial intelligence in Ukraine."] [Online]. Available: https://zakon.rada.gov.ua/laws/show/1556-2020-%D1%80#Text [Accessed: Aug. 18 ,2024]

[10] A.H. Nabih, Adaptive Social Learning Management System to Develop University Students Achievement. Egyptian Computer Science Journal. Vol. 44, no. 1, 2020, pp. 35—47.

[11] H.A. Abu-Alsaad, Agent applications in e-learning systems and current development and challenges of adaptive e-learning systems. 11th international conference on electronics, Computers and artificial intelligence (ECAI), 2019, pp. 1–6. IEEE. DOI:10.1109/ECAI46879.2019.9042015

[12] A. Ciupe, D.F. Mititica, S. Meza and B. Orza, Learning agile with intelligent conversational agents. IEEE global engineering education conference (EDUCON), 2019, pp. 1100–1107. IEEE. DOI:10.1109/EDUCON.2019.8725192

[13] B.J. Grosz, Smart enough to talk with us? Foundations and challenges for dialogue capable ai systems. Computational Linguistics, 44(1), 1–15, 2018, DOI:10.1162/COLI_a_00313

[14] N. Dmitrenko, Y. Koliadych, L. Melnyk and O. Voloshyna, The Use of ICT in Learning ESP by Pre-Service Teachers of Mathematics in the Wartime (O uso de tecnologias de informação e comunicação no estudo do inglês para fins específicos por futuros professores de matemática em tempos de Guerra). Texto Livre, Belo Horizonte-MG, v. 17, 2024. p. 47-58, DOI: 10.1590/1983-3652.2024.47588.

[15] P. Johanes and L. Lagerstrom, Adaptive Learning: The Premise, Promise, and Pitfalls ASEE Annual Conference & Exposition, Columbus, Ohio, 2017.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 213-216

Joystick Control of a 3D Printed Robotic Manipulator for Student Learning

Nikolay Komitov
dept. "Electrical engineering, electronics and automation"
University of Food Technologies
Plovdiv, Bulgaria
nkomitov @uft-plovdiv.bg

Veselin Mengov
dept. "Electronics, communications and information technologies"
University of Plovdiv "Paisii Hilendarski"
Plovdiv, Bulgaria
vmengov@uni-plovdiv.bg

Georgi Komitov
dept. "Agricultural Mechanization"
Agricultural University – Plovdiv
Plovdiv, Bulgaria
gkomitov@au-plovdiv.bg

Evelin Shopov
dept. "Electrical engineering, electronics and automation"
University of Food Technologies
Plovdiv, Bulgaria
eshopov01@abv.bg

***Abstract*—In the present work, the control mode of a robotic manipulator with a joystick when moving an object to a desired position is considered. In automated systems, it is always necessary, in addition to the main automatic mode, to have an additional mode allowing additional adjustment. In addition, it can serve to determine the most suitable trajectory for the robot's motion, both for its recording and for motion training. 3D printing technology was chosen to create the individual details of the robot, which significantly reduces its cost. The details can be restored at any time if necessary. Arduino IDE and Nano board are used as the control development platform. The project is the basis of a student's thesis on automatic control of a robotic manipulator. The finished project will serve to train students and make it easier to adopt and adapt to these modern technologies. This step-by-step project implementation approach was chosen, as it will lead to consolidation and acquisition of new knowledge at each stage of implementation.**

Keywords*— *Arduino, robot, joystick, 3D printing.

I. INTRODUCTION

The entry of robotic systems into people's lives is happening without much fanfare, and in recent years it has increasingly manifested itself in one form or another. Industrial enterprises have long used various types of industrial robots or manipulators for specific purposes in production. Training people to work with robots could start at a very early age, as it is taught in elementary, middle, and high school. The user working with a robot must not only be able to program, but have knowledge of electronics, electrical engineering, mechanics, mechanical engineering. Universities offer training on different types of robots, some of which are like industrial robots, using the same programming language and control controllers. This is nice on the one hand as it offers access to this cutting-edge technology, but on the other hand such robots are only found in universities and factories. After passing the relevant course, the student does not have access to this technique, unless he works with it and can't realize his ideas or projects. On the other hand, 3D printing technology offers opportunities for creating prototypes, thus everyone can create their own projects, choose management and implementation options themselves, can gain experience working with this technology. A systematic review specific to robotics research is done in a report [1]. The greatest interest is in applications of robots in medicine, industry, space, military affairs, agriculture. The research shows that there are very few studies on communication between robots. Of great importance is the design of the robot's joints and their mobility. In a report [2], various control strategies for robots applied to flexible joints were investigated with MATLAB to improve their interaction with disabled people. A robot operating system (ROS)-based joystick remote control method for KUKA industrial robots is developed in a report [3]. An independent application programming interface (API) has also been developed for data transfer. MATLAB's Robotic Toolbox package for designing the motion trajectory of a 6- degrees of freedom

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8600
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

(DOF) mechanical arm by the triple and five-fold polynomial interpolation techniques has been used in a report [4]. In report [5], an optimal parameter finding algorithm based on soft-actor-critic (SAC) instead of a conventional PID controller is proposed to stabilize the robot operation affected by changing environmental conditions. In a report [6], a modification of a commercial haptic device was made to convert it into a 2D haptic joystick. A simplified haptic interface (API) has been created for the joystick feedback. A gamepad as a control device for KUKA industrial robots in order to improve existing solutions is proposed in a report [7]. The control of the gamepad has been improved by adding a smartphone, for visualization of information to the user. The gamepad robot control method was tested with two different tasks for data validation. A comparative analysis of basic controllers from the ROS control package and advanced controllers in a 3D Gazebo simulator of a 7 DOF robotic arm has been conducted in a report [8]. A disturbance resistance test was also conducted. A new design of ergonomic gesture control with visual feedback for collaborative work with a UR3 robot is presented in a report [9]. The system enables users with little or no knowledge of robots to perform basic tasks and programming. The principle of operation mirrors that of a 3D joystick, but a Leapmotion device is used to track the user's hands and prevents the need for a physical joystick or buttons. A report [10] proposed an LSTM neural network to achieve safe trajectory planning and navigation for a mobile robot from start point to end point while avoiding dynamic obstacle. The mobile robot and its dynamic environment are simulated in the Gazebo 3D simulator. Controlling the movement of a robotic arm through a Raspberry pi remotely using an internet connection is proposed in a report [11]. A report [12] described the mechanical system, design and prototype of a 6 DOF robotic arm. A Raspberry Pi and a graphical user interface (GUI) written in Python were used for control. The values of the PID controller are obtained in MATLAB Simulink. There are areas of life where the environment is dangerous or harmful to humans and the efforts of developers are directed in this direction. Deep-sea robots are widely used in studying the seas and oceans [13]. If necessary, robotic arms controlled by a person on the surface are used to perform certain operations underwater [14]. In the present report, a model of the MK2 manipulator [15] produced by 3D technology is used. All the necessary files for its production are open source. The project will serve as the basis of an undergraduate student's thesis.

II. Materials and Methods

The manipulator has four degrees of freedom. Manipulator manufacturing can be divided into three distinct parts: mechanical, hardware, and software.

A. The mechanical part

It includes printing the parts of the robot, assembling and fitting the individual parts. 3D printing technology is very convenient for this project. On the one hand, the student can be trained by creating the physical model of the robot, and on the other hand, directly reproduce it. Another important point is the duplication of a damaged part or correction on the very details of the robot if necessary. The time is not far when this type of printer will become a part of people's daily life, like personal computers. Having a home 3D printer, the user will be able to independently create a more complex manipulator without the need to work with an expensive industrial robot. For the movement of the base, 6 mm diameter 3D-printed spheres were initially used, but later they were replaced by metal ones. They act as a bearing around which the base of the manipulator rotates. Added a 4mm axle running through the base and arms that are connected to the motors. In this way, the structure and movements are stabilized. The robot has four servo motors: M1 for base rotation (x-axis), M2 for up-down movement (y-axis), M3 for forward-backward movement (z-axis), M4 for grasping objects (x-axis). The manipulator file was inserted into the Oneshape software to check the 3D model as well as the movement of the individual motors along the axes (Fig. 1). After selecting a motor, its direction of movement is set and the robot is driven to the desired position.

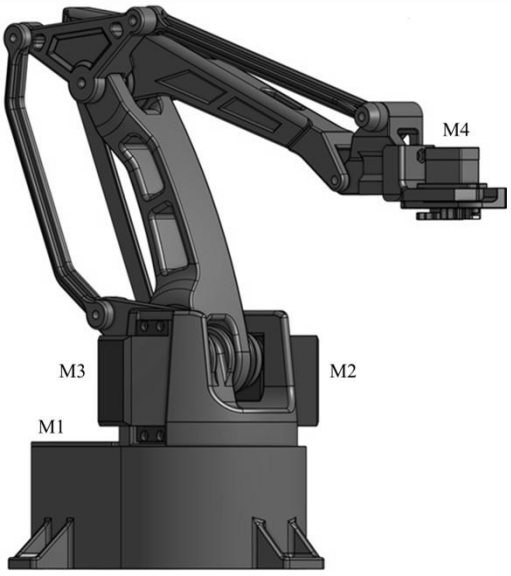


Fig. 1. View of the 3D model in Oneshape.

B. Hardware part

When the mechanical part of the manipulator was assembled, the servo motors were run separately. Initially, a board (CCPM Servo Consistency Master/Servo tester) was used to test the motors. It can be used to control three engines simultaneously in manual or automatic mode, but is suitable for starting only one engine. If all three motors are connected at the same time, unpredictable behaviour of the robot may result. Each motor was tested individually with this board, which showed the performance of the manipulator, but also showed its shortcomings. The board is useful to visualize the operation of a particular servo motor from the manipulator. For manual mode involving rotation, lifting, lowering and gripping, four such boards are required, making free control pins redundant. Due to these

shortcomings, a variant with two joysticks was chosen to control the four servo motors. Each joystick outputs two analogue signals indicating the presence of movement along the x, y axes. The analogue signals from it are converted by the controller's ADC, and then it produces a control signal to the motors. The first joystick is for controlling M1, M2 along the x, y axes, and the second for controlling M3, M4 along the y, x axes. Actually, the second joystick is for controlling the M3 motor along the z axis, but it is marked y on the joystick. When the joystick is in the centre position, it outputs an analogue signal proportional to the value in bits (512, 512) for x, y. This report uses a 4$ Nano board, but in the thesis, project will use the UNO R3. The control unit and joystick are powered by the computer. Servomotors M1, M2, M3 are MG996R type, and M4 is SG90 type. Since the consumption of the three motors is high, a separate power source is provided. All motors move in the range of 0 to 180 degrees. The controller in turn outputs a control signal to each servo motor. An additional driver is not used at the moment, but one is planned at a later stage in order to obtain a higher resolution output signal for smoother movement. In fig. 2 shows a block diagram of the hardware part.

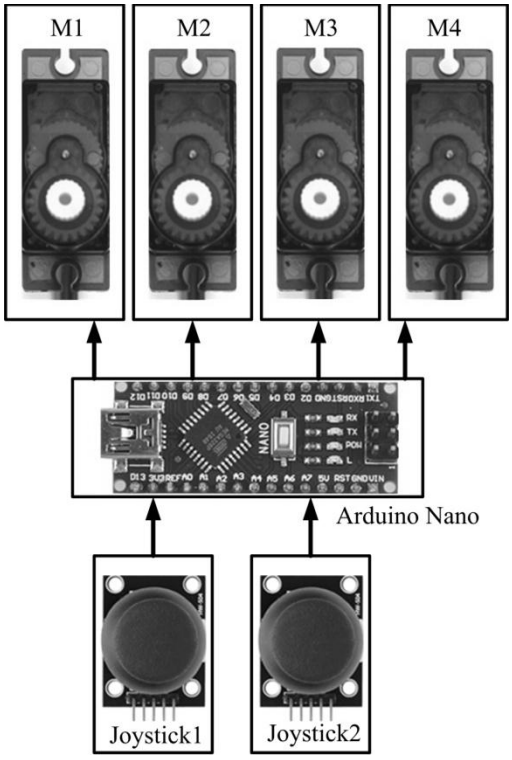


Fig. 2. Block diagram of the hardware part.

C. Software part

The open source development platform Arduino IDE was chosen. The software part includes initialization of variables, analogue inputs, servo motors. The position of the servo relative to the joystick is determined. A dead zone is set in the central part of the joystick in the range from 400 to 600, which are marked in Fig. 3 with the abbreviation dBL and dBH. The status of the analogue inputs is read. Then their value (xval, yval) is checked. If it is within the dead zone range, the motors do not operate. When the value of the signal goes out of the dead zone, a check is made to see if the value is below 400 or above 600, then the servo motor is started in the desired direction. Finally, the position is updated. A block diagram of the program is shown in Fig. 3.

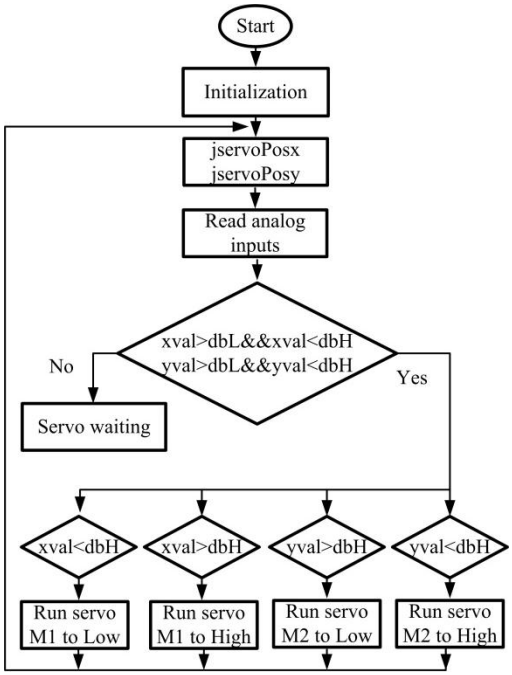


Fig. 3. Block diagram of the program.

III. RESULTS AND DISCUSSION

A photo of the manipulator is presented in fig. 4. The MK2 manipulator is manufactured using 3D technology with PLA material with 15% infill. Part of the received data from the serial channel can be seen in fig. 5. When serial communication starts, the positions of both joysticks are in the centre of the range. Changing the position of the joystick along the x-axis brings the servo motor to a minimum value. The mode of simultaneous movement of two or more servomotors is not foreseen. Currently the motors do not have current protection, this will be added at a later stage. Visualization and recording of the readings is provided for the purpose of designing the movement trajectory.



Fig. 4. Picture of the manipulator.

COM7 (Elecrow CrowPanel 7.0P)

```
x1=0   y1=515   x2=528   y2=502
x1=502   y1=528   x2=528   y2=503
x1=0   y1=515   x2=527   y2=503
x1=502   y1=527   x2=528   y2=502
x1=0   y1=514   x2=528   y2=503
x1=503   y1=527   x2=528   y2=502
x1=0   y1=515   x2=527   y2=502
x1=502   y1=528   x2=527   y2=502
x1=0   y1=515   x2=527   y2=503
x1=502   y1=528   x2=528   y2=503
x1=0   y1=515   x2=527   y2=503
x1=502   y1=527   x2=528   y2=502
x1=0   y1=515   x2=528   y2=502
x1=502   y1=528   x2=528   y2=503
x1=0   y1=515   x2=528   y2=502
x1=502   y1=528   x2=528   y2=503
x1=0   y1=514   x2=528   y2=503
x1=502   y1=528   x2=528   y2=502
x1=519   y1=515   x2=526   y2=502
x1=502   y1=528   x2=528   y2=502
x1=519   y1=515   x2=528   y2=503
x1=503   y1=527   x2=528   y2=502
x1=519   y1=515   x2=528   y2=502
x1=503   y1=528   x2=528   y2=502
x1=519   y1=515   x2=528   y2=502
x1=502   y1=528   x2=528   y2=503
```

Fig. 5. Data from analog inputs.

IV. CONCLUSIONS

The introduction of the MK2 manipulator in the training of students will significantly improve the level of their professional skills. They will be able to program and control the robot not only in the exercises, but also outside of them, with whatever control modules they want. The 3D printing technology allows the students to print, assemble and put the manipulator into operation themselves. The student has the opportunity to see the construction of an article from start to finish. The materials used free software significantly reduce the cost of the robot. The most valuable thing about the case is the experience they will get in developing it. Adding a display, driver, protection scheme at a later stage to the project will improve the operation of the manipulator. Another aspect of the project is connecting the robot to the Internet or controlling it via a smart phone, as well as adding a surveillance camera.

REFERENCES

[1] M. Al-Razgan, L. F. Alfallaj, N. S. Alsarhani, and H. W. Alomair, "Systematic review of robotics use since 2005," International Journal of Mechanical Engineering and Robotics Research, vol. 5, no. 2, 2016, pp. 129-132, DOI: 10.18178/ijmerr.5.2.129-132.

[2] R. Zotovic-Stanisic, R. Perez-Ubeda and A. Perles, "Comparative study of methods for robot control with flexible joints," Actuators, 2024, 13, 299. https://doi.org/10.3390/act13080299.

[3] S. Yang, S. Wang and S. Huang, "ROS-based remote control of industrial robot joystick," Proceedings of the Institution of Mechanical Engineers, Part C, Journal of Mechanical Engineering Science, 2023;237(1):160-169. doi:10.1177/09544062221115549.

[4] Q. Jiang and Y. Zhang, "Research on Trajectory planning and simulation of six-degree-of-freedom manipulator," Journal of Physics, Conference Series 2528, 2023, pp. 1-6, doi:10.1088/1742-6596/2528/1/012067.

[5] C. Rei, Q. Wang, L. Chen, X. Yan, P. Zhang, L. Fu, C. Wang and X. Liu, "Constant force grinding controller for robots based on SAC optimal parameter finding algorithm," Sci Rep 14, 14127 (2024). https://doi.org/10.1038/s41598-024-63384-2.

[6] D. J. Brooks, M. Lunderville and H. A. Yanco, "Design of a 2D joystick for robot control based on a 6 DOF haptic device, " 2013, IEEE Conference on Technologies for Practical Robot Applications (TePRA), Woburn, MA, USA, 2013, pp. 1-6, doi: 10.1109/TePRA.2013.6556378.

[7] M. Wagner, D. Avdic and P. Heß, "Gamepad control for industrial robots - new ideas for the improvement of existing control devices," In Proceedings of the 13th International Conference on Informatics in Control, Automation and Robotics, vol. 2, ICINCO, 2016, pp. 368-373. DOI: 10.5220/0005982703680373.

[8] B. Zhang and P. Liu, "Control and benchmarking of a 7-DOF robotic arm using Gazebo and ROS," PeerJ Computer Science 7:e383, 2021, https://doi.org/10.7717/peerj-cs.383.

[9] S. Bordoni and G. Tang, "Development and assessment of a contactless 3D joystick approach to industrial manipulator gesture control," International Journal of Industrial Ergonomics, Elsevier, vol. 93, 2023, pp. 1-14, https://doi.org/10.1016/j.ergon.2022.103376.

[10] A. Molina-Leal, A. Gómez-Espinosa, J. A. E. Cabello, E. Cuan-Urquizo and S. R. Cruz-Ramírez, "Trajectory planning for a mobile robot in a dynamic environment using an LSTM neural network," Applied Sciences, vol. 11, issue 22, 2021, pp. 1-21, https://doi.org/10.3390/app112210689.

[11] N. Srivastava and J. Joshi, "Raspberry Pi controlled robotic arm," International Journal of Research, vol. 3, issue 5, 2016, pp. 54-58.

[12] M. Z. B. A. Karim and N. M. Thamrin, "Servo Motor Controller using PID and Graphical User Interface on Raspberry Pi for Robotic Arm," Journal of Physics: Conference Series, vol. 2319, issue 1, pp. 1-10.

[13] S. A. Watson and P. N. Green, "Robust control of a micro-autonomous underwater vehicle (μAUV) using low-tolerance components," IFAC Proceedings Volumes, Elsevier, vol. 45, issue 5, 2012, pp. 7-12.

[14] F. Dukan and A. J. Sørensen, "Joystick in closed-loop control of rovs with experimental results," IFAC Proceedings Volumes, vol. 45, issue 5, 2012, pp. 293-300.

C. Franciscone, EEZYbotARM Mk2 - 3D Printed Robot, https://www.instructables.com/EEZYbotARM-Mk2-3D-Printed-Robot/[Accesed March 30, 2025]

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 217-220

Patient Client Consumer Behavior in Physical and Online Pharmacies. A Comparative Analysis of Pharmaceutical Care and Artificial Intelligence

Tatiana Krumova
New Bulgarian University
Sofia, Bulgaria
tatiana.krumova@gmail.com

***Abstract* - This study highlights distinct consumer behaviors in physical versus online pharmacies, revealing critical insights into the evolving landscape of pharmaceutical care. Findings indicate that online pharmacy users are more likely to make impulsive purchasing decisions driven by promotional offers, spending an average of only 50 seconds on websites. In contrast, consumers in physical pharmacies engage in more deliberate decision-making, heavily influenced by personal interactions with pharmacists. The implications of these findings suggest that consumer behavior in the pharmaceutical sector is significantly shaped by the purchasing environment. The integration of artificial intelligence (AI) in online pharmacies enhances operational efficiencies and personalization but raises concerns regarding the loss of human interaction and emotional intelligence, both crucial for building trust. This highlights the need for further research into balancing technology and personal care in e-health environments. From a practical standpoint, pharmacies must adapt to these evolving consumer preferences by adopting hybrid models that leverage the strengths of both physical and online settings. This includes enhancing the online shopping experience through personalized AI-driven recommendations while maintaining robust patient-pharmacist interactions in physical locations. Implementing tele pharmacy services can bridge the gap, facilitating access to pharmacist consultations without sacrificing personal connection. Ultimately, the study emphasizes the necessity for pharmacies to prioritize the human elements of care that foster trust and loyalty among patients, especially as the industry increasingly incorporates digital solutions. By doing so, pharmacies can improve patient satisfaction and adherence while ensuring a competitive advantage in a rapidly changing healthcare landscape. These insights are vital for pharmacy practitioners, healthcare policymakers, and researchers navigating the complexities of consumer behavior in the digital age.**

Keywords* - *Artificial Intelligence, Consumer Behavior, Online Pharmacy, Physical Pharmacy.

I. INTRODUCTION

The pharmaceutical industry is undergoing a significant transformation driven by technological advancements, particularly the rise of online pharmacies and the increasing integration of artificial intelligence (AI). As consumers increasingly turn to digital solutions for their healthcare needs, the landscape of pharmaceutical care is evolving rapidly. The COVID-19 pandemic has further accelerated this trend, with many patients preferring the convenience and accessibility of online pharmacies (Deloitte, 2021) [2]. This shift necessitates a thorough re-evaluation of traditional pharmacy models, as patients seek not only greater convenience but also competitive pricing and improved access to health information (Miller & Davis, 2021) [8].

Recent data from multiple sources, including a comprehensive analysis of pharmacy behaviors and trends from various studies (Miller & Davis, 2021; Heller et al., 2020) [4, 8] alongside Phoenix Pharma Bulgaria (2024) [7], highlight key behavioral trends in pharmacy usage. For online pharmacies, the analysis shows an average click-through rate of 2.5% on Facebook, with users spending an average of just 50 seconds on the site. This brevity suggests a tendency towards impulsive purchasing behaviors driven by promotional content, as noted by Bagali (2021) [1]. Additional studies corroborate these findings, indicating that such quick decision-making is

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8588
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

common in digital environments, where users are often exposed to targeted marketing (Thompson & Reid, 2022) [15]. In contrast, visits to brick-and-mortar pharmacies are characterized by intentionality; the data indicates that random visits are virtually non-existent. Customers typically plan their visits around prescriptions, checks, prevention, or maintenance of chronic conditions, leading to a more deliberate purchasing process. Furthermore, the personal interaction with pharmacists plays a crucial role in shaping consumer decisions, as recommendations from pharmacists foster trust and loyalty. In many cases, the absence of such interaction may deter customers from making a purchase or returning to the pharmacy altogether.

The application of consumer behavior theory is critical in understanding these dynamics. The Theory of Planned Behavior (Ajzen, 1991) suggests that consumer intentions guide their actions, influenced by attitudes, subjective norms, and perceived behavioral control. In the context of pharmacy settings, consumers' attitudes towards online and physical pharmacies are shaped by their experiences, the perceived ease of use of digital platforms, and the relationship with pharmacists, which affects their purchasing decisions (Kumar & Reinartz, 2016) [16].

Numerous studies have examined the dynamics of consumer behavior in pharmacy settings. Miller and Davis (2021) [8] highlight that online pharmacies have gained popularity due to their ease of use, allowing consumers to compare prices and access a wider range of products. Conversely, Heller et al. (2020) [4] emphasize the importance of personal interactions in physical pharmacies, where trust and loyalty are built through relationships with pharmacists. This sentiment is echoed by Huh et al. (2021) [5], who found that personal consultations significantly enhance patient confidence in medication choices, especially for those managing chronic conditions. Additionally, Dimova (2021) [3] discusses the broader influence of digitalization on consumer behavior in retail, noting that the shift to online platforms has fundamentally changed how consumers interact with products and services. Costa et al. (2020) [18] also highlight the evolving consumer behavior in e-pharmacies, emphasizing the need for a systematic understanding of these changes. According to Statista (2023) [12], the increasing number of online pharmacies in Bulgaria illustrates the growing trend towards digital solutions in the pharmaceutical sector.

The integration of AI technologies is reshaping customer interactions in online pharmacies. Raza (2021) [10] notes that AI-driven tools, such as chatbots and predictive analytics, have the potential to personalize the shopping experience, thus enhancing customer satisfaction. Specific AI solutions, such as virtual health assistants and automated prescription refills, streamline customer interactions and provide tailored recommendations based on user behavior and preferences (Fischer et al., 2020) [17]. However, while these technologies improve operational efficiency, they raise concerns about the loss of human interaction and the emotional intelligence that pharmacists provide (Smith & Jones, 2019) [11]. According to a study by Khan (2021) [6], the reliance on AI can create a gap in trust, particularly among older consumers who may prefer personal interactions over automated services. Alshahrani et al. (2021) [19] further support this notion by exploring consumer behaviors towards online pharmacies in Saudi Arabia.

Furthermore, Kuo (2022) [13] explores consumer trust in online pharmacies, highlighting the critical role that AI plays in shaping perceptions and influencing user confidence. Similarly, Johnson and Taylor (2022) [14] review the impact of e-pharmacy on medication adherence, identifying both the benefits and challenges posed by digital pharmacy models in maintaining patient engagement and compliance. Additionally, Patel et al. (2023) [9] discuss the influence of digital health technologies on consumer behavior, emphasizing the need for pharmacies to adapt their strategies to meet evolving consumer expectations in a digital landscape. The impact of COVID-19 on consumer behavior in the online pharmacy market is also noted by Alharthi (2021) [20], underscoring the urgency of understanding these dynamics.

Despite the growing body of literature on online pharmacies and AI integration, there remains a gap in understanding the comparative consumer behavior between physical and online pharmacy settings. The nuances of how trust and loyalty are built in these different environments require further investigation, particularly as consumer preferences continue to evolve. A comparative analysis of consumer behavior in physical versus online pharmacies is essential for identifying effective strategies that pharmacies can adopt in this changing landscape. This publication aims to explore the differences in consumer behavior among patients in both physical and online pharmacy settings, focusing on the influence of pharmaceutical care and AI on patient experiences and decision-making processes. By analysing these dynamics, this study seeks to provide insights into how pharmacies can effectively adapt to the evolving landscape of healthcare delivery.

II. MATERIALS AND METHODS

This research adopts a mixed-methods approach, combining quantitative data analysis with qualitative insights to comprehensively understand consumer behavior in both physical and online pharmacies. For online pharmacies, web analytics tools, particularly Google Analytics, were employed to gather data on user behavior. Key metrics such as click-through rates and time spent on-site were analyzed. For example, one of the leading online pharmacies in Bulgaria reported a click-through rate of 2.5% on Facebook and an average site visit duration of 50 seconds over the past six months (Phoenix Pharma Bulgaria, 2024) [7]. Additional studies have verified this average time spent, confirming that online users tend to browse quickly due to the abundance of choices available (Thompson & Reid, 2022) [15].

Physical pharmacies were analysed through point-of-sale (POS) data and customer feedback interviews, focusing on sample sizes that included 200 participants across various demographics. The demographic characteristics of the participants were as follows:

- Age: 18-65 years
- Gender: 52% female, 48% male
- Socioeconomic Status: 30% low income, 40% middle income, 30% high income
- Health Conditions: 25% with chronic conditions, 75% without chronic conditions

The data collection method involved structured questionnaires administered during interviews, ensuring a representative cross-section of the population. To address potential confounding variables, the study employed multiple regression analysis to control for factors such as age, gender, socioeconomic status, and frequency of pharmacy visits. This analytical procedure allows for a clearer understanding of how these variables influence consumer behavior, providing robust insights into the differences between physical and online pharmacy settings.

Significance Testing: Statistical analyses included significance values, effect sizes, and 95% confidence intervals for key metrics. For example, the regression analysis indicated a significant effect of online shopping frequency on impulsive purchasing behavior ($p < 0.05$), with an effect size (Cohen's d) of 0.4, suggesting a moderate relationship.

III. Results and Discussion

The findings reveal significant differences in consumer behavior between physical and online pharmacies. Online pharmacy users tend to make quicker, more impulsive purchasing decisions, as evidenced by the short average time spent on sites. This suggests a convenience-driven behavior, where promotional offers heavily influence purchases. Research indicates that the promotional share online is significantly higher compared to physical pharmacies, where decisions are often based on prescriptions and pharmacist recommendations (Miller & Davis, 2021) [8].

In contrast, visits to physical pharmacies are generally more planned and deliberate. According to Heller et al. (2020) [4], a negligible percentage of visits to physical pharmacies are random; these interactions are typically driven by specific health needs or prescriptions. Patients visiting physical pharmacies tend to deliberate longer on their purchasing decisions, and the presence of a pharmacist encourages them to seek information and ask questions, leading to a more informed decision-making process.

The role of pharmacists in physical pharmacies is critical in shaping consumer decisions. Personal interactions significantly influence trust and loyalty. A study by Huh et al. (2021) [5] found that 70% of patients reported feeling more confident in their medication choices when receiving guidance from a pharmacist. This trust is particularly vital for patients managing chronic health conditions, where ongoing support and education are essential for adherence and health outcomes.

To further illustrate the influence of pharmacists on consumer trust and decision-making, Table 1 outlines the contrasting roles that pharmacists play in physical and online pharmacy settings.

Table 1: Contrasting roles of pharmacists in physical and online pharmacies

Influence Factor	Online pharmacies	Physical pharmacies	Source
Interaction with pharmacists	Minimal interaction	High interaction	Heller et al. (2020) [4]
Confidence in medication choices	Lower confidence	70% of patients feel more confident	Huh et al. (2021) [5]
Role in decision-making	Limited role	Critical role in shaping decisions	Dimova (2021) [3]
Patient education	Limited to AI-assisted tools	Continuous support and education	Raza (2021) [10]
Trust level	Lower due to lack of personal interaction	Higher due to personal consultations	Miller & Davis (2021) [8]

Adapted from Huh et al. [5] and other cited sources.

AI technologies are increasingly influencing decision-making processes in online pharmacy settings. The integration of AI allows for personalized experiences, where algorithms analyze user behavior to deliver tailored product recommendations and enhance customer interactions (Patel et al., 2023) [9]. Specific AI solutions, such as virtual health assistants and automated prescription refills, streamline customer interactions and provide tailored recommendations based on user behavior and preferences (Fischer et al., 2020) [17]. However, the reliance on AI also presents challenges. While AI can improve efficiency and reduce wait times, it cannot replicate the emotional intelligence and empathy that human pharmacists provide (Smith & Jones, 2019) [11]. Striking a balance between leveraging AI and maintaining the human touch in pharmaceutical care is essential for maximizing patient satisfaction and improving health outcomes.

The shift towards online pharmacies creates both challenges and opportunities for the pharmaceutical industry. A primary challenge is ensuring that the quality of care provided through online platforms remains high. As pharmacies increasingly adopt AI and digital solutions, they must also prioritize the human elements of care that foster trust and loyalty among patients. Opportunities exist for developing hybrid models that combine the strengths of both physical and online pharmacies. For instance, telepharmacy services can provide patients with access to pharmacist consultations without compromising the personal connection that many consumers value. Additionally, leveraging AI to enhance in-store

experiences can bridge the gap between digital and physical interactions.

IV. Conclusions

This study highlights the distinct consumer behaviors exhibited in physical versus online pharmacies, revealing critical insights into the evolving landscape of pharmaceutical care. The findings indicate that online pharmacy users are more likely to make impulsive purchasing decisions driven by promotional offers, spending an average of only 50 seconds on websites. In contrast, consumers in physical pharmacies engage in more deliberate decision-making processes, heavily influenced by personal interactions with pharmacists.

The theoretical implications of these findings suggest that consumer behavior in the pharmaceutical sector is significantly shaped by the environment in which products are purchased. The integration of artificial intelligence (AI) in online pharmacies enhances operational efficiencies and personalization, yet it raises concerns regarding the loss of human interaction and emotional intelligence that are crucial for building trust. This underscores the need for further research into the balance between technology and personal care in e-health environments.

From a practical standpoint, pharmacies must adapt to these evolving consumer preferences by adopting hybrid models that leverage the strengths of both physical and online settings. This includes enhancing the online shopping experience through personalized AI-driven recommendations while maintaining robust patient-pharmacist interactions in physical locations. Additionally, implementing telepharmacy services can bridge the gap, facilitating access to pharmacist consultations without sacrificing personal connection.

Ultimately, the study emphasizes the necessity for pharmacies to prioritize the human elements of care that foster trust and loyalty among patients, particularly as the industry increasingly incorporates digital solutions. By doing so, pharmacies can not only improve patient satisfaction and adherence but also ensure a competitive advantage in a rapidly changing healthcare landscape. These insights are vital for pharmacy practitioners, healthcare policymakers, and researchers aiming to navigate the complexities of consumer behavior in the digital age.

V. References:

[1.] A. Bagali, "E-pharmacies consumer behavior, in the digital era to target new-age customers, which is transforming the retail pharmacy business model," International Journal of Pharmaceutical Sciences and Research, vol. 12, no. 6, pp. 2950-2957, 2021.

[2.] Deloitte, "2021 Global health care outlook," 2021. [Online]. Available: https://www2.deloitte.com/us/en/insights/industry/health-care/global-health-care-outlook.html (https://www2.deloitte.com/us/en/insights/industry/health-care/global-health-care-outlook.html). [Accessed: Feb 27, 2025].

[3.] N. Dimova, "Influence of digitalisation on consumer behaviour in retail," Journal of Retailing and Consumer Services, vol. 58, p. 102302, 2021. doi:10.1016/j.jretconser.2020.102302.

[4.] S. Heller, H. Cohen, and L. Shapiro, "Patient behavior in pharmacy settings: A study of consumer preferences," Journal of Pharmaceutical Health Services Research, vol. 11, no. 3, pp. 245-250, 2020.

[5.] J. Huh, H. Kim, and J. Lee, "The impact of pharmacist recommendations on medication adherence: A systematic review," International Journal of Clinical Pharmacy, vol. 43, no. 2, pp. 352-360, 2021.

[6.] O. Khan, "The future of pharmacy: How AI is revolutionizing the industry," Pharmacy Today, vol. 27, no. 2, pp. 45-50, 2021.

[7.] Market Analysis Phoenix Pharma Bulgaria, 2024.

[8.] T. Miller and S. Davis, "The shift to online pharmacies: Consumer trends and insights," Journal of Health Economics, vol. 45, pp. 200-215, 2021.

[9.] R. Patel, A. Kumar, and T. Wong, "The influence of digital health technologies on consumer behavior in the pharmaceutical sector," Journal of Digital Health, vol. 5, no. 1, pp. 15-28, 2023. doi:10.1177/20552076221145678.

[10.] M. A. Raza, "Artificial intelligence (AI) in pharmacy: An overview of innovations," Journal of Pharmacy Technology, vol. 37, no. 4, pp. 162-168, 2021.

[11.] J. Smith and L. Jones, "The value of face-to-face pharmacy consultations," Pharmacy Practice, vol. 17, no. 4, pp. 123-128, 2019.

[12.] Statista, "Pharmacies - Bulgaria," 2023. [Online]. Available: https://www.statista.com/outlook/hmo/pharmacies/bulgaria (https://www.statista.com/outlook/hmo/pharmacies/bulgaria). [Accessed: Feb 27, 2025].

[13.] T. Kuo, "Consumer trust in online pharmacies: The role of artificial intelligence," Journal of Medical Internet Research, vol. 24, no. 1, e12345, 2022. doi:10.2196/12345.

[14.] M. Johnson and R. Taylor, "The impact of e-pharmacy on medication adherence: A review of the literature," International Journal of Pharmacy Practice, vol. 30, no. 6, pp. 850-856, 2022. doi:10.1111/ijpp.12999.

[15.] L. Thompson and J. Reid, "Understanding online shopping behavior: The role of time spent on site," Journal of Marketing Research, vol. 59, no. 3, pp. 345-358, 2022. doi:10.1177/00222437221034567.

[16.] V. Kumar and R. Reinartz, Creating Enduring Customer Value, Harvard Business Review Press, 2016.

[17.] A. Fischer, D. R. de Boer, and H. J. H. van der Meulen, "Leveraging AI in Health Care: A Review of AI Technologies for Pharmacy Practice," American Journal of Health-System Pharmacy, vol. 77, no. 14, pp. 1033-1041, 2020.

[18.] E. T. D. B. Costa, P. A. A. de Oliveira, and M. A. M. de Lima, "Consumer behavior in e-pharmacy: A systematic review," Journal of Retailing and Consumer Services,vol. 57, p. 102198, 2020. doi:10.1016/j.jretconser.2020.102198.

[19.] R. N. M. Alshahrani, M. T. S. Alkhathlan, and A. A. Alharbi, "Understanding consumer behaviors towards online pharmacies: A study in Saudi Arabia," Journal of Pharmaceutical Health Services Research, vol. 12, no. 2, pp. 163-171, 2021. doi:10.1111/jphs.12418.

[20.] J. A. Z. M. Alharthi, "The impact of COVID-19 on consumer behavior in the online pharmacy market," International Journal of Health Planning and Management, vol. 36, no. 3, pp. 785-797, 2021. doi:10.1002/hpm.3070.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 221-224

Comparative Analysis of Heuristic Algorithms for Optimizing the Distribution of Medical Equipment in a Crisis

Iryna Kyrychenko
Department of Software Engineering
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
iryna.kyrychenko@nure.ua

Artem Oliinyk
Department of Software Engineering
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
artem.oliinyk@nure.ua

Kirill Smelyakov
Department of Software Engineering
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
kyrylo.smelyakov@nure.ua

Loreta Savulioniene
Faculty of Electronics and Informatics
Vilniaus Kolegija
Vilnius, Lithuania
l.savulioniene@viko.lt

Paulius Sakalys
Faculty of Electronics and Informatics
Vilniaus Kolegija
Vilnius, Lithuania
p.sakalys@eif.viko.lt

***Abstract*— The article presents a comparative analysis of the effectiveness of several heuristic algorithms used to optimize the distribution of medical equipment in a crisis. The key approaches, including the genetic algorithm (GA), the particle swarm optimization algorithm (PSO), and the ant colony optimization algorithm (ACO), are considered, and the performance and accuracy of the problem are investigated. Based on the experiments, the advantages and limitations of each method are determined, and practical recommendations are formulated for choosing the appropriate algorithm, considering the scale of the problem and limited resources. The study's results improve the reliability and efficiency of decision-making in healthcare systems during emergencies.**

Keywords*— Crisis conditions, heuristic algorithms, medical equipment, performance assessment.

I. Introduction

Healthcare systems, especially in times of crisis (e.g., epidemics or natural disasters), are under significant strain, leading to acute shortages of medical resources and equipment. During such periods, it is crucial to ensure the prompt and efficient distribution of limited ventilators, diagnostic systems, and other devices, as patient survival rates and the overall functioning of hospitals depend on them. Studies have shown that optimizing the allocation of medical resources during crises is a key factor in reducing mortality and improving treatment efficiency [1]. Planning and coordinating the supply of such equipment has many limitations: heterogeneity of needs in different regions, different technical conditions, storage reserves, and the risk of a sharp increase in demand due to emergencies.

Classical optimization methods, such as linear programming or deterministic algorithms, can only guarantee the search for a precisely optimal solution when the problem is relatively small and the conditions are stable. In crises, where demand parameters change simultaneously, technical failures occur, and forecasts of the number of patients are uncertain, adaptive solutions are needed that can quickly adjust to new circumstances. That is why heuristic algorithms are becoming increasingly popular: they do not guarantee optimality but can find high-quality solutions quickly and easily change the search trajectory in an unstable environment [2, 3]. In particular, GA and PSO are widely used in large-scale resource allocation problems [4, 5], and the ACO sometimes effectively solves combinatorial variants of logistics problems.

This article aims to conduct a comparative analysis of GA, PSO, and ACO in optimizing the distribution of medical equipment for 50 hospitals in five different regions against the background of sharply changing conditions. The study used a synthetic dataset that simulates massive patient flows, various levels of criticality of their conditions, unplanned equipment

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8612
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

failures and sudden increases in demand. The analysis was performed in terms of speed, accuracy, stability of solutions, and the ability of algorithms to adapt to crisis events.

II. Materials and Methods

The study considered three heuristics. The first is the GA, which is based on natural selection simulation. It works with a population of possible solutions that are gradually improved using crossover and mutation operators. The study used Python and the DEAP library, a powerful tool for evolutionary algorithms, to implement GA. This library allows you to model a population of possible solutions and apply crossover, mutation, and selection operators, which are essential for achieving high-quality solutions under complex constraints [6]. The main stages of using the GA in this study include:

- Encoding solutions: Each potential resource allocation is represented as a vector of chromosomes:
$$x = (x_{11}, x_{12}, \dots, x_{NM}); \quad (1)$$
- Crossover: Combining solutions from the "parent" chromosomes to create new options for resource allocation. For example, homogeneous recombination is used.
- Mutation: Random changes in the distribution of equipment x_{ij} within acceptable limits to avoid local extremes.
- Selection: Tournament selection or roulette strategies are used to determine which solutions are passed on to the next generation.

The second technique is the PSO [7]. The main idea of this approach is that each potential solution (particle) moves in the space of possible solutions and adjusts its trajectory based on its own best experience and the collective experience of the entire swarm. This allows the algorithm to quickly adapt to environmental changes and find practical solutions even under challenging constraints. Within PSO, each particle represents a possible option for resource allocation, and the following formula determines its movement:

$$v_{k+1} = w \cdot v_k + c_1 r_1 (p_{\text{best}} - x_k) + c_2 r_2 (g_{\text{best}} - x_k) \quad (2)$$

where w — is the inertia coefficient, which affects the speed of solution update; c_1, c_2 — learning rates, which determine how much a share is guided by its best practices (p_{best}) and the best solution found in the entire swarm (g_{best}), r_1, r_2 — random values that add a stochastic element to the search.

The main advantage of PSO is the ability to efficiently handle large-scale optimization problems while quickly finding solutions to variable conditions, such as fluctuations in demand or resource constraints [8]. Due to this, PSO is widely used in complex distribution systems, allowing for dynamic adaptation of medical resource management even in crises. The Python programming language and the PySwarms library [9] were used to implement PSO, simplifying the management of swarm parameters.

The third approach is the ACO. Its basic idea is that "ants" consistently build equipment distribution by adding types of resources according to a certain probability function that depends on "pheromone traces". These traces accumulate faster on more successful routes (combinations) and then evaporate, leaving the heuristic search for better states in focus. The ACO was implemented in a custom Python script using a matrix representation of the relationships between states and a mechanism for updating pheromones after each iteration [10]. This approach is often practical in complex discrete problems, but its performance for continuous distributions can also be satisfactory, depending on the parameters.

To verify the methods, we needed data that reflected the dynamics of equipment utilization in many hospitals, including sudden failures and fluctuations in demand. Obtaining such a sample from a real healthcare system proved problematic due to ethical and confidentiality restrictions, so synthetically generated scenarios were used.

First of all, 50 hospitals were modelled, evenly divided into five regions (10 per region), where each had its initial stock of four types of equipment: ventilators (5-20 units), Magnetic resonance imaging (MRI) (1-3), ultrasound systems (3-10), and X-ray machines (2-6). This difference reflected the different specialization and capacity of the hospitals. Next, a stream of 10,000 patients was generated, arriving randomly during a 30-day period. Their distribution in time was close to Poisson, and the characteristics included the type of equipment needed, the region of origin, and the level of criticality (from 1 to 5).

Two stages of the crisis were provided for modelling emergency circumstances. Between the tenth and fifteenth days, the demand for lung ventilators increased by 50%: this simulated an exacerbation of the epidemiological situation when the number of patients with severe respiratory pathology increased significantly. Later, on the twentieth to twenty-first day, about 10% of the available MRI machines in some hospitals randomly broke down, reducing diagnostic capacity. All changes were recorded in additional scripts as "events" that appear during the simulation and change the availability of the resource. Using the NumPy and Pandas libraries, the final data stored information about each hospital, all patients, and changes in equipment status for 30 days.

III. Results and Discussion

To ensure correctness, we defined a universal fitness function consisting of an essential target (3) and additional penalties for non-compliance with the constraints (4, 5) [11].

$$Z = \max_{x_{ij}} \sum_{i=1}^{N} \sum_{j=1}^{M} \omega_{ij} x_{ij}, \quad (3)$$

where x_{ij} — is the amount of equipment of type i assigned

to hospital j; ω_{ij} — a weighting factor that considers the priority; N, M — number of equipment types and hospitals, respectively.

Several important limitations were taken into account. First, resource constraints that ensure that the total amount of equipment allocated to all hospitals does not exceed the available stock:

$$\sum_{j=1}^{M} x_{ij} \leq R_i \quad \forall i = 1, \dots, N \tag{4}$$

Secondly, the minimum needs of hospitals, which stipulate that each hospital should receive at least the amount of equipment it needs:

$$\sum_{i=1}^{N} x_{ij} \geq D_j \quad \forall j = 1, \dots, M \tag{5}$$

All of the above parameters (cost coefficients, procedure time, patient criticality) were used for all algorithms.

The calculations were performed in Python 3.9 using the DEAP (for GA), PySwarms (for PSO), and our code (for ACO) libraries. As part of the main experiment, each algorithm was executed for 200 search iterations, with all methods starting from different initial solutions five times to account for the random component. At the end of each run, the minimum and average Z values, standard deviation (SD), and time taken were recorded.

Based on the results of five repeated runs of each algorithm, the average values of the metrics were obtained. Table 1 compares the best and average values of the objective function Z, SD, and solution time. Each algorithm allocated the available equipment to minimize the logistics and penalty costs.

TABLE 1 COMPARATIVE RESULTS OF HEURISTIC ALGORITHMS

Algorithm	Performance Metrics			
	Best Z	***Average Z***	***SD (Z)***	***Average time, s***
GA	4820	4915	48,2	15,7
PSO	4765	4790	20,1	12,3
ACO	4880	4930	55,5	16,4

These results show that PSO, on average, finds the solution closest to the minimum value of Z and takes slightly less time. This indicates its high performance and ability to adapt well to dynamic scenarios. Although GA is inferior to PSO regarding the best achieved Z, the difference is insignificant. The GA also shows relatively stable solutions but sometimes requires more iterations to achieve better results. The ACO in the considered environment showed a slightly larger spread (SD 55.5), which may indicate more frequent "stuckness" in local minima, especially regarding the continuous nature of the distribution of quantitative resources, rather than a purely combinatorial routing problem.

A line graph is shown in Fig. 1 to compare how the value of Z changes during each of the five runs.

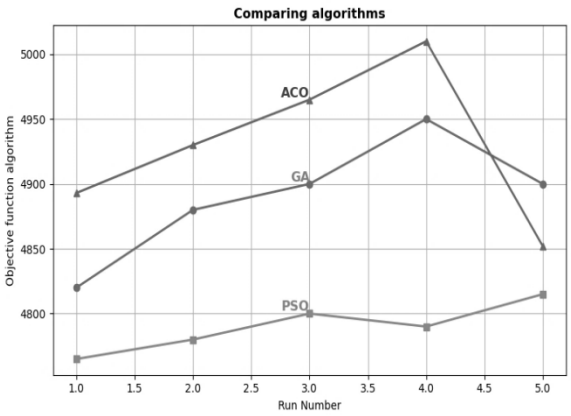


Fig. 1. Comparing algorithms.

It can be seen that PSO generally produces lower values of Z compared to GA and ACO, and the scatter of the ACO results confirms its greater sensitivity to variations in the initial decisions.

To test how quickly the algorithms adapt to changes, we monitored them during sudden changes in equipment availability. It turned out that PSO, after about 20 additional iterations after the "failures" and a doubling of the demand for ventilators, again found solutions very close to the minimum Z. GA reacted a little slower: compensating for the system failures took 30-35 iterations. The ACO turned out to be even more inert: its period of "re-adaptation" reached almost 50 iterations, but it also came to an acceptable level.

The overall result of the comparative analysis confirms that neither GA, PSO, nor ACO provide a universally best solution for all scenarios. The choice of algorithm often depends on how quickly the answer is needed and how critical the exact minimization is. If the goal is emergency resource management and flexible decision restructuring, then PSO seems more attractive, especially at the initial stage of the crisis. If it is possible to increase the number of iterations, GA can match PSO in terms of results. At the same time, ACOs can be used at stages where it is crucial to optimize the supply order or where there is a complex combination of discrete choices.

IV. CONCLUSIONS

The article compares three heuristic algorithms (GA, PSO, and ACO) in the example of medical equipment distribution in a dynamic crisis. The proposed synthetic dataset (50 hospitals with uneven initial stock, 10 thousand patients with different levels of criticality, and two waves of crisis events) allows us to check how the algorithms cope with the growing demand for ventilators and the failure of a part of the MRI. The results show that PSO

reaches an acceptable distribution level the fastest, GA provides a similar level of accuracy but is slower to respond to sudden changes, and ACO periodically gets stuck on local minimal solutions. At the same time, each approach has advantages: GA explores the solution space powerfully, PSO can adapt to changing conditions quickly, and ACO is sometimes more effective for combinatorial constraints.

In addition to traditional optimization methods, recent studies show that a promising area of research is the development of hybrid methods, when PSO performs the initial approximation, and the refinement is performed by a GA and data indexing in large systems [12, 13]. It is also advisable to introduce mechanisms for dynamically adjusting parameters (population size, inertia coefficients, pheromone intensity) depending on the system's current state. Actual practice shows that crises can develop rapidly, requiring constant updating of resource allocation plans and flexible strategies for their implementation [14-16]. Using heuristic algorithms in such conditions allows for more efficient control of equipment and timely response to critical situations.

REFERENCES

[1] F. Parker, H. Sawczuk, F. Ganjkhanloo, F. Ahmadi, and K. Ghobadi, “Optimal Resource and Demand Redistribution for Healthcare Systems Under Stress from COVID-19,” arXiv:2011.03528 [cs, math], Nov. 2020, Available: https://arxiv.org/abs/2011.03528

[2] S. E. Griffis, J. E. Bell та D. J. Closs, “Metaheuristics in Logistics and Supply Chain Management”, Journal of Business Logistics, vol. 33, no. 2, pp. 90–106, Jun. 2012, doi: https://doi.org/10.1111/j.0000-0000.2012.01042.x.

[3] A. Lameesa, M. Hoque, M. SB Alam, S. F. Ahmed, and A. H. Gandomi, “Role of metaheuristic algorithms in healthcare: A comprehensive investigation across clinical diagnosis, medical imaging, operations management, and public health”, Journal of Computational Design and Engineering, vol. 11, no. 3, pp. 223–247, Jun. 2024, doi: https://doi.org/10.1093/jcde/qwae046.

[4] S. M. Almufti, A. Yahya Zebari, and H. Khalid Omer, “A comparative study of particle swarm optimization and genetic algorithm,” Journal of Advanced Computer Science & Technology, vol. 8, no. 2, p. 40, Oct. 2019, doi: https://doi.org/10.14419/jacst.v8i2.29401.

[5] Y. -J. Gong et al., "An Efficient Resource Allocation Scheme Using Particle Swarm Optimization," in IEEE Transactions on Evolutionary Computation, vol. 16, no. 6, pp. 801-816, Dec. 2012, doi: 10.1109/TEVC.2012.2185052.

[6] J. Kim and S. Yoo, “Software review: DEAP (Distributed Evolutionary Algorithm in Python) library,” Genetic Programming and Evolvable Machines, vol. 20, no. 1, pp. 139–142, Nov. 2018, doi: https://doi.org/10.1007/s10710-018-9341-4.

[7] W. F. Abd-El-Wahed, A. A. Mousa, and M. A. El-Shorbagy, “Integrating particle swarm optimization with genetic algorithms for solving nonlinear optimization problems,” Journal of Computational and Applied Mathematics, vol. 235, no. 5, pp. 1446–1453, Jan. 2011, doi: https://doi.org/10.1016/j.cam.2010.08.030.

[8] Z. Ghaffari, M. M. Nasiri, A. Bozorgi-Amiri, and A. Rahbari, “Emergency supply chain scheduling problem with multiple resources in disaster relief operations,” Transportmetrica A: Transport Science, vol. 16, no. 3, pp. 930–956, Jan. 2020, doi: https://doi.org/10.1080/23249935.2020.1720858.

[9] L. James V. Miranda, “PySwarms: a research toolkit for Particle Swarm Optimization in Python,” The Journal of Open Source Software, vol. 3, no. 21, p. 433, Jan. 2018, doi: https://doi.org/10.21105/joss.00433.

[10] M. Dorigo, V. Maniezzo and A. Colorni, "Ant system: optimization by a colony of cooperating agents," in IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics), vol. 26, no. 1, pp. 29-41, Feb. 1996, doi: 10.1109/3477.484436.

[11] R. Farmani and J. A. Wright, "Self-adaptive fitness formulation for constrained optimization," in IEEE Transactions on Evolutionary Computation, vol. 7, no. 5, pp. 445-455, Oct. 2003, doi: 10.1109/TEVC.2003.817236.

[12] I. Kyrychenko, G. Tereshchenko, K. Smelyakov, “Optimized Indexing Method in a Hybrid Image Storage Model for Efficient Storage and Access in Big Data Environments,” 2022 IEEE 16th International Conference on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering (TCSET), pp. 1–4, Oct. 2024, doi: https://doi.org/10.1109/tcset64720.2024.10755763.

[13] A. F. Ali and M. A. Tawhid, “A hybrid particle swarm optimization and genetic algorithm with population partitioning for large scale optimization problems”, Ain Shams Engineering Journal, vol. 8, no. 2, pp. 191–206, Jun. 2017, doi: https://doi.org/10.1016/j.asej.2016.07.008

[14] A. B. Eisman, B. Kim, R. G. Salloum, C. J. Shuman, and R. E. Glasgow, “Advancing rapid adaptation for urgent public health crises: Using implementation science to facilitate effective and efficient responses,” vol. 10, Aug. 2022, doi: https://doi.org/10.3389/fpubh.2022.959567.

[15] K. Smelyakov, D. Tovchyrechko, I. Ruban, A. Chupryna and O. Ponomarenko, "Local Feature Detectors Performance Analysis on Digital Image," 2019 IEEE International Scientific-Practical Conference Problems of Infocommunications, Science and Technology (PIC S&T), 2019, pp. 644-648, doi: 10.1109/PICST47496.2019.9061331.

[16] J. Braithwaite, E. Hollnagel, and G. S. Hunte, “Methods and Solutions,” in Resilient Health Care, 1th ed. London: CRC Press, 2016, ch.9, pp.186-236.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 225-230

Application of Digital Telecommunication Environment to Solve Legal Issues

Oleg Latyshev
Vasil Levski National Military University
International Mariinskaya Academy
Veliko Tarnovo, Bulgaria
papa888@list.ru

Nikolay Todorov Dolchinkov
Vasil Levski National Military University, Veliko Tarnovo, Bulgaria
Veliko Tarnovo, Bulgaria
n_dolchinkov@abv.bg

***Abstract* — At the given stage of development of mankind, the algorithm for acquisition and termination of the constitutional-legal status of an individual in different countries of the world is in a stage of active development in the digital telecommunications environment. This is facilitated by the relatively rapid changes that regularly occur in the internal legislation of different countries, the differences between them, and sometimes the contradictions in the regulatory acts in different countries. In some cases, this leads to the fact that at a certain point the algorithm for acquisition and termination of the constitutional-legal status of an individual in the digital telecommunications environment is already beginning to acquire the quality of stability, but new changes in the legislation again encourage us to start bringing different legal norms into line with each other, which is a complex process. Therefore, the guarantor of the balance of stability in the field of establishing the algorithm for acquiring and terminating the constitutional-legal status of an individual in the digital telecommunications environment may be precisely the idea of the authors of modern legislative initiatives about when it is most reasonable to stop the constant changes in numerous legislative acts so that their end user can still apply them in practice. Otherwise, the domestic legislative system may irretrievably lose authority among the vast majority of citizens of the respective country, and the number of appeals to domestic and foreign courts to resolve numerous controversial issues will constantly increase more and more. As a result, the level of legal nihilism, which the relevant state bodies are rightly trying to fight at the moment, will also increase much faster than such problems will be solved. Moreover, the number of illegal actions will also increase not only in the virtual environment, but also in real life, as the rule for algorithmizing the actions performed by citizens of the respective country will come into force, both in the virtual environment and simultaneously in real space, which is a very complex process.**

***Keywords*— authorities, constitutional and legal status, digital telecommunications, domestic legislation.**

I. INTRODUCTION

The relevance of the topic stems from the current social situation in many countries of the world, from all continents, where the digital transformation of the constitutional and legal status of an individual and its documentary support is taking place at a fairly high pace. But the pace of change in the regulatory framework and social networks is different in different countries, and there are no uniform criteria by which a global assessment of the situation can be made. The current realities of social development concern, among other things, the issues of deactivation of Instagram and Facebook, in which millions of citizens of the Russian Federation, Turkey, Syria, Ukraine and other countries, as well as legal entities registered in the relevant countries, opened their accounts and used them for several years. From this moment on, every citizen of the relevant countries or organizations will have to make cardinal decisions on how to replenish the lost results of their many years of work in these networks. In addition, it is necessary to understand what other network tools can be used instead of Instagram and Facebook to solve commercial, scientific, educational problems, as well as for the activities of public organizations. In many countries, this has been solved by using local social media channels, but this is typical of large countries, China, the USA, Russia, and others.

II. MATERIALS AND METHODS

Works and scientific articles of authors from all continents were used, using the specific solutions to the problem in different countries around the world. However, due to the differences in the countries, both in geographical location and in economic development and social status of citizens, the most general results were taken, and to reflect the specifics of each individual country, a more in-depth and detailed study is necessary. The knowledge of members of the Mariinsky Academy from more than 100 countries around the world was used.

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8614
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

The methods used in the study can be reduced to analysis of scientific literature, synthesis, comparison, juxtaposition, generalization, bibliographic method.

III. RESULTS AND DISCUSSION

In the foreseeable future, this property may extend to the entire space of the digital telecommunications environment and be realized in it in the form of communication, implying the functioning of this environment as a social system that can acquire a global character. In principle, the property of autopoiesis is realized both in the form of life and in the form of consciousness, inherent in this case to proactive and responsible users of this branched digital telecommunications environment [1], [2].

In this case, law becomes to some extent an "external environment" in relation to the digital telecommunications environment, which the digital environment as a self-organizing system gradually begins to ignore. The regulation of this problem on a global scale is still in the realm of wishes, but the time will not be far off when people will feel the need for such regulation. This happens precisely because the digital telecommunications environment forms its own regulatory rules, which are largely determined by the original mechanisms of this self-reproducing system and are uniform for all users. The issue of realizing the constitutional and legal status of the individual in the digital telecommunications environment acquires a fundamentally new significance due to the special influence of the properties of information multiplication, the reliability of the information presented and its use. It should be noted that it seems impossible to stop the process of information multiplication in the digital telecommunications environment and its regulation, otherwise the destruction of this information system itself will occur. The influence of the principle of network neutrality, actively postulated within the digital telecommunications environment, is also undeniable, which implies that any information, regardless of its legal value, is considered equally important. This is becoming increasingly difficult to achieve, and after the leak of information about censorship by large social networks, the importance of this process is once again emphasized. One cannot fail to mention the significant influence of the technological characteristics of the digital telecommunications environment, in particular the so-called "digital trace" left in it by each user. But this also has a positive effect, because in this way the malicious actions of different people from different regions of the world who have an unregulated impact on social networks are revealed. For the virtual space, the technological characteristics of the digital telecommunications environment represent natural conditions, due to which they lead to the formulation of the question of the implementation of natural human rights in the digital environment. At the same time, lawyers from all countries of the world are faced with the following dilemma: should the already formed regulatory norms within the framework of the digital telecommunications environment, which has the properties of an autopoietic system, be legalized? Under this condition, additional guarantees should be provided to all participants in the digital telecommunications environment without exception, otherwise the rules should be introduced in the traditional way, which can lead to a double risk. First, this is the risk of violating the digital telecommunications environment itself, and secondly, which is no less, if not more important, is the risk of an inevitable reduction in the authority of the law due to an attempt to violate intra-system rights. Let us assume that the fact of the existence of the digital telecommunications environment as a system built on a contractual basis has been taken into account, as a result of which domain names have been allocated and the corresponding connection to the Internet telecommunications network has been established [3].

In this case, at the same time, it is necessary to assume the existence of strong private law mechanisms within the digital telecommunications environment, the activities of which are aimed at regulating social processes. However, in the conditions of Russia and many foreign countries, it is precisely administrative and legal means that have a serious impact on the digital environment. In addition, one cannot lose sight of the dependence of subjects of natural law on the terms of user and similar agreements that are not, in essence, accession agreements, since they cannot be subject to any adjustment in accordance with the interests of any parties joining this agreement [4], [5].

In the course of this study, its goal was achieved: a study of the digital transformation of the constitutional and legal status of an individual took place.

In the course of this study, its goal was achieved: a study of the digital transformation of the constitutional and legal status of the individual in different countries was conducted, and an analysis of the results in several countries was also made.

To achieve the above goal, the following tasks of the work were set and successfully solved:

1. The theoretical foundations of the constitutional and legal status of the individual in the digital telecommunications environment were examined [6].

2. Based on the results obtained, the most acceptable doctrinal and legislative approaches to determining the constitutional and legal status of the individual in the digital telecommunications environment were determined.

3. The trends in the formation of a conceptual and categorical apparatus in ensuring the constitutional and legal status of the individual in the digital telecommunications environment were studied.

4. The key elements of the constitutional and legal status of the individual in the digital telecommunications environment in several characteristic countries were examined. The exact need for digital transformation of the

constitutional and legal status of the individual has been determined and a model has been developed that can serve to continue the research on a larger scale [7], [8].

5. The legitimate interests and legal risks of the individual in the digital telecommunications environment have been examined, and the obligations and responsibilities of the individual in the digital telecommunications environment have been determined.

The dynamics of the constitutional and legal status of the individual in the digital telecommunications environment have been studied.

6. The conditions, methods and consequences of the acquisition and termination of the constitutional and legal status of an individual in the digital telecommunications environment have been determined. The factors, forms and criteria for transforming the constitutional and legal status of an individual in the digital telecommunications environment have been determined, and in a subsequent study the scope of the countries considered may be expanded [6], [9], [10].

7. The constitutional and legal status of a natural person in law enforcement practice has been specified on the basis of the current regulatory documents in the relevant countries.

The object of the work was the digital transformation of the constitutional and legal status of a natural person. In turn, the subject of the work was directly defined as the study of the digital transformation of the constitutional and legal status of a natural person.

Legitimate interests in the digital telecommunications environment have been the subject of prolonged and intensive discussions for a considerable period of time. Therefore, there are still no unambiguous answers to this issue under consideration, because it has been relatively recent and there is not enough legal practice. This discussion directly affects numerous interests of the authors of modern legislative initiatives from various political parties and unions, law enforcement agencies, and at the same time, physical and legal users of the digital telecommunications environment [11], [12].

There is an abundance of extremely diverse opinions of scientists from different countries about what timely and most acceptable expression legitimate interests in the digital telecommunications environment should acquire. Here the differences are quite significant, because the economic development of the respective country, its geographical location, the political system in the country, its involvement in international alliances and the education of the users have an impact. In the process of multilateral self-realization of the individual in the digital telecommunications environment, there are also certain legal risks arising from the uncertainty and insufficient stability of the conceptual apparatus in this area. It is necessary to remember that over time the number of such legal risks will increase continuously if the legitimate interests of users of the digital telecommunications environment do not become the subject of careful attention by the authors of modern legislative initiatives in the respective country [12], [13]. The obligations of every citizen of the Russian Federation, for example, are a consequence of the rights that he or she possesses. Or the presence of a right in one subject of law turns into the presence of an obligation in another citizen of the Russian Federation. In any case, the relationship between the rights and obligations of each Russian Federation remains quite close. The situation is different in Turkey, for example, where many social networks are significantly limited and there are even restrictive measures on their use. In China, they use their own social networks, and it is very difficult for a foreign citizen to use classic social networks such as Facebook, Instagram, and others. Just as without executors of obligations, holders of any rights cannot arise, so without holders of these rights, executors of obligations directly or indirectly arising from this circle of rights cannot arise. At the same time, it should be noted that for the most part, the rights and obligations of citizens of most countries of the world are in a state of relatively clear correlation. Therefore, failure to fulfill direct obligations by any citizen can lead to the fact that the rights of any citizen of the Russian Federation, Turkey, China, India, and others cannot be realized in a timely manner and in full. In addition, it is necessary to remember that in an era when the digital telecommunications environment begins to prevail over what is happening in the real world, the legal foundations of the real world must be refracted in a special way in relation to users of virtual space. Currently, in the digital telecommunications environment, the algorithm for acquiring and terminating the constitutional and legal status of an individual is in a stage of active formation. This is facilitated by the relatively rapid changes that regularly occur in domestic legislation, but still tailored to the specifics of the particular country [12], [14], [15].

In some cases, this leads to the fact that at a certain point the algorithm for acquiring and terminating the constitutional-legal status of an individual in the digital telecommunications environment is already beginning to acquire the quality of stability, but new changes in legislation once again encourage us to begin to bring various legal norms into line with each other. Therefore, a guarantor of the balance of stability in the field of establishing the algorithm for acquiring and terminating the constitutional-legal status of an individual in the digital telecommunications environment may be precisely the idea of the authors of modern legislative initiatives about when it is most reasonable to stop the constant changes in numerous legislative acts so that their end user can still apply them in practice. This is a very complex problem to solve in view of the fact that there is still not enough legal practice in the field of the digital telecommunications environment in different countries of our planet.

Otherwise, the domestic legislative system may irretrievably lose authority among the vast majority of citizens of the respective country, and the number of appeals to local and foreign courts to resolve numerous controversial issues will constantly increase more and more. As a result, the level of legal nihilism, which state authorities are currently quite rightly trying to combat, will also increase much faster than such issues will be resolved. In addition, the number of illegal actions will increase not only in the virtual environment, but also in real life, since the rule of algorithmizing of actions performed by citizens of the respective countries will come into force, both in the virtual environment and simultaneously in real space. This process is also very complicated in terms of which legislation should be used, because these processes are international and very often the servers are located in third countries, and sometimes in several countries at once [12], [16].

The factors that in one way or another contribute to the transformation of the constitutional and legal status of the individual in the digital telecommunications environment are quite multifaceted and widespread. The leading one is the current state of the domestic legislative system of the relevant country, which is not always able to take into account all the forms and criteria of the processes of such transformation, generally accepted in everyday practice, to an equally high degree. The insufficient readiness of the legal instrument to take for granted the realities that are already quite firmly established in broad everyday practice, unfortunately, does not allow modern domestic and international legislation in this area to develop properly. As a result, reality in its unformed relations in a number of cases significantly outstrips the existing Russian, Turkish, Chinese, European or other legislation, which will still need a lot of time and other resources for the timely implementation of significant and multilateral transformations. It seems of fundamental importance to specify the constitutional and legal status of the individual in law enforcement practice and for these formulations to acquire international status, in order to unify the current legislation. As a result of considering the problem posed in this study, it seems appropriate to assume that specifying the constitutional and legal status of the individual in modern law enforcement practice can play a decisive role in the fate of the further formation of relations between subjects who increasingly exercise their rights and obligations in the digital telecommunications environment. With each passing day, it seems more and more certain that the insufficiently clear expression or even the complete lack of specification of the constitutional and legal status of the individual in law enforcement practice will not become a reason for users of the digital telecommunications environment to refuse to use new information and communication technologies to solve their everyday problems [4], [7], [17].

In practice, in many countries around the world, it is recognized that, even in the case of a complete lack of legal certainty within the digital telecommunications environment, many of its users will be more inclined to be content with accepting agreements for the use of a particular information system “as is”, at their own risk, rather than replacing it with more legislatively supported tools that do not have a similar degree of organizational and technological perfection. It is a very common practice for users of digital information to agree to the terms of use, even without familiarizing themselves with these terms. Therefore, the authors of modern legislative initiatives should not aimlessly expect that users of the digital telecommunications environment will stop performing any actions that interest them in it before they have acquired the appropriate level of their consolidation in specific legislative acts. Very often, users agree to terms that they have not even read and do not know the legal consequences of their actions, as is noticeable with users from all over the world, who cannot be categorized by any criterion. The demand for quick execution of a specific order or task leads to neglect of basic legal norms and sometimes to thoughtless actions on the part of the user. In their effort to postulate the ideals of a legal society, the authors of modern legislative initiatives must prevent the emergence of any uncertainties in the digital telecommunications environment with its constant development. The rights and freedoms that can arise and be realized in the digital telecommunications environment still have a long way to go and the legal norms are still being built. The persistence of traditions for the implementation of rights and freedoms under modern domestic and international legislation significantly helps, but sometimes also hinders the successful implementation of the process of forming the digital telecommunications environment as a clearly expressed legal space of clearly law-abiding actions of all subjects participating in its development. The unambiguous assistance of the modern legal system for the formation of the legal space of the digital telecommunications environment is due to the fact that rights in the real and virtual worlds must have the property of continuity. At the same time, the obstacle from the modern legal system for the formation of the legal space of the digital telecommunications environment is mainly that not all rights and freedoms implemented in the real world sufficiently take into account the peculiarities of the virtual world and the relations of subjects in it. Legitimate interests in the digital telecommunications environment are the subject of a long and intensive discussion. There are an abundance of extremely diverse opinions of domestic and foreign scholars about what timely and most acceptable expression legitimate interests in the digital telecommunications environment should acquire. This process will require more time and effort from all parties to the process. In the process of self-realization of the individual in the digital telecommunications environment, there are also certain legal risks arising from the uncertainty and insufficient stability of the conceptual apparatus in this area [4], [12], [18], [19]. The main difficulty in this case is the relative

"youth" of the digital telecommunications environment as such and at the same time - the resulting unpreparedness of traditional jurisprudence for dialogue with new realities. At the same time, the formation of completely independent social foundations within the digital telecommunications environment is occurring at a fairly rapid pace, and the unwillingness or unpreparedness of the existing legal system for dialogue with these relations may prove detrimental to its own condition. As a result of the progressive improvement of the digital telecommunications environment and the formation of consumer habits among millions of its civically active and proactive users, this may lead to the latter's reluctance to support the existence of the traditional legal system operating in the respective country in one way or another.

IV. CONCLUSIONS

Based on the research conducted and summarizing the experience of colleagues from a number of countries from all continents, the following conclusions can be drawn:

1. Doctrinal approaches to determining the constitutional and legal status of an individual or legal entity in the digital telecommunications environment currently require significant legal improvement from the point of view of the existence of a modern subject of activity in the digital telecommunications environment. The state of legal uncertainty in which the digital telecommunications environment continues to function largely contributes to the affirmation of natural rights characteristic of this environment, in accordance with agreements that are not changed by any of the users joining them. To improve the legal situation, joint participation in the process of all interested parties from the entire planet is necessary.

2. The progressive development of the digital telecommunications environment throughout the world encourages a responsible approach to the issue of establishing legal certainty in this virtual space. Moreover, given that in the near future in many respects the digital telecommunications environment will be able to prevail over many forms of relations developing in the real world, this is even more necessary and efforts should be made to achieve it. In addition, it should be known that if the digital telecommunications environment is not placed in a timely manner within certain legal frameworks, over time it will independently begin to dictate its own conditions to the real world and will not obey legal norms set at a later stage.

3. The trends in the formation of the conceptual-categorical apparatus in ensuring the constitutional-legal status of an individual in the digital telecommunications environment are mainly that the rapid development of technologies significantly outstrips the capabilities of the traditionally existing legal system of the country and the world, which in every way demonstrates its complete unpreparedness to establish the most adequate legal regulation of the virtual world. For this, it is necessary to unite the efforts of lawyers from all over the world and to prepare a valid international legal framework in a timely manner.

4. It is in the digital telecommunications environment that an increasing number of forms of activity of legal entities are currently being carried out, which increasingly often remain unregulated by the modern legal system, which carries a risk of violating the subjective rights of Internet users without the possibility of using the state mechanism for their protection. In fact, in this case, it is necessary to maintain a balance between the personal interests of each citizen of the respective country and the direct interests of the rule of law in such a way that the implementation of the former does not violate the latter and vice versa. If a user of the digital telecommunications environment signs agreements on the rules for using a certain site on his own initiative, which are not within the legal framework, then in this case there is a risk of committing more and more illegal actions on his part. And, on the contrary, if a certain citizen has experienced for some reason a feeling of dissatisfaction as a result of his work on a certain site, has requested legal support from the state, it is still not known how he will receive it and in what volume. The mechanism of this support is not so well developed to satisfy all the claims of this user of the digital telecommunications environment, who is dissatisfied with any services.

The legal regulations of the users of the digital information system and the system itself are still not sufficiently regulated, and this study can help the relevant specialists to chart the path for the development of legal regulation in the individual country and internationally. Each country has its own specifics, and when developing the rules, local specialists must adapt them to the specific conditions.

The authors of the study and members of the Mariinsky Academy express their readiness to provide additional information on the topic in order to achieve good legal regulation of these specific relations.

REFERENCES

[1] N. Luhmann, The Autopoiesis of social systems // Luhmann N. Essays on self-reference. New York: Columbia University Press, 1990.

[2] O. Latyshev, P. Latysheva, M. Luizetto, Digital transformation of the constitutional and legal status of an individuals Vitebsk, December 13, 2023: electronic scientific publication, pp. 15-18.

[3] S. Goranova, K. Anguelov, Critical review of bulgarian legislation related to circular economy, ETR, vol. 1, pp. 168–172, Jun. 2024, doi: 10.17770/etr2024vol1.7965.

[4] O. Latyshev.,P. Latysheva, S. Pavlovich, K. Tadic-Lesko, Doctrinal approaches to determining the constitutional and legal status of an individuals in the digital telecommunications environment, October 17-19, 2024.

[5] G. Dimcheva, I. Stoyanov, Modern perspectives in bulgarian engineering education through the prism of experts from the it sector (empirical study), ETR, vol. 2, pp. 345–351, Jun. 2024. doi: 10.17770/etr2024vol2.8082

[6] R. Dimov, Z. Savova, Antivirus performance evaluation against powershell obfuscated malware, ETR, vol. 4, pp. 71–78, Jun. 2024, doi: 10.17770/etr2024vol4.8201.

[7] O. Latyshev, P. Latysheva, M. Luizetto, Digital transformation of the constitutional and legal status of an individual in the sphere of education, June 30 - July 3, 2023, Nalchik pp. 54-59.

[8] R. Marinov, Contemporary challenges to the protection of the country's sovereignty, ETR, vol. 4, pp. 168–172, Jun. 2024. doi: 10.17770/etr2024vol4.8187.

[9] O. Latyshev, P. Latysheva, S. Pavlovich, Transformational processes in the field of jurisprudence in the context of the digital telecommunications environment, Volume 12. MPSU, 2024. 1740 p. pp. 1393-1397. doi: 10.51944/9785977010252. ISBN 978-5-9770-1025-2

[10] M. Musaev, A. Boboev, and E. Arziyev, Formalization of tasks to ensure the safety of emergency and explosive operations in the mining industry, ETR, vol. 1, pp. 257–260, Jun. 2024, doi: 10.17770/etr2024vol1.8007.

[11] S. Kodors, G. Kanepe, D. Zeps, I. Zarembo, and L. Litavniece, Rapid development of chatbot for tourism promotion in latgale, ETR, vol. 2, pp. 179–182, Jun. 2024, doi: 10.17770/etr2024vol2.8060.

[12] O. Latyshev, Sustainability of the economic and legal status of an agro-industrial enterprise in the context of digitalization, Priority areas of scientific and technological development of the agricultural sector of Russia, Ulan-Ude, February 6–10, 2023. – Ulan-Ude: 2023. – pp. 305–311. – EDN FQHQBN

[13] V. Vasilev, D. Stefanova, M. Icheva. Green human resource management as a component of sustainable organizational development in environmental and natural economics, ETR, vol. 1, pp. 402–407, Jun. 2024, doi: 10.17770/etr2024vol1.7966

[14] S. Madzharov, I. Ivanov, N. Yordanov, A Digitally Manipulated Gunshot Sound Identification. In Environment. Technologies. Resources. Proceedings of the International Scientific and Practical Conference, 2024, Vol. 3, pp. 170-174 , ISSN: 16915402 , doi: 10.17770/etr2024vol3.8150E.

[15] E. Cubars and L. Poiša, Analysis of Composite Biomass Fuels Properties, Environment. Technology. Resources. Rezekne, Jun 2019, Latvia. Proceedings of the 12 th International Scientific and Practical Conference, vol. 1, pp. 39–43, Jun. 2019, doi: 10.17770/etr2019vol1.4043

[16] N. Dolchinkov, Optimizing energy efficiency in the conditions of a global energy crisis, Optimizing Energy Efficiency During a Global Energy Crisis, 2023, pp. 1–9, ISBN13: 9798369304006 EISBN13: 9798369304013, doi: 10.4018/979-8-3693-0400-6

[17] T. Trifonov, I. Simeonov, N. Yordanov, Advanced signal processing methods for analysis of high dynamic range acoustic phenomena , Communication, Electromagnetics and Medical Application, 2018, October, pp. 52–56.

[18] M. Simeonov, M. Marinov, Determine the location of nodes in wireless sensor network by using genetic algorithm, Environment. Technology. Resources. Proceedings of the 15th International Scientific and Practical Conference June 27-28, 2024, Vol. 2, pp 247-252, doi.org/10.17770/etr2024vol2.8059

[19] N. T. Dolchinkov, B. E. Karaivanova-Dolchinkova, Impact of types of electromagnetic radiation on living nature, ETR, vol. 1, pp. 55–59, Jun. 2023, doi: 10.17770/etr2023vol1.7224

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 231-236

Detection and Mitigation of Malicious Activities Based on DNS Query Analysis

Georgi Markov
Department of Information Technologies
Nikola Vaptsarov Naval Academy
Varna, Bulgaria
g.markov@naval-acad.bg

Borislav Nikolov
Department of Information Technologies
Nikola Vaptsarov Naval Academy
Varna, Bulgaria
nikolov@naval-acad.bg

***Abstract*-With the increasing number of cyber threats and the growing complexity of attacks on network infrastructures, the need for effective methods to detect malicious activities has become critically important. One of the key attack vectors is the Domain Name System (DNS), which plays a fundamental role in internet communication. Although DNS is essential for every end user, it often remains unnoticed and unprotected, making it vulnerable to abuses such as DDoS attacks, attack surface reconnaissance, and data exfiltration. The aim of this study is to develop a method for automated analysis of DNS traffic to enable early detection of suspicious patterns and prevent potential attacks. To achieve this, open-source tools, publicly available databases, and log files from a real authoritative DNS server are utilized. The methodology includes analysing the frequency and type of DNS queries, as well as evaluating the IP addresses from which they originate. The results of the analysis demonstrate that automated processing of DNS logs allows for the identification of anomalous query patterns associated with malicious activities. Systematic monitoring of DNS traffic provides an opportunity for early threat detection and faster implementation of protective measures. The proposed approach enhances cybersecurity mechanisms by strengthening threat intelligence capabilities and automating the detection process. This underscores the significance of the research and the necessity of continuously improving protection methods in the dynamic landscape of cybersecurity.**

Keywords- DNS query, automation, logging, Python script, cybersecurity.

I. INTRODUCTION

The Domain Name System (DNS) is a fundamental component of modern computer networks, particularly in Internet-connected environments. It allows users to access network resources and services without the need to memorize numerical IP addresses, facilitating seamless interaction between clients and hosts. From the perspective of public institutions and commercial enterprises, DNS serves as a critical infrastructure element, providing accessibility and visibility for online services to end users.

DNS operates as a hierarchical and distributed naming system. Organizations that wish to establish a public domain must configure and maintain an authoritative DNS server, which is responsible for resolving Fully Qualified Domain Names (FQDNs) to corresponding IP addresses. To achieve this, authoritative DNS servers maintain a local database of resource records, including forward lookup zones and, in many cases, reverse lookup zones. Key resource records include A/AAAA (host addresses), PTR (reverse lookup), SOA (Start of Authority), DS (Delegation Signer), MX (Mail Exchanger), SRV (Service Locator), NS (Name Server), and TXT records, which provide various forms of metadata [1] – [4].

Despite its critical role, DNS is increasingly being exploited in cyber-attacks. Malicious actors frequently attempt to exfiltrate data by performing unauthorized DNS zone transfers or leveraging lesser-known DNS record types to obtain sensitive information. Attackers also take advantage of the fact that DNS traffic is often unrestricted by organizational firewalls, allowing it to serve as a covert channel for data exfiltration, botnet communication, and command-and-control (C2) operations [5] – [7]. Studies highlight that DNS tunnelling techniques have been widely adopted by cybercriminals to bypass traditional security measures, making DNS security an essential aspect of modern cybersecurity frameworks [8] – [12].

Given the increasing sophistication of DNS-based threats, there is a growing need for automated detection and mitigation mechanisms. Existing research explores various approaches for identifying suspicious DNS activities, such as anomaly detection methods based on statistical analysis, machine learning, and rule-based filtering systems [13] – [14]. However, many of these methods require significant computational resources or lack adaptability to evolving attack patterns.

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8582
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

The growing number of cyber threats leveraging DNS infrastructure underscores the necessity of real-time monitoring and automated threat mitigation solutions. This study aims to develop a practical, automated approach for analysing DNS query patterns to detect and mitigate malicious activities targeting authoritative DNS servers. Unlike conventional detection methods, which often rely on static signatures or reactive security measures, the proposed approach integrates real-time log analysis, rule-based filtering, and automated threat intelligence validation using public databases.

This paper contributes to the field by presenting an efficient, open-source-based solution for analysing DNS traffic, dynamically generating firewall rules, and preventing future cyber threats. Through periodic execution, the proposed system adapts to new attack vectors and reduces the risk of repeated exploits. The comparative analysis of literature sources further highlights the necessity of combining statistical, behavioural, and rule-based techniques for enhanced DNS security.

By addressing both theoretical and practical aspects of DNS security, this study provides a foundation for improving network resilience against cyber threats while ensuring minimal disruption to legitimate traffic.

II. MATERIALS AND METHODS

A. Defining the scope of DNS analysis

Before proceeding with the analysis of DNS queries, the scope of the analysis should be determined. Depending on the purpose of the authoritative DNS server, different types of queries can be observed, as well as different percentage ratios between them.

To determine the scope of our research, as well as to confirm the functionality of the developed approach for automating the analysis of DNS queries, we will use the Bulgarian Naval Academy's (NVNA) authoritative public DNS server.

The Bulgarian Naval Academy is a higher educational institution with a technical profile in the fields of military affairs, maritime sciences, and information technologies. The school is part of the Ministry of Defence of Bulgaria. Nevertheless, it provides education for many foreign students, mainly from Turkiye and Greece. The school maintains very good international contacts with educational institutions and business companies from other NATO and/or European Union member or partner countries.

Regarding its presence in the Internet space, the Bulgarian Naval Academy owns the Internet domain (*naval-acad.bg*), as well as a class C public network (*194.XXX.XXX.0/24*). The authoritative DNS server for this domain uses BIND9 software [15]. Local clients with private IP addresses use the same DNS server to resolve internet names.

Given the specified profile of this educational institution, several reasonable assumptions can be made regarding legitimate Internet traffic to the domain naval-acad.bg, which in turn can provide a basis for analysis and classification of suspicious or malicious traffic.

For example, legitimate DNS queries can be considered to be all those directed to the authoritative DNS server of the domain naval-acad.bg for resolving the FQDN names of publicly available Internet services provided by the academy, such as the official web page, e-mail, student status system, etc. It can also be reasonably assumed that such queries will essentially come from IP addresses from "friendly" or "partner" countries. Any other type of query can be classified as suspicious and subject to additional analysis.

With the framework thus set for implementing automated analysis of DNS queries, the flowchart presented in Fig. 1 can be followed. The flowchart can be adapted to other types of authoritative DNS servers.

Fig. 1 presents the procedure for performing the preparatory part of the analysis. We assume that the necessary DNS software has already been installed (in our case, this is BIND9, but the principle of operation will be identical for other DNS servers).

By default, BIND9 does not record separate event logs for DNS queries it processes. Audit logging must be enabled by adding an option to its configuration file.

Once audit logging is enabled, it is necessary to determine where the logs will be stored and how they will be managed. If this configuration is not performed, all audit events related to the BIND9 operation will be recorded in the main system log (in most cases, this is the /var/log/syslog file). The syslog file is quite dynamic, so we chose an approach in which audit logs from BIND9 will be recorded in separate files. This allows us to perform an easier analysis of the recorded events. Also, these log files can be shared with third parties for additional evaluation and analysis, if necessary, without providing any other information [16] – [17].

We have chosen an approach where different events are recorded in separate log files. As a result, we have 17 separate categories [18] of audit records, which allows us to perform detailed and quick analysis of different types of queries or other types of events related to the operation of the BIND9 DNS server. In the process of work, it was found that four categories of audit records are mainly used:

- default.log – audit records that do not fall within the scope of any of the other defined categories. A review of this log file for the server in question shows that it records events related to queries that are outside the scope of its defined forward and reverse lookup zones.
- lame-servers.log – audit records in case a problem is detected in the resolution chain to other DNS servers.
- queries.log – main log file for recording incoming queries.
- security.log – contains information about rejected queries for zone transfers or cached

information. It should be noted that the configuration of the DNS server in question prohibits performing zone transfers or cached information, but this information is useful for detecting malicious activity against the server and the domain it serves.

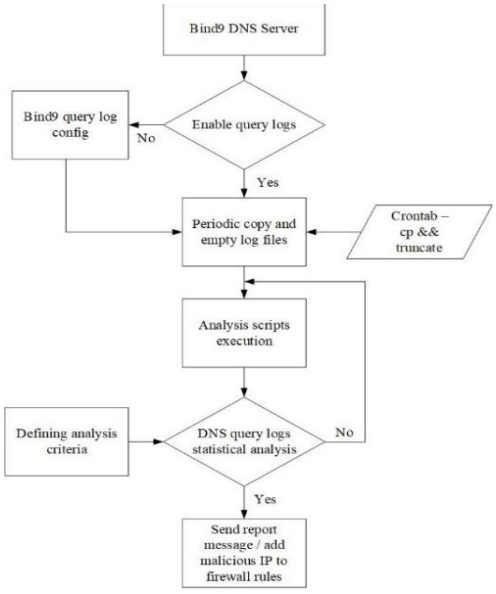


Fig. 1. DNS query analysis process flowchart.

The analysis we perform is on the audit records from these four log files. If malicious activity is detected, the other log files can be used by administrators for a more detailed analysis of the events. For this reason, the storage of three time versions of the log files has been determined, which should be a sufficiently long period of time to organize their storage for a longer period.

We have adopted an audit logs analysis approach that uses periodic copies of log files. For this purpose, we have configured a periodic task that copies all BIND9 log files, regardless of the number of records in them, and then resets the contents of the files to the main storage location. The latter is done to avoid duplication of analysis queries. The periodic task is configured to run every 30 minutes. The period is chosen by considering the average duration of WWW use by ordinary users, during which DNS queries are generated. As shown [19], the average duration of WWW use is about two hours per day. We assume that a session will hardly exceed 30 minutes, and by a session, we mean visiting one specific web page or those that are related to it. To exclude missing sessions that fall within the scope of two consecutive executions of the periodic task, we also store log files from the previous execution. In this way, the subsequent analysis is performed over 60 minutes.

B. DNS query logs analysis script development

We perform the analysis itself using Python script, and as evaluation criteria, we have defined the occurrence of the following events:

- A zone transfer query.
- A cache transfer query.
- An ANY type query.
- Queries from a single client exceed the percentage distribution of the same type of queries among all clients. For thresholds of the percentage distribution of queries, we use the data from [1].

The defined criteria should be periodically assessed and adjusted if necessary [20] – [24].

For individual clients for whom the volume of queries generated by them raises doubts about the purpose of their activity, an additional check is performed in a public database [25] – [26]. This evaluation is done using a separate Python script [27] – [29].

If suspicious clients are identified during the statistical analysis, information about their activity and the result of the check in the public database are sent to the email address of the DNS server administrator, and the client's IP address is added to a blacklist and BIND9 will automatically reject all subsequent queries from this client.

Fig. 2 presents the workflow of the created script for analysing DNS queries. The script is configured to run periodically after completing the log file copying.

The first step of its execution is to read log files from the specified working folder. This is followed by generating summary information for all clients and types of received queries. This summary information is saved in a separate file to be added to the analysis during the next script execution cycle to avoid missing client sessions that fall on the border between the 30-minute log files.

The script summarizes data from the current and previous cycles and compares the results to predefined criteria to determine suspicious activity. The current criteria are:

- IP address sends a zone transfer query;
- IP address sends a query of type “ANY”;
- IP address sends a query of type “SOA”;
- IP address sends more than 10% of all received queries;
    - IP address sends more than 2% of all received “PTR”, “A”, “AAAA”, or “TYPE65” queries;
    - The percentage distribution of queries from a single IP address exceeds any of the following thresholds – 40% type “A”, 10% type “AAAA”, 5% type “PTR”, 15% type “TYPE65”. This rule applies when there are at least 20 queries generated from a single IP address.

The next step in executing the script is to perform an online check against a publicly available database of the IP addresses identified in the previous step. It checks whether these IP addresses have already been reported for malicious activity. This check is performed only for public IP addresses.

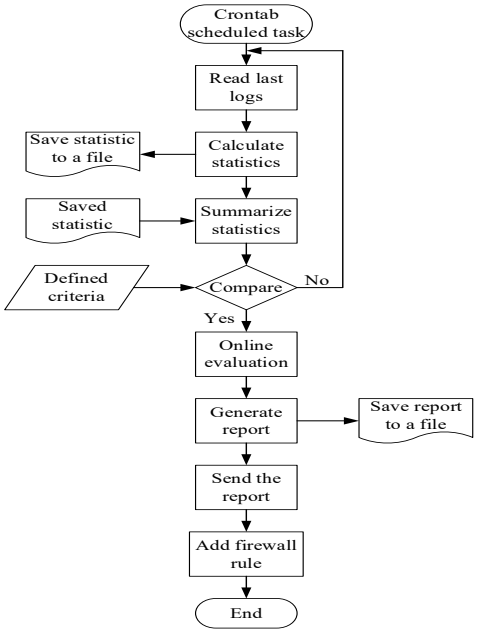


Fig. 2. DNS query analysis script flowchart.

The summary report is then generated and stored in a file. The file is then emailed to the DNS server administrators.

The script also generates inbound traffic rules to be added to the server's firewall. In this case, it is iptables. These rules aim to drop any type of traffic from the specified IP addresses. Information about the generated rules is added to the email sent to administrators, who have the opportunity to review them and, if necessary, modify or remove them.

This completes the script execution cycle and the next moment for its execution is awaited.

III. Results and Discussion

We have assumed that reporting malicious IP addresses is not a continuous process, but usually requires a certain response time, both on the part of the reporter and on the part of the public databases. For this reason, we have configured checking suspicious IP addresses to be performed once every 24 hours. For this purpose, we use an additional file with information accumulation, which records all IP addresses checked in the public database for each script execution cycle. The contents of this file are reset every day.

Using such a file prevents us from duplicating the generated iptables rules for a single IP address. Without such stored information, every two consecutive script execution cycles would cause the generation of two iptables blocking rules that concern the same IP address. We have adopted a threshold of 75% "bad" reputation of a checked IP address for a rule to be generated for its blocking.

The execution of each script cycle ends with sending an email to the DNS server administrators (Fig. 3).

This email contains the following information:

- Date and time of script execution;
- List of IP addresses for which blocking iptables rules have been generated;
- Attached file containing complete statistics of processed DNS logs in Excel spreadsheet format. Part of the content of this file is presented in Fig. 4.
- Attached file containing a report of the checked IP addresses in the public database with the score received for them (Fig. 5). This file contains information about all checked IP addresses with their scores, not just the blocked ones.

The script being executed colors the data for each client IP address when it matches any of the specified conditions described above, using the following color coding:

- Zone transfer queries – "Red" (FF0000);
- Queries of type "ANY" – "Light Red" (FF9999);
- Queries of type "SOA" – "Orange" (FF9900);
- Other matched rules – "Yellow" (FFFF00).

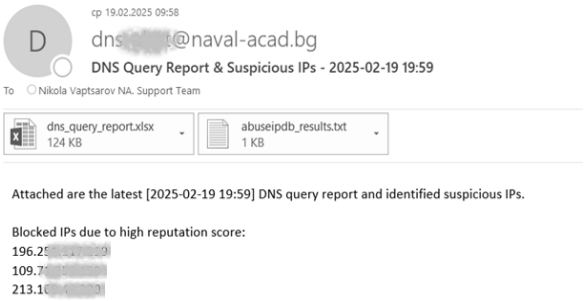


Fig. 3. Content of a received email with a report on the script execution.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	IP Address	A	AAAA	PTR	DNSKEY	SRV	TYPE65	SOA	TYPE64	NS	MX	TXT	CNAME	SPF	ANY	CAA	AXFR	Total Queries	Reputation Score
2	.10...44.	0	0	58	0	0	0	0	0	0	0	0	0	0	0	0	0	58	100
3	.71...3.	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	100
4	25...17	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	100
5	).20...63.	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	29	53
6	.21...3.	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	13
7	25...28	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	9
8	.7...2.	2	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	4	8
9	.25...2.	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	2	8
10	2.3...	2	4	0	0	1	1	1	0	0	0	0	0	0	0	0	0	9	4
11	.90...3.	2	1	0	0	0	0	1	0	0	2	1	0	0	0	0	0	7	4
12	.1...2	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	2
13	2.3...	8	8	0	0	#	1	4	0	0	0	0	0	0	0	0	0	35	1
14	.2...	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	4	1
15	.25...	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	1
16	4.1...	219	127	32	0	0	0	0	0	9	39	31	0	15	0	0	0	472	0
17	1.1...	330	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	389	0
18	1.1...	86	84	16	0	0	0	0	0	0	0	6	0	0	0	0	0	192	0
19	4.1...	84	84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	168	0

Fig. 4. Content of the Excel file with statistics of processed logs.

The public IP addresses in Fig. 3, Fig. 4, and Fig. 5 are intentionally masked in this paper.

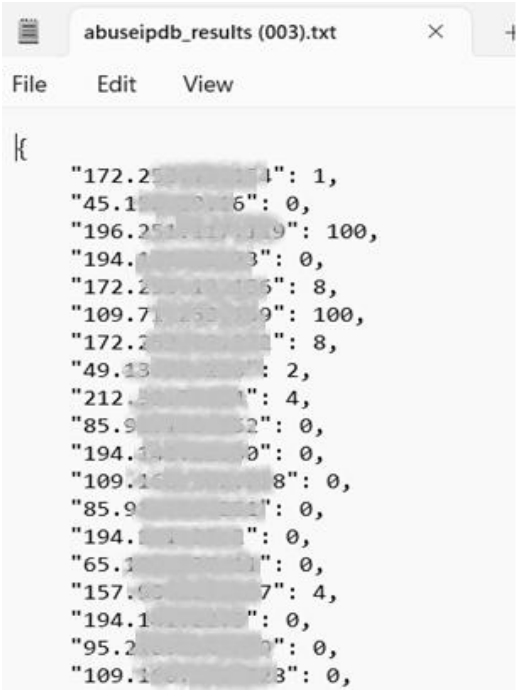


Fig. 5. Contents of the file with the checked IP addresses and their reputation score.

TABLE 1 NUMBER OF IPTABLES RULES GENERATED

Number of days since the initial script execution	Number of blocked IP addresses
Day 1	8
Day 2	8
Day 3	6
Day 4	3
Day 5	3
Day 6	7
Day 7	4
Day 8	1

Table 1 presents data on the generated iptables rules over a specific period, with the first day covering less than a full 24-hour cycle.

IV. CONCLUSIONS

A Python script has been developed to analyse the log files of a BIND9 DNS server. By applying predefined rules and cross-referencing data with a public database, it generates summarized statistics on potential malicious activities targeting the server. The process of creating filtering rules for incoming Internet traffic, based on the assessed reputation of IP addresses initiating DNS queries, has been automated. This automation enhances the server's security by enabling proactive threat mitigation and reducing the risk of repeated attacks.

With the script's periodic execution, iptables rules are dynamically generated to block IP addresses that match any predefined criteria. These rules are applied immediately upon detection of suspicious activity, ensuring real-time protection. A decreasing trend in the number of generated rules has been observed (Table 1), suggesting the effectiveness of the filtering mechanism in reducing malicious traffic over time.

The proposed approach relies exclusively on open-source software, making it accessible, cost-effective, and adaptable for different environments. Future improvements may include the integration of machine learning techniques for adaptive threat detection and enhanced accuracy in identifying malicious behaviour.

ACKNOWLEDGMENTS

This work was supported by the National Scientific Program "Security and Defence", adopted with RMS No. 731/21.10.2021, and financed by the Ministry of Education and Science of the Republic of Bulgaria according to Agreement No. D01-74/19.05.2022.

REFERENCES

[1] J. Ginesin and J. Mirkovic, Understanding DNS Query Composition at B-Root, 2022 IEEE/ACM International Conference on Big Data Computing, Applications and Technologies (BDCAT), Dec 06-09, 2022, Vancouver, WA, USA, pp. 265-270, doi: 10.1109/BDCAT56447.2022.00044

[2] P. Mockapetris, "Domain names - concepts and facilities," RFC 1034, Nov. 1987. [Online]. Available: https://datatracker.ietf.org/doc/html/rfc1034 [Accessed February 2, 2025].

[3] P. Mockapetris, "Domain names - implementation and specification," RFC 1035, Nov. 1987. [Online]. Available: https://datatracker.ietf.org/doc/html/rfc1035 [Accessed February 2, 2025].

[4] R. Arends, R. Austein, M. Larson, D. Massey and S. Rose, "DNS Security Introduction and Requirements," RFC 4033, Mar. 2005. [Online]. Available: https://datatracker.ietf.org/doc/rfc4033/ [Accessed February 2, 2025].

[5] Y. Wang, A. Zhou, S. Liao, R. Zheng, R. Hu and Lei Zhang, "A comprehensive survey on DNS tunnel detection," Computer Networks, vol. 197, 2021. doi: 10.1016/j.comnet.2021.108322

[6] Y. Zhauniarovich, I. Khalil, T. Yu and M. Dacier, "A Survey on Malicious Domains Detection through DNS Data Analysis," ACM Computing Surveys, vol. 51, 2018. doi: 10.1145/3191329

[7] I. Ghafir and V. Prenosil, DNS Traffic Analysis for Malicious Domains Detection, 2015 2nd International Conference on Signal Processing and Integrated Networks (SPIN), February 19-20, 2015, Noida, India.

[8] A. Ramdas and R. Muthukrishnan, A servey on DNS Security Issues and Mitigation Techniques, Proceedings of the International Conference on Intelligent Computing and Control Systems (ICICCS 2019), June 27-28, 2019, Secunderabad, India.

[9] K. Borgolte, T. Chattopadhyay, N. Feamster, M. Kshirsagar, J. Holland, A. Hounsel and P. Schmitt, "How DNS over HTTPS is Reshaping Privacy, Performance, and Policy in the Internet Ecosystem," SSRN Electronic Journal, 2019. doi:10.2139/ssrn.3427563

[10] I. Dube and G. Wells, An Analysis of the Use of DNS for Malicious Payload Distribution, 2nd International Multidisciplinary Information Technology and Engineering Conference (IMITEC), November 25-27, 2020, Kimberley, South Africa. doi: 10.1109/IMITEC50163.2020.9334104

[11] M. Luo, Q. Wang, Y. Yao, X. Wang, P. Yang and Z. Jiang, Towards Comprehensive Detection of DNS Tunnels, 2020 IEEE Symposium on Computers and Communications (ISCC), July 07-10, 2020, Rennes, France. doi: 10.1109/ISCC50000.2020.9219547

[12] S. Lysenko, K. Bobrovnikova, O. Savenko and R. Shchuka, Technique for Cyberattacks Detection Based on DNS Traffic Analysis, Proceedings of the 16th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, October 06-10, 2020, Kharkiv, Ukraine, pp. 171-182. Available: https://ceur-ws.org/Vol-2732/20200171.pdf. [Accessed February 2, 2025].

[13] M. Antonakakis et al., Understanding the Mirai Botnet, Proceedings of the 26th USENIX Security Symposium, August 16–18, 2017, Vancouver, BC, Canada, pp. 1093-1110.

[14] C. Xuan, T. Nikolaevich, N. Dam, N. Hoang and D. Long, "Malicious domain detection based on DNS query using Machine Learning," International Journal of Emerging Trends in Engineering Research, vol. 8, 2020, pp. 1809-1814. doi: 10.30534/ijeter/2020/53852020

[15] BIND 9 - Versatile, classic, complete name server software – ISC – isc.org. https://www.isc.org/bind/ [Accessed January 21, 2025].

[16] S. Ma, T. Pang, R. Cui and D. Yang, A Malicious Domain Detection Method Based on DNS Logs, 4th International Conference on Blockchain Technology and Information Security (ICBCTIS), August 17-19, 2024, Wuhan, China. doi: 10.1109/ICBCTIS64495.2024.00051

[17] M. Stevanovic, J. M. Pedersen, A. D'Alconzo and S. Ruehrup, "A method for identifying compromised clients based on DNS traffic analysis," International Journal of Information Security, vol. 16, pp. 115–132, 2017. doi: 10.1007/s10207-016-0331-3

[18] BIND 9 Administrator Reference Manual – ISC – isc.org. https://bind9.readthedocs.io/en/latest/reference.html#the-category-phrase [Accessed January 24, 2025].

[19] Y. Lut, M. Wang, E. M. Redmiles and R. Cummings, How We Browse: Measurement and Analysis of Browsing Behavior, 2024 IEEE 6th International Conference on Cognitive Machine Intelligence (CogMI), October 28-30, 2024, Washington D.C., USA, pp. 257-264. doi: 10.1109/CogMI62246.2024.00041

[20] D. Dimitrova, "Selection and Justification of Criteria for Comparative Analysis of Lightweight Ciphers," Mathematics and Informatics, vol. LXVI, no. 5, 2023, pp. 534–542. doi: 10.53656/math2023-5-8-sel

[21] Y. Dechev, "Research on the impact of online learning on individual learning styles," Mathematics and informatics, vol. 66, no. 2, 2023, pp. 155-169. doi: 10.53656/math2023-2-5-res

[22] M. Maroun and A. Ivanova, "Ontology-based approach for cybersecurity recruitment," AIP Conf. Proc., vol. 2333, 070014, March 2021. doi: 10.1063/5.0042320

[23] Y. Huang, J. Negrete, A. Wosotowsky, J. Wagener, E. Peterson, A. Rodriguez and C. Fralick, Detect Malicious IP Addresses using Cross-Protocol Analysis, 2019 IEEE Symposium Series on Computational Intelligence (SSCI), December 6-9, 2019, Xiamen, China, pp. 664-672. doi: 10.1109/SSCI44817.2019.9003003

[24] M. Sotirov, V. Petrova and D. Nikolova-Sotirova, Personalized Gamified Education: Feedback Mechanisms and Adaptive Learning Paths, 2024 8th International Symposium on Innovative Approaches in Smart Technologies (ISAS), December 6-7, 2024, Istanbul, Turkiye, pp. 1-6. doi: 10.1109/ISAS64331.2024.10845384

[25] AbuseIPDB - making the internet safer, one IP at a time - AbuseIPDB LLC - abuseipdb.com. https://www.abuseipdb.com/ [Accessed January 28, 2025].

[26] S. Torabi, A. Boukhtouta, C. Assi and M. Debbabi, "Detecting Internet Abuse by Analyzing Passive DNS Traffic: A Survey of Implemented Systems," IEEE Communications Surveys & Tutorials, Volume 20, Issue 4, Fourthquarter 2018, pp. 3389 – 3415, June 2018. doi: 10.1109/COMST.2018.2849614

[27] W. McKinney, Python for Data Analysis: Data Wrangling with pandas, NumPy, and Jupyter 3rd Edition. Sebastopol, USA: O'Reilly Media; 2022

[28] openpyxl - A Python library to read/write Excel 2010 xlsx/xlsm files. https://openpyxl.readthedocs.io/en/stable/index.html# [Accessed January 28, 2025].

[29] J. Whitington, Python from the Very Beginning: With 100 exercises and answers. Cambridge, UK: Coherent Press, 2020

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 237-241

Research on the Impact of the User Experience for the Success of a Virtual Product: Bulgarian Travel Agency Websites

Stela Mincheva
Faculty of Mechanical Engineering Technical University of Sofia
Sofia, Bulgaria
stella.mincheva23@gmail.com

Veselka Stoyanova
Artillery, AD and CIS faculty
National Military University V.Levski
Shumen, Bulgaria
veselka_tr@abv.bg

***Abstract*— The huge and ubiquitous of the Internet usage, confirms that websites consist a critical competitive resource for tourism business. For the purpose of this report, a study of the user experience of virtual products - websites of Bulgarian travel agencies were prepared. Nine of most of popular Bulgarian sites were selected, namely: "Alexander Tour", "Bohemia", "Ecuador", "Emerald", "Globus", "Mistral", "Red Tours", "RuAl" and "Sun Travel". Data collection was performed through an electronic questionnaire, which was based on Google Forms. The results obtained showed that among all the quality factors, ease of understanding, response time and intuitive functioning of the website (ease of use and navigation) were the most important. The study was tested on a sample of 95 customers of travel websites targeting the Bulgarian market. In conclusion, a positive correlation was found between the overall perceived quality and purchase intentions.**

Keywords*— *Travel websites, user experience, digitalization.

I. Introduction

Nowadays in the world of information technologies and programming are so important and help us reach unexpected opportunities. Web design, user experience and information architecture play an important role in improving user trust and customer engagement in all areas of our daily lives.

Travel websites are extensively used by travellers for their travel bookings, yet very little is known about the hedonic effectiveness of such experiences for the customer. The end users of these websites are customers who may not always be sophisticated information system (IS) users [1].

One of the key points of travel websites is that their products have their ability to inspire consumers' dream. Travel websites are widely used by travelers for their travel bookings, but very little is known about sales performance and the emotional experiences for the customers.

For the purpose of this report, a study of the user experience of virtual products - websites of Bulgarian travel agencies, was conducted. Nine of the most popular Bulgarian travel agency websites were selected, namely: *„Alexander Tour", „Bohemia", „Ecuador", „Emerald", „Globus", „Mistral", „RedTours, „RuAl"* and *„Sun Travel*". The websites of the compared agencies could be seen at: [2, 3, 4, 5, 6, 7, 8, 9, 10]. The empirical study was based on a quantitative approach. The sample consisted of 95 internet users who have visited this travel agencies's websites, 54 of whom were women (57.5%) and 41 men (43.5%), and their age ranged from 18 to 50, with the majority of participants belong to the age category of 18–25 years old (40%). The target group ranges from people looking for customized vacations, excursions and adventure experiences, families looking for convenient and safe destinations with entertainment options for children festivals to youth oriented budget travels, adventures and.

The measurement of emotional user experience according to the static method is based on subjective evaluations. Through these evaluations, users self-declare their emotional state during interaction with the product or its elements. One of the most common and widely used tools for generating user experience data in the static method is questionnaires. Exactly this method of collecting data on the emotional user experience was used for this study. Data collection was performed through an electronic questionnaire, which was based on Google Forms.

II. Materials and Methods

According to [11] in Bulgaria for 2024г. 47% of the Bulgarian respondents get information about their trips from family and friends, approximately 36% search on

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8591
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

travel websites and 34% travel agencies and their brochures, and finally 24% use social networks such as Instagram, Facebook and TikTok as a source of inspiration. Based on these sources of information, Figure 1 shows where Bulgarians get the majority of information while making their decisions.

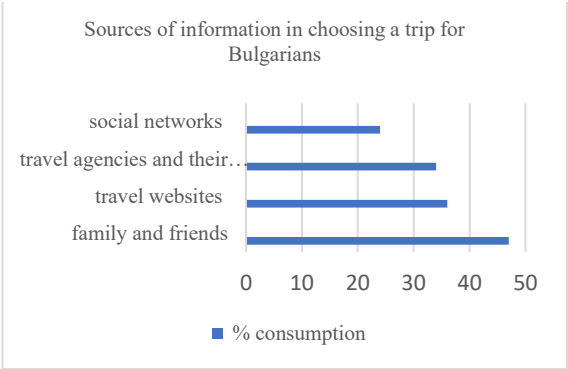


Fig. 1. Sources of information in choosing a trip for Bulgarians.

Over a third of Bulgarians choose package holidays for their trips - 39% [11]. A little over half of them, or 51%, were purchased at the office of a travel agency, and 49% of through online platforms with offers from different agencies or from the travel agency's website (fig.2). Data collected by Response Now S.R.O. in December 2024 through a representative sample of Internet users in Bulgaria between the ages of 18 and 60. The total number of respondents was 1028 [12].

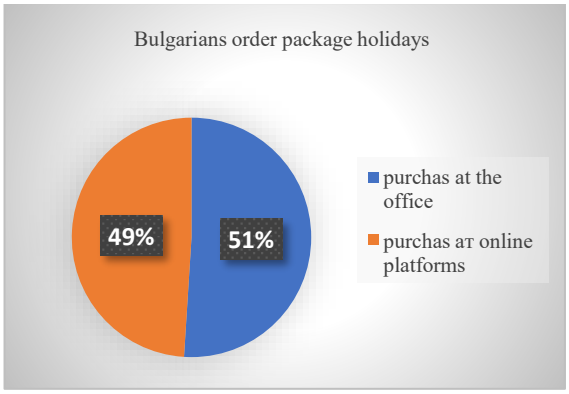


Fig. 2. Bulgarians order package holidays.

The total num digitalization is the basis for the development of a modern economy, and this process covers all aspects of management, including consumer behavior in the environment [13].

The static emotional user experience design study starts with questionnaire wording. There are more than 100 different methods for measuring user experience. The most commonly used tools in those tasks are the questionnaires. There are over 20 types of questionnaires. They are based on methods like Aesthetic scale, Hedonic utility scale, Game experience, Mental effort, Product semantic analysis, etc [14]

For the study was used the "Likert scale", according to which the user indicates a specific rating in an interval between two extremes – negative and positive Figure 3 shows the Rating scale for our study.



Fig. 3. Rating scale (1- I don't like it at all, 2- I don't like it, 3- I rather don't like it, 4- Neutral, 5- I rather like it, 6- I like it, 7- I really like it).

The criteria by which the audience evaluates dominants is how much they like them. The selected elements are the overall appearance, the web header, its main image and the main colour. Overall the sites are evaluated on how each one has chosen the combination of graphic elements and what is the impact on the target group.

The observance of a comparative regularity of principles in the construction of the assessed sites is noted. Basic norms for a well-functioning site have been adopted. For example, having a header that includes a menu that allows for easy navigation, a main image that is engaging, colourful and of high quality, consistent with the top destinations on offer.

The main goal of the study was to research and analyse the effect of the perceived quality on customers' overall satisfaction, and intentions to use online travel agency services.

The clarity of the approach to the digital representation of emotions and the way of recording the evaluations allows to move on to the construction of the structure of the questionnaire itself. The parts' into which the questionnaire is divided usually coincide with the steps of work on generating static dominance data. The consistency condition is met, in the individual parts of the questionnaire, the evaluation grades should be the same in number and value.

For the professional presentation of statistics and the creation of charts and clear results was used [15].

III. Result and Discussion

Table 1 presents the results of the qualitative technical characteristics of the user experience of the compared sites. In it, the highest ratings are marked in green, the lowest in red.

TABLE 1 AVERAGE VALUES OF COMPARED TECHNICAL PROPERTIES

Properties / Web	*Full coverage*	*Heather*	*Main Image*	*Colour*
Web 1 [2]	4.77	4.60	5.08	5.12
Web 2 [3]	4.10	3.85	4.25	4.12
Web 3 [4]	4.58	4.62	4.88	4.56
Web 4 [5]	4.04	4.15	3.94	4.11
Web 5 [6]	4.94	5.13	4.79	4.75
Web 6 [7]	4.92	4.44	4.62	4.71
Web 7 [8]	4.94	5.00	4.87	4.60
Web 8 [9]	4.88	4.87	4.75	4.60
Web 9 [10]	5.19	5.25	5.17	5.20

Figure 4 shows the final grades as a total value of the grades for all criteria. It is clear that website 9 is the favourite.

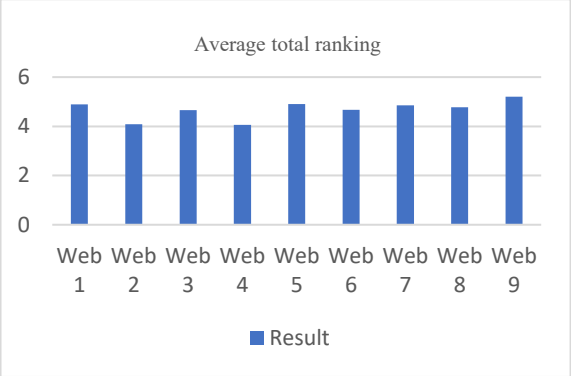


Fig. 4. Average Total Ranking.

Figure 5 shows the preferences of the respondents, comparing the highest rated and the lowest rated website.

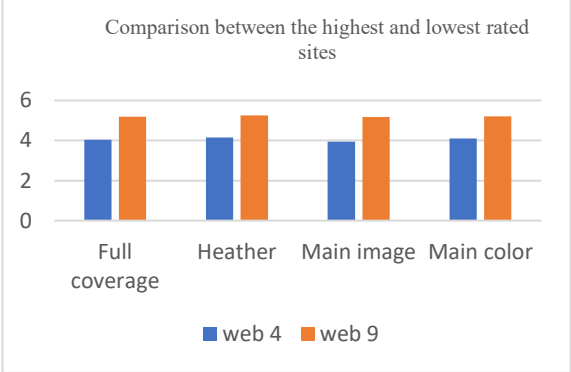


Fig.5. Comparison between the highest and lowest rated sites.

Sun Travel (*Web9*) is favoured by respondents for its clean look and bright vision, while Emerald (*Web 4*) takes a back seat due to a cluttered first impression, despite the enchanting image of a woman on the first page.

For the evaluation of the results is going to be used the box plot method. In descriptive statistics, a box plot or boxplot is a method for demonstrating graphically the locality, spread and skewness groups of numerical data through their quartiles [16]. In addition to the box on a boxplot, there can be lines (which are called whiskers) extending from the box indicating variability outside the upper and lower quartiles.

A boxplot is a standardized way of displaying the dataset based on the five-number summary: the minimum, the maximum, the sample median, and the first and third quartiles. The characteristics studied are represented by formula (1):

$$IQR = Q_3 - Q_1 = q_n * (0.75) - q_n * (0.25) \qquad (1)$$

where Q_3 or 75th percentile, and Q_1 or 25th percentile, are the median of the lower half of the dataset and the median of the upper half of the dataset. Interquartile range (*IQR*) is the distance between the upper and lower quartiles.

A boxplot usually includes two parts, a box and a set of whiskers.

For the formula to work we need to have the median known as Q_2 or 50*th* percentile. It is the middle value in the data. The box is drawn from Q_1 to Q_3 with a horizontal line drawn inside it to denote the median Q_2.

The *IQR* plays a major part in how long the whiskers extending from the box are. Each whisker extends to the furthest data point in each wing that is within 1.5 times the *IQR* as represented by formulas (2) and (3):

$$a = Q_3 - 1.5 * IQR \qquad (2)$$

$$b = Q_1 - 1.5 * IQR \qquad (3)$$

where ***a*** and ***b*** are the maximum and minimum point of the whisker's extensions from the box.

For every criteria and it is results the boxplot method was applied, so the data can be further analysed. Figures 6, 7, 8 and 9 show the visualization of the analysis and the boxplot.

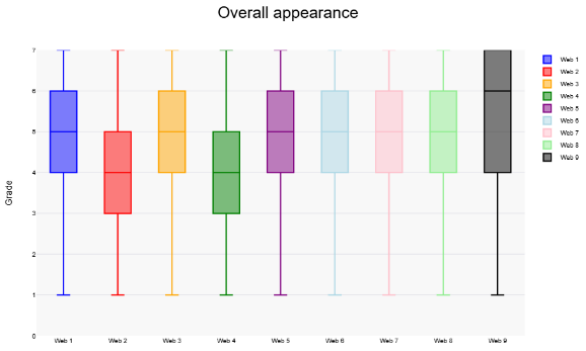


Fig.6. Boxplot of the highest and lowest rated sites based on the overall appearance.

Figure 6 shows that most websites have median grades (*Q2*) between 4 and 6, suggesting a moderate perception of overall appearance. However, *Web 3* and *Web 5* appear to have higher median values, indicating better user ratings for appearance. *Web 9* has a slightly higher median compared to the others, suggesting its overall appearance was rated favourably.

Web 1, Web 3, and *Web 9* have larger *IQRs*, suggesting diverse opinions among users. *Web 6* and *Web 7* have narrower *IQRs*, showing more consistent user feedback. Some websites exhibit wider whiskers (e.g., *Web 9),* indicating extreme ratings.

Websites with higher medians and consistent feedback (e.g., *Web 3, Web 5*) provide a more universally pleasing design.

Websites with larger *IQRs* and ranges (e.g., *Web 9*) might have polarizing designs that appealed strongly to some users while alienating others.

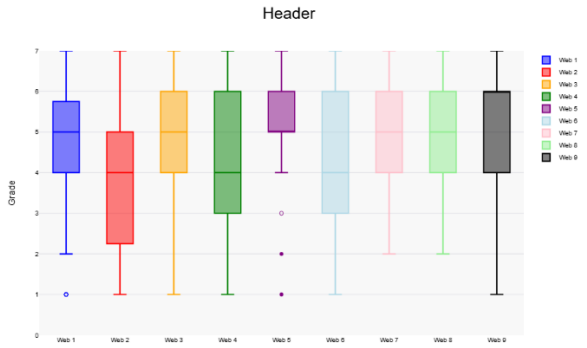


Fig.7. Boxplot of the highest and lowest rated sites based on the header.

Figure 7 shows the medians for the header range between 4 and 6, indicating moderate to good ratings for the header design across most websites. *Web 9* has the highest median value, showing better user satisfaction with its headers. *Web 2* has the lowest median, suggesting its header design and usability were less appealing to users.

Websites such as *Web 1, Web 3, and Web 9* show larger *IQRs*, meaning the opinions on these headers were more diverse. The extreme lower whisker for Web 2 (minimum of 1) suggests some users were highly dissatisfied with its header.

This analysis can guide improvements to header design, focusing on visual appeal, layout clarity, and most importantly usability.

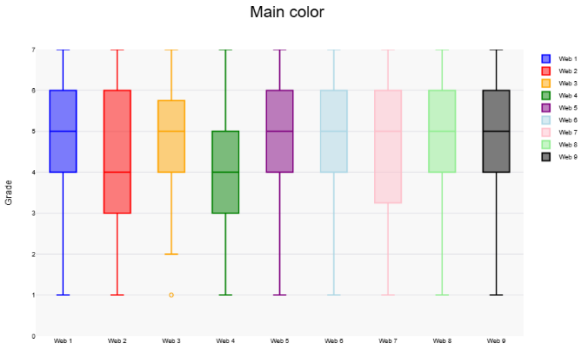


Fig.8. Boxplot of the highest and lowest rated sites based on the main image.

Figure 8 shows all websites received ratings across the full scale (1 to 7), reflecting varied user opinions on main colours. The results *for Web 3, Web 5,* and *Web 9* have higher median values, suggesting users were more satisfied with their main colour selection. *Web 2* and *Web 4* have lower medians, indicating less favourable opinions of their colour schemes.

An outlier can be observed in *Web 3,* where a user rated its main colour as *1* despite a generally favourable distribution. This suggests some users had strong negative reactions.

Sites with lower medians (e.g., *Web 2* and *Web 4*) need to address divisive colour choices that negatively impacted some users and could consider revising their colour palettes to align more with user preferences.

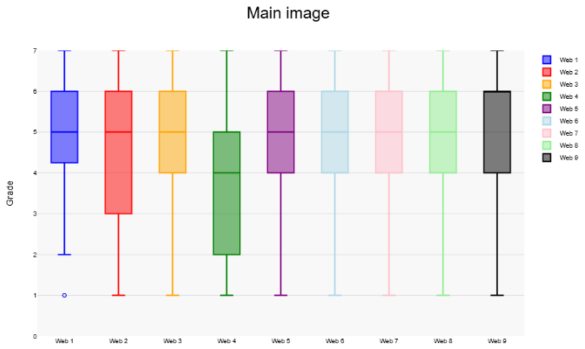


Fig.9. Boxplot of the highest and lowest rated sites based on the main colour.

Figure 9 shows the Best-Rated Main Image is that of *Web 9*. However, *Web 1, Web 2, Web 3, Web 5* also have high median scores, meaning users generally found these images attractive, high-quality, and appropriate. The narrow *IQR* suggests consistent approval, meaning most users had similar positive impressions.

Web 1 has an outlier at *Grade 1,* indicating at least one user strongly disliked its main image. Improving the main image's quality, emotional impact, and relevance can significantly enhance user experience and engagement.

All of the points above and the receiving of the highest score for all dominants, which is consistent with its clean look proves that *Web 9* has the most preferred vision and combination of elements from the user's point of view. It also has one of the highest average scores for overall appearance.

The 9th website features a clean and modern design, with a minimalist style, clear navigation, and well-organized content. They want to make it easier for the user to quickly find offers. The participants in this study highlighted that the large main image is engaging, colourful, and with high-quality, which is tailored to top destinations and points to the idea of travel and creates inspiration for destinations in Europe. The main palette is white with orange accents and black texts. This combination is fresh while maintaining good contrast for readability. Orange is usually associated with energy, sunshine and a positive mood, which complements the „Sun Travel" brand.

Based on their personal perceptions of the services, customers generally form their experiences [16, 17]. The proposed study conducted to examine the relationship of service quality and customer satisfaction. [18] summarizes the importance of the relationship between tourism and information technology is also justified by their place in the national economy.

IV. CONCLUSION.

Results indicated that among all the quality factors, the ease of understanding, response time, and the website intuitive operation (ease to use and navigation) emerged as

the most important. Quality perception was significantly different in terms of gender and age. Visiting the travel agency websites, with regard to the Internet user profile, are the reason of influence the perceived quality and user experience. Finally, a positive correlation was found between the overall perceived quality and purchase intentions.

All of the points above and the receiving of the highest score for all dominants, which is consistent with its clean look proves that site 9 has the most preferred vision and combination of elements from the user‘s point of view. It also has one of the highest average scores for overall appearance.

All sites rely on large, attractive images and clear search engines - typical for the tourism industry. The main differences are in the choice of colour palette and style of presentation of the offers. Some (*Globus Tours, Mistral, Ekvator.bg*) prefer a light background with bright accents, others (*RedTours, Rual Travel*) combine more photos in collages or categories, and Emerald and Alexander Tour are distinguished by more special visual solutions (Northern Lights, desert dunes), which create a specific atmosphere.

For travel websites, it is crucial to have quick and easy navigation, clearly distinguishable search and offers buttons, as well as a strong, attention-grabbing main image or slider that instantly transports the user to the desired destination or highlights promotional offers. Main images and headers play a key role in the overall perception.

The results of this study are considered important for practitioners in the online travel sector, by identifying significant factors that affect online consumers’ willingness to purchase and will also contribute to building the concept of online travel agency quality performance. Additionally, tourism agencies should design guest satisfaction programs and counselling sessions focused on new quality and visual performance their virtual product-websites.

ACKNOWLEDGMENTS.

The author would like to thanks that paper was supported by the Technical University of Sofia from the Research and development sector.

The author would like to thanks that paper was supported by the NSP DS program, which has received funding from the Ministry of Education and Science of the Republic of Bulgaria under the grant agreement no. Д01-74/19.05.2022

REFERENCES

[1] M. Wani, A. Raghavan, V.Abraham, et al. “Beyond utilitarian factors:User experience and travel company website successes.“ Inf Syst Front 19, p.769–785 , 22 March 2017, [Online]. Available: https://link.springer.com/article/10.1007/s10796-017-9747-1, [Accessed: Feb. 02, 2025],.https://doi.org/10.1007/s10796-017-9747-1.

[2] Alexander Tour Home Page, [Online]. Available: https://alexandertour.com. [Accessed: Feb. 02, 2025].

[3] Bohemia Home Page, [Online]. Available: https://www.bohemia.bg. [Accessed: Feb. 02, 2025].

[4] Ekvator Home Page, [Online]. Available: https://ekvator.bg. [Accessed: Feb. 02, 2025].

[5] Emerald Home Page, [Online]. Available: https://emerald.bg/bg. [Accessed: Feb. 02, 2025].

[6] Globus Home Page, [Online]. Available: https://www.globuses.com. [Accessed: Feb. 02, 2025].

[7] Mistral Home Page, [Online]. Available: https://www.mistralbg.com. [Accessed: Feb. 02, 2025].

[8] RedTours Home Page, [Online]. Available: https://redtours.bg. [Accessed: Feb. 02, 2025].

[9] RuAL Home Page, [Online]. Available: https://rual-travel.com. [Accessed: Feb. 02, 2025].

[10] Sun Travel Home Page, [Online]. Available: https://www.suntravel.bg. [Accessed: Feb. 02, 2025].

[11] P.Stoyanova, "80%Bulgarians will pay with digital means during their vacations abroad", https://www.investor.bg/a/566-novini-i-analizi/395423-pochti-80-ot-balgarite-shte-plashtat-s-digitalni-sredstva-po-vreme-na-vakantsiite-si-v-chuzhbina?utm_source.com, [Accessed: Feb. 02, 2025].

[12] National Board of Tourism, “Visa survey: 67% of Bulgarians plan winter vacation in the mountains, digital payments preferred“, Feb. 04, 2025. [Online]. Available: https://tourismboard.bg/news/prouchvane-na-visa-67-ot-balgarite-planirat-zimna-pochivka-v-planinata-predpochitani-sa-digitalnite-plashtaniya/. [Accessed: Feb. 06, 2025].

[13] O. M. Ali, The digital economy and its impact on consumption in the regions of Bulgaria. In: 3rd International Conference Spatial Development of Territories (SDT 2020). Atlantis Press, p. 256-261, 2021.

[14] Y. Svezhenov, A. Nikov, L. Dimitrov, Modelling in dynamic user experience design of educational toys packages, In: AIP Conference Proceedings, SP -090015, 13.11.2019.

[15] Statistics Kingdom, “Advanced box and whisker plot maker” [Online]. Available: https://www.statskingdom.com/advanced-boxplot-maker.html [Accessed: Feb. 06, 2025].

[16] S. H. C. Toit , A. G. W. Steyn and R. H. Stumpf, Graphical exploratory data analysis.Springer, 1986, ISBN 978-1-4612-9371-2. OCLC 1019645745.

[17] F. Khan, A. Rasli, R Mdyusoff, and A. Ahmad. "Do Demographic Make a Difference to Job Burnout Among University Academicians?", International Journal of Economics and Financial, Issues 5,p. 229-237, July 2015.

[18] O. Mancheva-Ali and V. Dimitrova, Factors influencing hotel industry, XIV-th International Scientific Conference,At: Agia Triada, Greece, April 2019, [Online]. Available: https://www.researchgate.net/publication/332523141_factors_influencing_hotel_industry, [Accessed: Feb. 06, 2025].

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 243-250

Historical Development of Technologies in the Field of Artificial Intelligence

Ventsislava Nikolova-Minkova
Department of Social and Economic Sciences
Technical University of Gabrovo
Gabrovo, Bulgaria
minkova.ventsislava@gmail.com

***Abstract* — This study traces the historical development of technologies in the field of artificial intelligence (AI). The relevance of the topic stems from the subsequent rapid development and implementation of computer technologies in various fields of human knowledge. Nowadays, the development of AI, as a leading computer technology in the last decade, creates unceasing interest among specialists in the field and the scientific community, given that the boundaries of its application are immense. The aim of this study is to trace the historical development of technologies in the field of artificial intelligence, using patent statistics as a measure of innovative creativity. In this regard, by applying empirical methods (comparison method, graphical method) and historical approach to analyzing data on the number of patented inventions through the Patent Cooperation Treaty (PCT), administered by the World Intellectual Property Organization (WIPO), the evolutionary development of artificial intelligence is illustrated. As a result of the study, the leading countries in which the inventive capacity in the selected technological field is concentrated are identified. The main conclusions we reached identify nine leading countries, in which 94.68% of the patent activity in the field of AI is concentrated for the period from 1980 to 2023, and 2.75-times higher research activity in 2022 compared to 2010. Despite the data, the Government and Industry sectors do not invest the necessary efforts in AI research (the Education sector conducts 81.07% of the research), which predetermines their inability to take advantage of the advantages that AI can generate.**

Keywords—Artificial intelligence, patent grants, technology.

I. INTRODUCTION

For centuries, people's creativity has been a generator of their development and a prerequisite for high scientific and technical achievements, giving the appearance of modernity. Man, although limited in his physical and mental abilities, has unlimited ambitions and thirst for new knowledge and its implementation in innovative technological solutions that can "change the world". In parallel with human evolution, more complex and multifaceted problems are emerging to solve, the need to process ever larger volumes of data to make more accurate forecasts that support the development of society and the economy as a whole. There is a need to develop innovative machines, systems and algorithms for their work, which, on the one hand, will facilitate and on the other hand increase the efficiency of a person. This innovative process of creativity, during which in the period 1937-1942 the prototype of the modern computer was created by John Atanasoff and Clifford Berry [1], laid the foundation for the development of computer science, the digital transformation of industry [2] and modern artificial intelligence (AI).

The relevance of the topic stems from the rapid development and implementation of computer technologies in various areas of human knowledge. Nowadays, computer technologies are used in almost every economic sector, they are successfully implemented in medicine, education and support the development of science and society. This is a prerequisite for the development of AI, as a leading computer technology in the last decade, to create unceasing interest among specialists in the field and the scientific community, given that the boundaries of its application are immense.

The analysis of the specialized literature presents the wide range of research related to AI in different directions, therefore, for the purposes of this work, we will limit ourselves to analyzing some of them, using the historical approach to studying AI development trends. Fundamental research on the historical development of AI, with Hiremath & Kenchakkanavar pointing out that AI contributes to technological advances not only in the field of human management, but also as a motivator for increasing productivity in various industries and promoting

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8609
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

innovation. The authors also prove the role of AI in transforming educational paradigms, especially during COVID-19 [3]. Garcia-Murillo and MacInnes take a historical approach to predict the impact of AI on society and employment, analyzing examples from the past of the introduction of revolutionary computing machines in the United States [4]. Hirani et al. identified the evolution of healthcare under the influence of AI in the period 1960-2024 and reported positive trends in improving the quality of healthcare services and the possibilities for remote monitoring of patients' health status through wearable devices with integrated AI or through AI-driven telemedicine and chatbots providing support and consultation to patients [5]. Hassan, Ewis & Kamel used a historical approach to establish the application of AI in the creative industries and found that in the film industry, from an aid to AI, it became a major tool for creating scenes through automated simulation tools and generative AI techniques [6].

The above predetermines the purpose of this study, which is aimed at tracing the historical development of technologies in the field of artificial intelligence, using patent statistics as a measure of innovative creativity. The object of the study is artificial intelligence, and the subject of the study is patent statistics as an indicator of technological development.

In the next part of the paper, some of the definitions outlining the characteristics of artificial intelligence are presented. The empirical part of this work examines inventive activity in the field of computer technology, and in particular technologies related to AI. For this purpose, data on patent documents issued through the Patent Cooperation Treaty, administered by the World Intellectual Property Organization (WIPO), were used. Next, data on granted patents in the field of AI are analyzed. Information on the development of scientific publications in the field of AI is also offered. Methods of comparison and graphical representation of data are used to illustrate the evolutionary development of artificial intelligence. As a result of the study, the leading countries in which the inventive capacity in the chosen technological field is concentrated are deduced. In conclusion, the risks arising from the development and use of AI in modern times are also taken into account.

II. MATERIALS AND METHODS

A. Literature review

The field of application of artificial intelligence is extremely diverse, which is why for years it has been associated with a number of areas of computer technology, including: natural language processing – NLP [7]; machine learning [8]; computer vision- CV [9]; planning, scheduling, and optimization [10]; and robotics [11], but it is not limited to them. That is why experts from the academic community offer different definitions of the essence of artificial intelligence.

Among the first definitions is the one derived from Minsky, according to whom AI is the science of the ability of machines to perform actions that require the intelligence of humans [12]. This statement is further developed by Kurzweil [13], who goes beyond the theoretical limits set and suggests the creation of machines to perform tasks performed by intelligent human beings. Newer definitions expand the scope of artificial intelligence, due to the increase in expectations for its capabilities. According to Haenlein and Kaplan AI is *"a system's ability to interpret external data correctly, to learn from such data, and to use those learnings to achieve specific goals and tasks through flexible adaptation"* [14, p.5]. According to Frankenfield AI is *"simulation of human intelligence in machines that are programmed to think like humans and mimic their actions"* [15]. Zúñiga, Homero, Goyanes, and Durotoye define AI as *„the tangible real-world capability of non-human machines or artificial entities to perform, task solve, communicate, interact, and act logically as it occurs with biological humans "*[16].

Although the presented definitions constitute a limited part of the author's opinion on the question of the essence of artificial intelligence, they largely reflect the stages of its development (see Fig. 1). From a scientific point of view [17], [14], the evolution of AI goes through three main phases, each of which is accompanied by the achievement of a certain level of capabilities for artificial intelligence (see Fig. 1). The first phase (*Spring* 1940-1979) covers the birth of technology and the golden years of AI, born of the enthusiasm of researchers and inventors. During the second phase (*Summer and Winter* 1980-2010) there is a real boom in the development of technology, and the third phase (*Present* 2011-2022) is related to big data and deep learning [18].

The different evolutionary stages of development of artificial intelligence according to [18] are artificial narrow intelligence (ANI), artificial general intelligence (AGI) and artificial super intelligence (ASI). First-generation narrow artificial intelligence (ANI) is limited to performing a single task and is unable to replicate complex operations characteristic of human intelligence. AGI is designed to mimic human intelligence and behavior and can learn to solve certain problems. ASI are the third generation of the development of the future self-aware machines, surpassing human intellectual capacity and capable of scientific creativity and common wisdom [18].

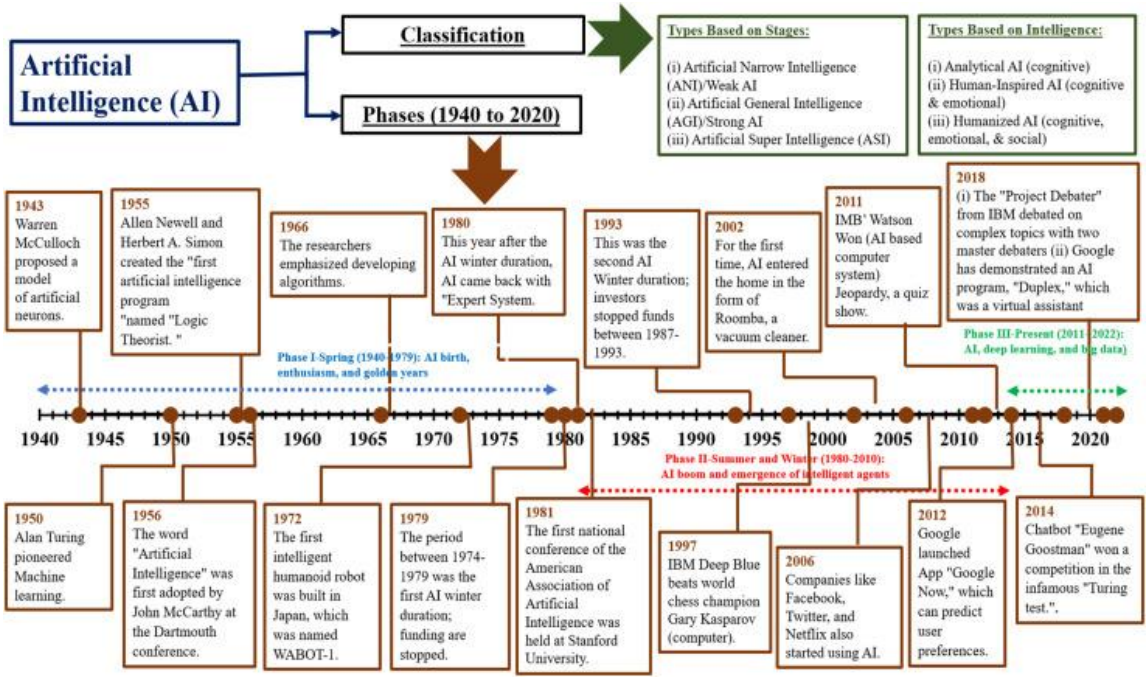


Fig. 1. Artificial Intelligence (AI) History and Phases [18, p.2].

B. Methodology of the research

The present paper aims to trace the historical development of artificial intelligence technologies, using patent statistics as a measure of innovative creativity. In this regard, the object of the research is artificial intelligence and its development. The subject of the study is the patent activity conducted through the Patent Cooperation Treaty in the period 1980-2023.

To achieve the formulated goal, the following tasks have been set:

1. Analysis of patent publications in the field of AI-related technologies for the period 1980-2023.
2. Study of the dynamics of patent activity for the period 1980-2023.
3. Study of patents grants related to AI technologies in the period 2010-2023.
4. Bringing out the leading AI patent holders.
5. Presenting the development of scientific publications in the field of AI.
6. Uncovering the potential problems posed using AI.

We have fulfilled these tasks through patent activity data obtained from the WIPO database [19], as well as from the Center for Security and Emerging Technology [20].

The limitation in this study is caused by the time span for which data on patents applied for and granted are collected and provided. Data on patent activity are not specified by type of AI-related technologies.

The author's research interest in the study of AI is dictated not only by its relevance and growing importance in modern times, but also by the fact that it is able to transform society and our everyday life in an unexpected and unknown direction.

The research presented and the scientific results achieved will enrich research in the field of artificial intelligence and reveal the leading innovative leaders in the field of AI and the role of scientific development in achieving technological progress.

III. RESULTS

A. Analysis of patent publications in the field of AI technologies

The characteristics of artificial intelligence determine unlimited possibilities for its application, which is why WIPO experts, using the Computing Classification Scheme of the Association for Computing Machinery (ACM), define three main categories AI [21]:

- AI techniques: advanced forms of statistical and mathematical models, such as machine learning, fuzzy logic and expert systems, allowing the computation of tasks typically performed by humans; different AI techniques may be used to implement different AI functions.
- AI functional applications: functions such as speech or computer vision which can be realized using one or more AI techniques.
- AI application fields: different fields, areas or disciplines where AI techniques or functional applications may find application, such as

transportation, agriculture or life and medical sciences. [21]

The subsequent analysis of patent publications is tied precisely to the categories thus specified, which provide the framework for AI research. By using keywords and International Patent Classification classifications, the scope of AI technologies on which WIPO collects and processes information is defined [22].

It has been found that patent documents for the protection of artificial intelligence technologies often refer to more than one category of AI (see Fig. 2).

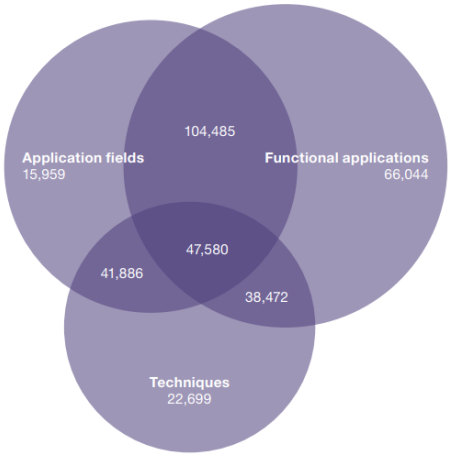


Fig. 2. Patent families related to AI techniques, functional applications, application fields and their overlaps [21, p.40].

According to WIPO data [19], 1,292,086 patent publications in the field of AI were made between 1980 and 2023. Their number is determined on the basis of an equivalent count, according to which each application/patent filed by a national intellectual property office is counted multiple times according to the number of territories on which protection is sought. The dynamics of this activity are presented in Fig. 3.

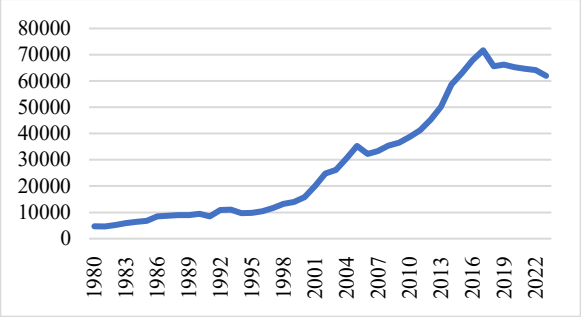


Fig. 3. Dynamics of patent activity in the field of artificial intelligence technologies [19].

The data (see Fig. 3) include information on 143 countries in which the total patent activity from 1980 to 2023 has seen a noticeable increase. From the beginning of the study period in 1980, when 4,754 publications were reported, to 2023, when they reached 61,950 pcs. there is an increase in the issued patent documents, on average by 6.54% per year. These data can be interpreted, on the one hand, as an increase in patent activity (13.03 times in 2023 compared to 1980), and on the other hand, as an extension of the territorial coverage of patent protection.

Of all 143 countries and territories reporting activity from 1980 to 2023 through the Patent Cooperation Treaty, nine countries have the highest concentration of patent documents (see Fig. 4). They form 94.68% of the patent activity established for the period (1,223,385 patent documents out of a total of 1,292,086).

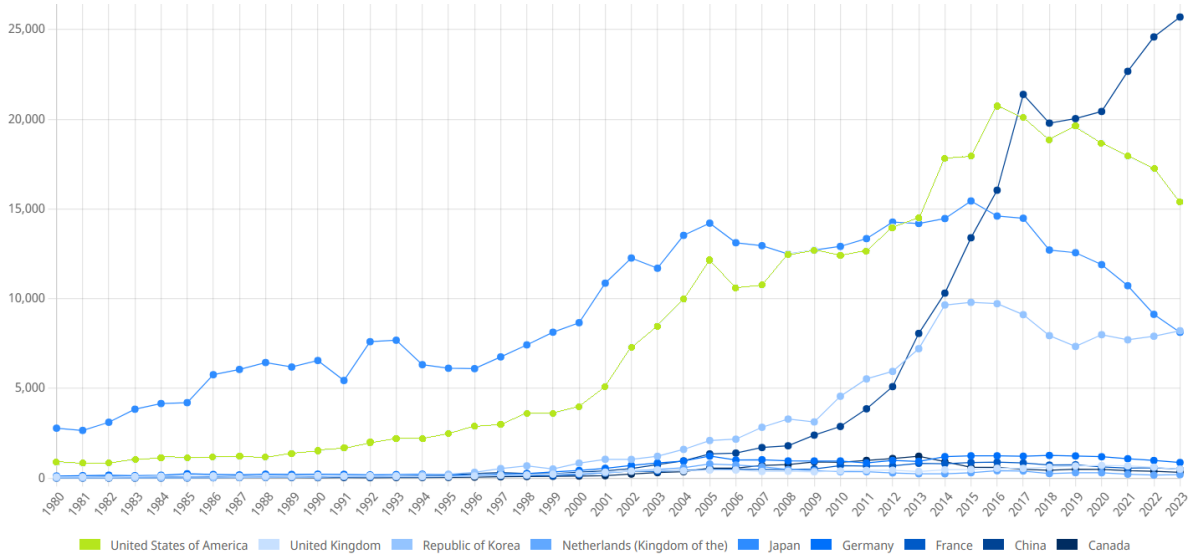


Fig. 4. Dynamics of issued patent documents in the field of artificial intelligence technologies among the top 9 countries [19].

The dynamics of the issued patent documents (see Fig. 4) is indicative of the predominance of inventors and researchers from Japan until 2012 (14,269 documents), when in 2013 they were overtaken by the United States.

The leadership of American scientific developments continued until 2016, and in 2017 a new leader appeared – China, whose researchers remained at the forefront until 2023. Observing the dynamics of the issued patent documents, Japan, the United States, China and South Korea clearly stand out as leaders in the field of technologies related to artificial intelligence.

We draw attention to the fact that not all patent applications end with a positive decision of the examination. Some of them do not receive legal protection due to non-compliance with the criteria for patentability and/or other specific regulatory requirements. There is also the possibility of infringement of other people's patent rights, which is a prerequisite for filing opposition by the owner of earlier rights, lawsuits and mediation.

The follow-up analysis is limited to the time span from 2010 to 2022 to track the trends evolving in the field of AI over the past two decades. Fig. 5 presents data on the number of refused and the number of patents granted to applicants from all over the world seeking legal protection for their technological developments in the field of AI.

The number of AI-related technologies that failed to pass patent examination (128,952) is 2.07 times higher than the patented inventions (62,264). Despite the fact that these technologies are not patented, their existence is sufficiently indicative of the desire of inventors to continue innovative developments in this field.

The emphasis in this work is placed on the issued patents, which illustrate the real and already legally protected achievements of the human mind and creativity. While not every patented invention has the same value and utility in making technological progress in this area, the total number of patents granted is indicative of the drive to develop AI-related technologies.

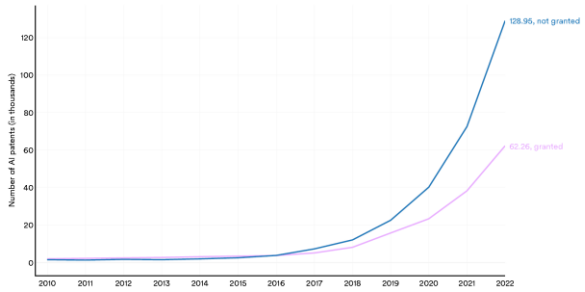


Fig. 5. AI patents by application status, 2010–2022 [23, p.39]

Fig. 6 presents information on the distribution by regions of the issued patents for technologies in the field. Data are represented in % of total AI patents granted globally.

China's leadership (see Fig. 4) undoubtedly has its impact on the distribution of issued patents by region of the world (see Fig. 6), with 75.2% of them attributed to East Asia and the Pacific. The second region is North America (21.21%), and the third Europe and Central Asia lags behind with only 2.33% share. The remaining regions report a contribution of less than 1% of the total activity in the development of AI.

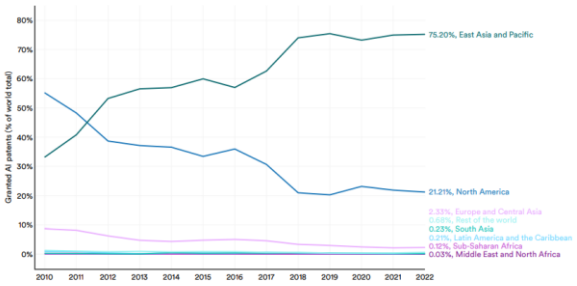


Fig. 6. Granted AI patents (% of world total) by region, 2010–22. [23, p.41]

A different perspective of analysis is presented in Fig. 7. It ranks countries by the number of patents issued for 2022 per 100,000 inhabitants.

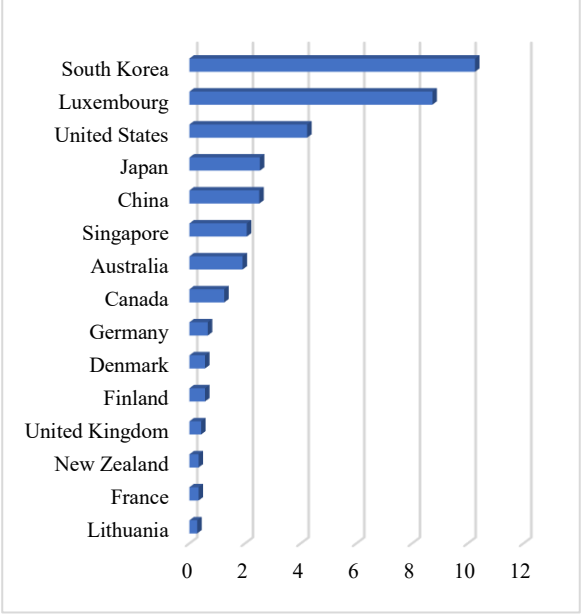


Fig. 7. Granted AI patents per 100,000 inhabitants by country, 2022 [23, p.43]

The ranking (see Fig. 7) in a sense expresses the importance of AI-related technologies for the country concerned and the concentration of inventors in a given field. Of course, countries such as China and the United States with a population of 1.4 billion, respectively and 340.1 million cannot achieve such high productivity as is found in South Korea (51.71 million) and Luxembourg (666,430 people). These data are also indicative of the commitment of the national policy of the countries in the field of scientific developments in certain technological areas, the compliance of the qualification of the employed personnel [24] with the requirements of the new digital age and the quality of the educational system, which is why in the next section of the study we will pay attention to the development of science in the field of artificial intelligence.

B. Analysis of the development of science in the field of artificial intelligence

One of the main factors that has given impetus to the evolution of technologies related to artificial intelligence is the scientific interest in the field. Of course, it dates back to the first mention of the term "artificial intelligence" by Prof. John McCarthy at the 1956 Dartmouth Summer Research Project on Artificial Intelligence [25] and has been growing ever since.

In this paper, we limit ourselves to an analysis of the last thirteen years of the development of scientific interests, using quantitative data to illustrate the dynamics of the publication activity of researchers.

Fig. 8 presents the development of scientific publications worldwide, through a number of articles published in English in journals and reports of international conferences in the field of AI.

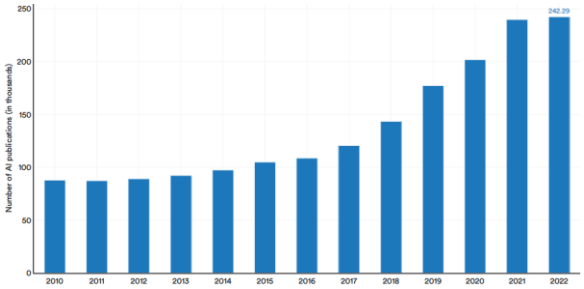


Fig. 8. AI publications in the world, 2010–22 [23, p.31].

As can be seen, the interest of researchers is 2.75 times higher at the end of the period (in 2022 the number of publications was 242,290) compared to its beginning (in 2010, 88,000 scientific studies were published). This is directly related to the expansion of the scope of AI as well as the growing interest in AI technologies, not only scientifically but also practically.

In order to identify the source of scientific publications that is indicative of the field in which AI research is developing, Fig. 9 presents the distribution of scientific publications by sectors.

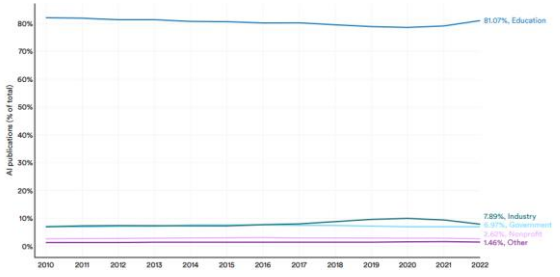


Fig. 9. AI publications (% of total) by sector, 2010–22 [23, p.34].

Globally (see Fig. 9), there is a significant predominance of research and publications carried out in the Education sector (81.07%) compared to those in other sectors: Industry (7.89%); Government (6.97%); Non-governmental sector (2.62%); Others (1.46%) [19, p.34]. These data support the view expressed above that it is the growing scientific interest in the field of AI that gives impetus to the technological development of the field.

Looking at the activity of LEADING countries and territories in the field of AI (see Fig. 10), there is again a predominance of publications made by the education sector over other sectors in each of the analyzed economies.

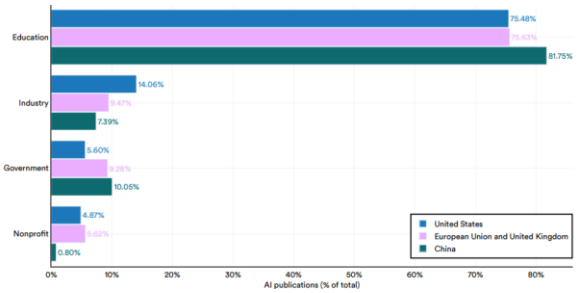


Fig. 10. AI publications (% of total) by sector and geographic area, 2022 [23, p.35].

Although limited in terms of the time span of the presented data and their nature, the current analysis of the scientific publications published in the period 2010-2022 presents them as an early indicator of technological developments in the field. Research reflects the existing societal needs at a given time and helps to solve them, as a result of which the efforts of inventors are directed towards the creation of fundamental innovative technologies.

IV. DISCUSSION

The data on patent activity in the field of AI-related technologies reviewed so far are the result of the overall efforts and policies of the listed countries in the field of development and absorption of new technologies. The increased interest of researchers and industry in the field of computer technologies in recent decades has provoked the opening of new educational programs in secondary and higher schools to prepare and create competent and motivated computer specialists [26]. Cooperation between business and science also contributes to transforming scientific knowledge into innovative and meaningful developments [27].

Increasing research into AI in modern times is fueled by its advantages of replacing some of the human activities by performing complex and time-consuming operations, supporting the decision-making process and providing informed solutions to remedy problems. But the widespread use and application of technologies in which AI is implemented and which are part of our daily lives, even if we do not realize it, are transforming our lives as we know it. And if innovations in artificial intelligence systems and advances in robotics have contributed to the development of a number of technological areas, then the existing threats should not be ignored.

Part of the problems related to AI are rooted in the misuse and unethical use of the technologies in which it is implemented. The AI Incident Database (AIID) [28] tracks cases of AI misuse, and according to their data, as the application of AI expands, cases of incidents also increase. From 2013 to 2023, there was a more than 20-fold increase

in incidents, reaching 123 in 2023. These incidents are a consequence of the risks posed by the development and use of artificial intelligence. A survey conducted by researchers [23] among 1000 organizations from all over the world developing and using AI technologies shows that the highest risk is the confidentiality of the data used and its unlawful dissemination (see Fig. 11).

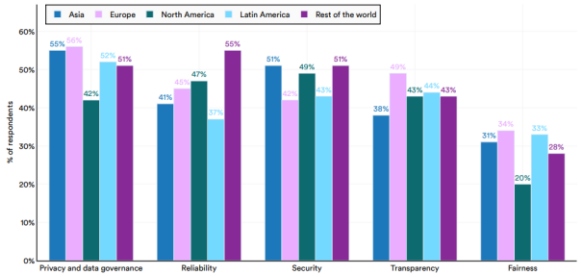


Fig. 11. Relevance of selected responsible AI risks for organizations by region [23, p.166].

Another risk of the development of AI technologies is their reliability and security of use. These threats were reported as the second and third most important among company leaders in Asia and North America. A significant percentage of respondents fear transparency in the development of these technologies (49% of respondents in Europe and 44% of those in Latin America), and the least accounted for is the risk of fair use of AI-related technologies [23].

Apart from this study, society faces the following threats regarding the use of AI:

- inability to understand the logic and mechanism of action of AI, which gives rise to distrust in the results obtained.;
- replacing human resources from robotic technologies with AI;
- continuous and unregulated surveillance of people through intelligent systems integrated into the urban environment, which creates fear for their privacy and security;
- developing dependence on AI technologies, which leads to limiting people's creative thinking and capacity to cope with routine tasks;
- the unethical use of AI can lead to disinformation and manipulation of public opinion.

In summary of the analysis prepared so far, we should note that any technological development based on striving to improve and increase the quality of life of people, in accordance with the ethical and moral values of society, needs to be stimulated and encouraged. But going beyond the human moral framework of developing AI-related technologies and providing them with unlimited and uncontrollable opportunities for self-improvement poses risks to people's lives and futures.

V. CONCLUSIONS

Through this paper, we have looked at the historical development of AI, referring to data on patent activity in the field of computer technology. As a consequence of the analysis prepared, we can point out that technologies related to AI are the new reality to which society needs to get used to. The leaders in the development of AI (China, USA, Japan, South Korea, Germany, Great Britain, the Netherlands, France and Canada), forming 94.68% of the patent activity established for the period (1,223,385 patent documents out of a total of 1,292,086), predetermine the development trends and areas of practical application of AI. In this regard, it can be said that these are the countries that will be the first to gain a competitive advantage through the applied innovative technologies. At the same time, they also stimulate the innovative development of other countries and contribute to the diffusion of AI.

In the current study, we found that researchers' interest increased 2.75 times at the end of the analyzed period (in 2022, the number of publications was 242,290) compared to 2010 (88,000 published scientific studies), which proves the expansion of the scope of application of AI, both by the scientific community and by practice. The predominance of the education sector (81.07%) in the development of specialized publications in the field of AI indicates that the Industry sector and the Government sector are still insufficiently engaged in studying the specifics and opportunities for application of AI.

Greater awareness of the possibilities of AI among individual communities would contribute to removing existing prejudices and limiting the possible misuse of AI technologies.

ACKNOWLEDGMENT

This article was published with the financial support of Technical University of Gabrovo, Bulgaria under project NIP2025-8 “Development and approbation of a methodology for implementation and evaluation of innovation strategies in business organizations”.

REFERENCES

[1] P. A. Freiberger and M. R. Swaine, "Atanasoff-Berry Computer". Encyclopedia Britannica, 20 Mar. 2023, https://www.britannica.com/technology/Atanasoff-Berry-Computer [Accessed February 18, 2025]

[2] N. Nikolova, “Industry 4.0 - development and consequences for sustainable development of Bulgaria”, ETR, vol. 3, pp. 245–251, Jun. 2021, [Accessed February 01, 2025] https://doi.org/10.17770/etr2021vol3.6543

[3] B. Hiremath, and A. Y. Kenchakkanavar. "A Historical Perspective on Artificial Intelligence: Development, Challenges and Future Directions." Journal of Advances in Library and Information Science 14.1, pp. 68-75, 2025.

[4] M. Garcia-Murillo and I. MacInnes, “The impact of AI on employment: a historical account of its evolution”, 30th European Conference of the International Telecommunications Society (ITS): "Towards a Connected and Automated Society", Helsinki, Finland, 16th-19th June, 2019, International Telecommunications Society (ITS), Calgary, 2019.

[5] R. Hirani, K. Noruzi, H. Khuram, A.S. Hussaini, E.I. Aifuwa, K.E. Ely, J.M. Lewis, A.E. Gabr, A.Smiley, R.K. Tiwari, et al. “Artificial Intelligence and Healthcare: A Journey through History”, Present Innovations, and Future Possibilities. Life, 14, 557, 2024. [Accessed April 24, 2025] https://doi.org/10.3390/life14050557

[6] K. A. N. Hassan, A. E. Khalid, and M. H. Kamel. "The Historical Evolution of Artificial Intelligence Technology in Cinema." International Design Journal 15.3, pp. 485-488, 2025.

[7] J. F. Allen, "Natural language processing". In A. Ralston, E. D. Reilly, & D. Hemmendinger (Eds.), Encyclopedia of computer science (4th ed., pp. 1218–1222). Wiley, 2003.

[8] G. W. Ng and W. C. Leung, "Strong artificial intelligence and consciousness," Journal of Artificial Intelligence and Consciousness, 7(1), pp. 63–72, 2020. [Accessed February 15, 2025] https://doi.org/10.1142/S2705078520300042

[9] S. Russell and P. Norvig, (Eds.). Artificial intelligence: A modern approach (4th ed.). Pearson Education Inc., 2022.

[10] A. Wölker and T. E. Powell, "Algorithms in the newsroom? News readers' perceived credibility and selection of automated journalism," Journalism, 22(1), pp. 86–103, 2021. [Accessed February 05, 2025], https://doi.org/10.1177/1464884918757072

[11] M. F. de Lima-Santos and W.Ceron, "Artificial intelligence in news media: Current perceptions and future outlook," Journalism and Media, 3(1), 13–26, 2021. [Accessed February 10, 2025], https://doi.org/10.3390/journalmedia3010002

[12] M. L. Minsky, Semantic information processing. Cambridge, MA: MIT Press, 1986.

[13] R. Kurzweil, The Age of Spiritual Machines: When Computers Exceed Human Intelligence. New York: Viking Press, 1990.

[14] M. Haenlein and A. Kaplan "A brief history of artificial intelligence: On the past, present, and future of artificial intelligence," California Management Review, 61(4), 5–14. 2019. [Accessed December 05, 2024], https://doi.org/10.1177/0008125619864925

[15] J. Frankenfield, "Artificial neural Network (ANN)". 2020 Retrieved May 05, 2024, from https://www.investopedia.com/terms/a/artificial-neural-networks-ann.asp.

[16] Gil de Zúñiga, M. G. Homero and T. Durotoye "A scholarly definition of artificial intelligence (AI): advancing AI as a conceptual framework in communication research." Political communication, 41.2, 2024, pp. 317-334.

[17] R. Anyoha, "The History of Artificial Intelligence," 2017, August 28, Retrieved January 04, 2025, from https://sitn.hms.harvard.edu/flash/2017/history-artificial-intelligence/

[18] S. Bahoo, M. Cucculelli, D. Qamar, "Artificial intelligence and corporate innovation: A review and research agenda," Technological Forecasting and Social Change, Volume 188, 122264, ISSN 0040-1625, 2023, [Accessed February 05, 2025], https://doi.org/10.1016/j.techfore.2022.122264

[19] WIPO IP Statistics Data Center, [Online]. Available at: https://www3.wipo.int/ipstats/ips-search/trademark

[20] Center for Security and Emerging Technology, [Online]. Available at: https://cset.georgetown.edu/

[21] WIPO, WIPO Technology Trends 2019: Artificial Intelligence. Geneva: World Intellectual Property Organization. ISBN: 978-92-805-3007-0, 2019. Available: WIPO, https://www.wipo.int/edocs/pubdocs/en/wipo_pub_1055.pdf [Accessed January 23, 2025]

[22] WIPO Technology Trends 2019: Artificial Intelligence. Data collection method and clustering scheme. Background paper. Geneva: World Intellectual Property Organization. 2019. Available: WIPO, https://www.wipo.int/documents/d/technology-trends/docs-en-techtrends_ai_methodology.pdf [Accessed Jan. 23, 2025]

[23] N. Maslej, L. Fattorini, R. Perrault, V. Parli, A. Reuel, E. Brynjolfsson, J. Etchemendy, K. Ligett, T. Lyons, J. Manyika, J. C. Niebles, Y. Shoham, R. Wald, and J. Clark, "The AI Index 2024 Annual Report," AI Index Steering Committee, Institute for Human-Centered AI, Stanford University, Stanford, CA, April 2024. [Online] Available: https://aiindex.stanford.edu/wp-content/uploads/2024/05/HAI_AI-Index-Report-2024.pdf [Accessed Feb. 15, 2025]

[24] N. Nikolova, "Development of a system for assessment of digital professional suitability in the company environment", ETR, vol. 3, pp. 211–216, Jun. 2024, [Accessed February 01, 2025], https://doi.org/10.17770/etr2024vol3.8136

[25] C. Manning, Artificial Intelligence Definition, Stanford University Human-Centered Artificial Intelligence. v 1.2, April 2022. [Online]. [Accessed February 02, 2025] https://hai.stanford.edu/sites/default/files/2023-03/AI-Key-Terms-Glossary-Definition.pdf

[26] N. I. Nikolova, "Human capital in the changing work environment of Industry 4.0", ETR, vol. 3, pp. 187–193, Jan. 2024, [Accessed February 12, 2025] https://doi.org/10.17770/etr2023vol3.7177

[27] D. Petrova, "Intelligent, innovative and sustainable industry in Bulgaria – prospects and challenges", ETR, vol. 1, pp. 210–215, Jun. 2019. [Accessed February 18, 2025] doi: 10.17770/etr2019vol1.4188.

[28] The AI Incident Database (AIID) [Online]. https://incidentdatabase.ai/ [Accessed February 20, 2025]

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 251-255

Vegetation Realistic Visualization in Virtual Reality Scenarios

Laura Ozoliņa
Vidzeme University of Applied Sciences
Valmiera, Latvia
laura.ozolina15@va.lv

Arnis Cīrulis
Vidzeme University of Applied Sciences
Valmiera, Latvia
arnis.cirulis@va.lv

Lauris Taube
Vidzeme University of Applied Sciences
Valmiera, Latvia
lauris.taube@va.lv

***Abstract*-This paper focuses on optimizing realistic 3D vegetation models for standalone virtual reality experiences considering the visualization of the plant growth over time. Most of the existing solutions are focusing on personal computer based virtual reality utilization, which allows for more computational power, yet it restricts the movement of the user. Experiences meant for standalone virtual reality headsets mainly feature low-poly and unrealistic plant representations. Since plants, especially trees, can be rather complex structures it is important to find a balance between realistic depiction and performance. By achieving this it would allow the headset user to have better immersion in the virtual world and would reduce the risks of cybersickness. To test and find out the most appropriate solution we created a 3D model of an apple tree and its growth animation in SpeedTree software and then created a scene of varying numbers of trees using Unreal Engine 5.3 and tested framerate count using Meta Quest 2 and OVR Metrics tool. Tests were split into two big groups – static mesh tests, where we observed the changes in framerate before and after optimizing and skeletal mesh tests, where framerate changes were noted as the tree growth animation was running. The results of the tests showcased that it might be difficult to visualize growth process of the plants by using animated models, since their performance was way below the target rate for the headset, while using static meshes and swapping the models over time to simulate growth yielded a better framerate.**

Keywords*— *performance optimization, standalone virtual reality, vegetation visualization, virtual reality.

I. Introduction

As of now virtual reality has a wide range of uses, such as entertainment, education, art and so on. Unlike the classic way where the virtual worlds are experienced through computer screens, virtual reality has been able to provide a higher level of immersion by considering the user's body and hands [1]. Virtual reality can also be experienced by people with mobility issues by using flexible and adaptive control schemes [2]. However, it is important to note that there are two main ways how virtual reality can be experienced and there are noticeable differences between them. One of the options is PCVR which stands for personal computer based virtual reality, where virtual headset is tethered to a computer and uses it for rendering and calculations. While this way allows the use of more complex objects and shaders within the environment it also restricts the movement of the user, since the headset needs to be connected to the computer. Standalone VR fixes this concern, but new ones arise – standalone headsets have less computational power.

One of the metrics that can be used to compare headset performance against a computer is FLOPS, which stands for floating-point operations per second [3]. This measure plays a vital role in three-dimensional scene rendering and higher FLOPS would provide more realistic and complex graphics and make the experience smoother and engaging [4]. For example, most sold headset, as of now, Meta Quest 2 [5] uses Adreno 650 GPU which offers approximately 1250 gigaflops [6], meanwhile NVIDIA GeForce RTX 4090 can provide 82600 gigaflops [7], which 66 times more than Quest 2. This means that it might be complicated to render realistic and complex geometry in standalone devices.

One of the most complex geometries to render are trees since they consist of a trunk, multiple branches and countless leaves, which all together increase the polygon count of the object and make rendering of multiple meshes a challenging ordeal [8]. There is previous research available regarding the improvement of tree rendering in virtual reality, but most of these papers focus on tethered headsets. It is also important to note that there is a distinct lack of research done regarding vegetation simulation in a timescale, which would help to showcase the growth of the vegetation after a certain time based on various factors,

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8584
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

such as light intensity, proximity to other vegetation, etc. Such visualizations could prove useful in botanic garden education, allowing future professionals to experiment with gardening and get predictions of how the garden would look in the future. It has been proven before that use of virtual and augmented reality in education can enhance learning and memory of the students and improve their social and collaborative skills [9]. Virtual gardens could help to improve human wellbeing. A short walk through a virtual forest can improve the emotional state of young adults and seniors who may not have a chance to explore the real environment due to sickness or restrictions, such as ones imposed during the Covid-19 pandemic [10]. Urban landscaping also could benefit from such visualizations, since it would allow for a long-term planning and management of tree planting initiatives, which can prove to be rather challenging due to environmental conditions in the cities and the maintenance, which may negatively impact the growth of the tree [11]. Thus, a virtual reality solution which could not only visualize various types of vegetation but also could showcase the growth of it over a time would prove to be useful in many areas.

The purpose of this study is to develop a methodology which would allow to efficiently visualize changes in plants over a time in a virtual reality scenario for a standalone device while considering the performance and visual fidelity of the environment.

We propose a hypothesis that by combining optimizing techniques, such as instancing and level of detail, it is possible to enable realistic vegetation visualization in standalone virtual headsets and keep visual fidelity and optimal performance.

A. *Plant generation techniques*

Historically there are multiple available algorithms which have been used to procedurally generate various types of vegetation, such as L-system, also known as Lindenmayer system, which uses grammar-based system and iterative rules [12]. A space colonization algorithm, where plant growth starts from the root and reaches towards attraction points, competing for space [13]. Even though space colonization algorithm can provide the end user with a tree, which has a desired shape, L-system algorithm will be able to create multiple trees faster. Despite the differences, both algorithms can be used to generate trees for various cases [14].

As it can be seen there is a decent amount of research done regarding vegetation modelling in three dimensional environments, yet very little can be found about the vegetation asset suitability for virtual reality scenarios. An approach has been proposed, which allows to generate multiple trees with similar branch patterns and uses LOD based optimization method to change the complexity of the models based on distance [15]. Nevertheless, very little is known about the performance of the generated tree models in a standalone virtual reality headset. Another solution was offered by allowing users themselves to create 3D trees in virtual reality by combining procedural modelling and allowing for a user input in virtual reality, such as sculpting and editing the geometry and using silhouette-based modelling [16]. A rather similar idea was presented where using L-systems and sketch-based modelling could allow users to avoid the learning curves which comes with classic tree modelling software and create simple tree models in virtual reality more efficiently [17].

The techniques mentioned before can help their users to experiment and create their own tree models, yet they do not guarantee how well they would perform on mobile devices and in virtual reality. It is important to further delve into techniques, which could help improve the usability of the 3D models in virtual reality.

B. *Asset optimization for virtual reality*

While previously mentioned studies were carried out in virtual reality environments, some of them still relied on external computational power and only used headsets to access the environment. This makes it hard to predict how well the created vegetation models will perform in a standalone device. There are multiple factors that need to be considered when optimizing 3D assets for virtual reality headsets.

One of them is the polygon count of the 3D model. By keeping the polygon count as low as possible it will help to reduce the count of calculations needed to render the object [18]. As of now according to Meta documentation Quest 2 can handle from 750000 to 1.8 million polygons per frame, but Quest 3 – 1.3 million to 1.8 million [19]. Yet even though a smaller number of polygons could help to keep the experience smooth it also can make the object appear less detailed and thus less realistic. Still, it may not apply to all 3D objects and it has been found that both position of the object in the scene and the original polygon count of the mesh could impact user perception of the mesh, noting that for meshes with more than 100000 vertices it is possible to remove up to 95% of them and it would not significantly affect the perception [20].

Alongside polygon count an important metric is the draw calls, which happen whenever GPU receives meshes and materials for drawing. Actions, like spawning meshes, changing materials can impact performance if not optimized properly. It is crucial to keep draw calls as low as possible to retain an acceptable framerate [21]. One of the ways it can be

achieved is by combining meshes into one, although it can be done only before the application is built, so to make the approach more adaptable a GPU instancing can be applied, which allows GPU to render one mesh with multiple transforms at once [22].

Materials and textures also play a big part in VR experiences, and it has been studied before that the users are way more perceptive of the material properties in virtual reality viewing mode than when the materials were

observed through a computer screen [23]. Optimizing them also can improve the performance of the experience. Just like meshes, each material that needs to be rendered would cost a draw call, so trying to keep material count as low as possible or making multiple 3D assets share one material can help lower the performance load [24]. Similar principle could be applied to textures and one of the most used techniques to keep texture count low and optimize performance is to use texture atlases, which are images made up from multiple smaller images [25].

By focusing on these factors, it could help to improve the performance of the 3D assets. Beyond optimizing static 3D assets, dynamic elements such as vegetation growth play a vital role in enhancing realism in virtual environments.

C. Vegetation growth over time period

There are many commercial solutions available, like garden simulation games and experiences, which can visualize changes in vegetation, only a small number of them are meant for virtual reality headsets. For example, Potioneer: The VR Gardening Simulator is an early access game, yet it is only available for PCVR, and the plant growth visualization is very simplified – plant mesh gets scaled up until it resembles a fully grown plant [26]. At Meta Connect 2022 Meta unveiled their open-source meditative gardening experience for WebXR called Project Flowerbed. Just like Potioneer, Project Flowerbed also contained simplified plant meshes and similar growth mechanics which were not accurate to real life [27]. A visually more realistic experience was created by Greener Games called Nature Trek VR, where, just like previously mentioned games, user can plant vegetation and immerse themselves into the scenario [28]. While those experiences can prove to be entertaining and even yield positive results regarding mental wellbeing, they rarely mimic real-life visuals, especially when time factor is being considered. It can be rather challenging to depict realistic plant visuals, especially for a standalone device, so in the next chapter we investigate ways how to make scenarios like these more doable.

II. MATERIALS AND METHODS

A. Virtual reality scene creation

To test the possible gains regarding optimization of plant meshes a realistic apple tree model and its growth animation were created using SpeedTree software. There the number of vertices was reduced to an acceptable amount, at the same time making it certain that the model does not lose its visual fidelity.

To test the model before and after optimization a simple virtual reality scene was created using Unreal Engine 5.3 and the scene was tested using Meta Quest 2 headset and the performance metrics were gained using OVR Metrics Tool.

A simple virtual reality scene was created consisting of ground and sky, with dynamic lighting turned off. Multiple tests were run, each of them featuring a different number of trees, which were arranged in a grid (See Fig.1). Even though it's possible that in real time such an arrangement might be unlikely, to stress test the model and keep the object placement consistent we chose to use this approach.

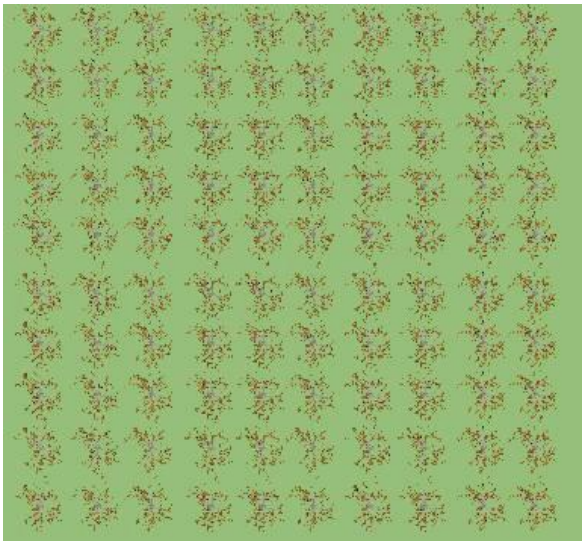


Fig. 1. Top view of the arranged apple tree models.

B. Testing the model performance

The tests were divided into two groups – one of them tested the performance of static tree models, which do not change their geometry at runtime, while the other focused on skeletal tree meshes, which can change their geometry. For the static model a fully grown representation of apple tree was used, which is the most complex one, while in skeletal meshes a growth animation was being played.

For the first test 30 static apple tree meshes were placed in the scene, each of them being rendered separately by the engine. Models were not further optimized in the engine and were kept the same as they were when they got imported into the project. No LOD methods were applied, which meant that the polygon count of the mesh would remain unchanged despite the distance from the camera. We then ran the test two more times with 50 trees and after that with 100 trees.

In the next testing phase instead of using separate meshes an instancing was used, which combined all the meshes into one entity. In Unreal Engine that was done by utilizing Hierarchical Instanced Static Mesh component, which would allow us to later combine this method with LOD usage [29]. Just like before, we run the tests with 30, 50 and 100 trees. For the last test we used both instancing and LOD. Four LODs were generated, where the most complex one consisted of 30643 triangles and the least complex one of 3831 triangles (See Fig. 2).



Fig. 2. LOD models of the apple tree. To left – the highest complexity model, to right – the least complex model.

For the tree animations we had two tests – one with two trees and the other one with ten trees. Here we took notice of the framerate when the animation was playing and when it was stopped.

III. RESULTS AND DISCUSSION

Running the scene with 30 static meshes on the headset showed that the average number of frames per second was 50 which is 30.56% less than what is recommended for Meta Quest 2, where interactive applications should achieve 72 frames per second [19]. In the next test with 50 trees, we noticed that the frames dropped by approximately 20% when comparing to the previous test. In the last test where 100 trees were rendered the number of frames remained around 25 and compared to the second test the difference between results had reached 33%. The results show that these unoptimized models cannot reach the target framerate of 72 and by adding more trees the performance would only decrease (See Table 1).

TABLE 1 FRAMERATE FOR STATIC TREES BEFORE AND AFTER USING INSTANCING AND LOD

Number of trees	Framerate before instancing and LOD, fps	Framerate when using instancing only, fps	Framerate when using both instancing and LOD, fps
30	50	72	72
50	40	50	70
100	25	45	55

The next tests using instancing yielded an improved framerate. The test with 30 trees had reached the recommended amount of 72. Then, the number of trees was changed to 50 and frame count decreased by 29%. Furthermore, after we increased the number of trees to 100, the frame count was approximately 45.

In the last phase of testing the static meshes, where both instancing and LOD was applied it was noted that this approach proved to be the most effective, since as seen in Table 1 the framerate is acceptable for up to 50 trees and for 100 trees the difference from the optimal framerate is 26%.

It can be noticed, that by increasing tree count the performance drops (see Fig. 3) even when both optimization techniques have been applied. Still, the performance drop is less rapid than the one which happens without any optimization applied.

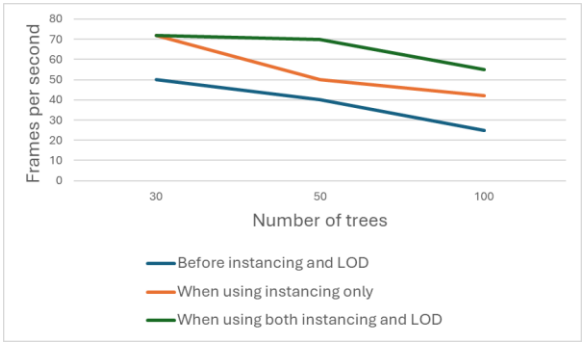


Fig. 3. Performance comparison for varying tree count with different levels of optimization applied.

The animated tree models performed rather poorly, and the framerate neared the target framerate only when the animation on the models was paused. The results are shown in Table 2.

TABLE 2 FRAMERATE FOR ANIMATED TREES WHEN ANIMATION IS RUNNING AND WHEN IT IS PAUSED

Number of trees	Framerate when animation is played, fps	Framerate when animation is paused, fps
2	45	70
10	28	65

IV. CONCLUSIONS

The gained results show that it can be rather challenging to optimize tree models for standalone virtual reality applications, especially if one wishes to visualize tree growth over time. As we saw in Table 2, where we observed the changes in the framerate when the tree was being animated, and its geometry became more complex, the end performance might not be acceptable as it is way below the target framerate for Meta Quest 2 headsets. It is easy to notice that by increasing the number of trees the performance becomes worse, thus it may cause the loss of immersion and overall discomfort for the end user.

We can see in Table 1 that the performance for static meshes when combined with various optimization techniques proves to be better than the animated counterparts. To showcase the growth of the tree we propose the idea of generating multiple static meshes from the animated tree file and swapping them to show the changes in the vegetation. By applying instancing and LOD it is possible to keep the performance at an acceptable level if no more than fifty trees are being rendered. While these results support the hypothesis, further studies are needed to evaluate how the methodology performs with different types of vegetation or on newer generations of VR hardware. Also, further tests with an increased number of trees would be fruitful.

V. ACKNOWLEDGMENTS

The authors would like to express gratitude to Socio-technical systems engineering institute of Vidzeme University of Applied Sciences for the grant funding "Sociotehnisko sistēmu inženierijas institūta grants.", project name "Veģetācijas reālistiska vizualizācija virtuālās realitātes scenārijos." to make this study possible.

We also want to thank for the received information and support to Institute of Horticulture.

REFERENCES

[1] M. Slater, "Immersion and the illusion of presence in virtual reality," British Journal of Psychology, vol. 109, no. 3, pp. 431–433, 2018, doi: https://doi.org/10.1111/bjop.12305.

[2] K. Gerling, P. Dickinson, K. Hicks, L. Mason, A. L. Simeone, and K. Spiel, "Virtual Reality Games for People Using Wheelchairs", in Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, Honolulu, HI, USA, 2020, pp.1–11 https://doi.org/10.1145/3313831.3376265.

[3] Indiana University, "Understand measures of supercomputer performance and storage system capacity-IUKB," 2016. [Online] Available: https://servicenow.iu.edu/kb?id=kb_article_view&sysparm_article=KB0023145 [Accessed: November 22, 2024]

[4] Lenovo, "The Importance of FLOPS and its Impact on Your PC's Speed and Efficiency | Lenovo US," 2021. [Online] Available: https://www.lenovo.com/us/en/glossary/flops/ [Accessed: November 22, 2024]

[5] T. Alsop, "VR headset unit sales worldwide 2024," Statista, 2021. [Online] Available: https://www.statista.com/statistics/677096/vr-headsets-worldwide/ [Accessed: November 22, 2024]

[6] D. Heaney, "So Just How Powerful Is Oculus Quest 2, Really?," UploadVR, 2020. [Online] Available: https://www.uploadvr.com/oculus-quest-2-benchmarks/ [Accessed: November 22, 2024]

[7] A. Bradley, "The best graphics card in 2019," PCgamer, 2019. [Online] Available: https://www.pcgamer.com/the-best-graphics-cards/ [Accessed: December 1, 2024]

[8] Q.-L. Zhang and M.-Y. Pang, "A Survey of Modeling and Rendering Trees," Lecture Notes in Computer Science, pp. 757–764, 2008, doi: https://doi.org/10.1007/978-3-540-69736-7_80.

[9] G. Papanastasiou, A. Drigas, C. Skianis, M. Lytras, and E. Papanastasiou, "Virtual and augmented reality effects on K-12, higher and tertiary education students' twenty-first century skills," Virtual Reality, vol. 23, no. 4, Aug. 2019, doi: https://doi.org/10.1007/s10055-018-0363-2.

[10] S. H. M. Chan, L. Qiu, G. Esposito, K. P. Mai, K.-P. Tam, and J. Cui, "Nature in virtual reality improves mood and reduces stress: evidence from young adults and senior citizens," Virtual Reality, vol. 27, Nov. 2021, doi: https://doi.org/10.1007/s10055-021-00604-4.

[11] J. M. Vogt, S. L. Watkins, S. K. Mincey, M. S. Patterson, and B. C. Fischer, "Explaining planted-tree survival and growth in urban neighborhoods: A social–ecological approach to studying recently-planted trees in Indianapolis," Landscape and Urban Planning, vol. 136, pp. 130–143, Apr. 2015, doi: https://doi.org/10.1016/j.landurbplan.2014.11.021.

[12] P. Prusinkiewicz and A. Lindenmayer, The algorithmic beauty of plants. Berlin, Heidelberg: Springer-Verlag, 1990.

[13] A. Runions, B. Lane, and P. Prusinkiewicz, Modeling Trees with a Space Colonization Algorithm. The Eurographics Association, 2025. [Online].Available: https://doi.org/10.2312/NPH/NPH07/063-070 [Accessed: December 1, 2024]

[14] H. Nuic and Z. Mihajlovic, "Algorithms for procedural generation and display of trees," 2019 42nd International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO), pp. 230–235, May 2019,doi: https://doi.org/10.23919/mipro.2019.8757140.

[15] J. Kim, "Modeling and Optimization of a Tree Based on Virtual Reality for Immersive Virtual Landscape Generation," Symmetry, vol. 8, no. 9, p. 93, Sep. 2016, doi: https://doi.org/10.3390/sym8090093 .

[16] Z. Liu et al., "Interactive Modeling of Trees Using VR Devices," 2019 International Conference on Virtual Reality and Visualization (ICVRV), pp. 69–75, Nov. 2019, doi: https://doi.org/10.1109/icvrv47840.2019.00020.

[17] M. Steiner, "Sketch based L-systems for tree modeling in virtual reality" M.S. thesis. Vienna University of Technology, Vienna, 2023.

[18] R. Leskovsky, E. Kucera, O. Haffner, Jakub Matisak, D. Rosinová, and E. Stark, "A Contribution to Workplace Ergonomics Evaluation Using Multimedia Tools and Virtual Reality," Federated Conference on Computer Science and Information Systems, Sep. 2019, doi: https://doi.org/10.15439/2019f292.

[19] Meta. "Meta Developers," 2024. [Online] Available: https://developers.meta.com/horizon/documentation/unity/unity-perf/ [Accessed: January 19, 2025]

[20] D. V. Nguyen, T. T. Hien, and T. T. Huong, "A Subjective Quality Evaluation of 3D Mesh With Dynamic Level of Detail in Virtual Reality," 2024 IEEE International Conference on Image Processing (ICIP), pp. 1225–1231, Oct. 2024, doi: https://doi.org/10.1109/icip51287.2024.10647962.

[21] Meta. "Meta Developers," 2024. [Online] Available: https://developers.meta.com/horizon/documentation/unity/po-draw-call-analysis/ [Accessed: January 28, 2025]

[22] Y. S. Sadek Hosny, M. A.-M. Salem, and A. Wahby, "Performance Optimization for Standalone Virtual Reality Headsets," 2020 IEEE Graphics and Multimedia (GAME), Nov. 2020, doi: https://doi.org/10.1109/game50158.2020.9315059.

[23] M. Niu and C.-H. Lo, "Effects of Roughness and Texture on Surface Material Perception in Virtuļa Environments: The Psychophysics Approach," International Conference on Computational & Experimental Engineering and Sciences, vol. 24, no. 1, pp. 1–3, 2022, doi: https://doi.org/10.32604/icces.2022.08669.

[24] S. Sukaridhoto, A. L. Haz, E. D. Fajrianti, and R. P. N. Budiarti, "Comparative Study of 3D Assets Optimization of Virtual Reality Application on VR Standalone Device," International Journal on Advanced Science, Engineering and Information Technology, vol. 13, no. 3, pp. 999–1008, Jun. 2023, doi: https://doi.org/10.18517/ijaseit.13.3.18375.

[25] M. Oksanen, M. "3D interior environment optimization for VR" B.S. thesis. Turku University of Applied Sciences, Turku, 2022.

[26] Focus on Fun Games. Potioneer: The VR Gardening Simulator [VR game], 2016.

[27] Meta. Project Flowerbed [WebXR game], 2022.

[28] J. Carline. Nature Treks VR. [VR game]. Greener Games, 2018.

[29] Epic Games. "Instanced Static Mesh Component in Unreal Engine | Unreal Engine 5.5 Documentation | Epic Developer Community," Epic Games Developer, 2025. [Online] Available: https://dev.epicgames.com/documentation/en-us/unreal-engine/instanced-static-mesh-component-in-unreal-engine [Accessed: February 5, 2025]

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 257-263

Neuroplasticity and Digital Tools in Lifelong Learning: Cognitive Challenges and Opportunities

Olha Palamarchuk
Department of Psychology and Social Work
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
ORCID: 0000-0002-6783-8380
olha.palamarchuk@vspu.edu.ua

Iryna Haba
Department of Psychology and Social Work
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
ORCID: 0000-0003-4606-4504
iryna.haba@vspu.edu.ua

Halyna Shulha
line 2: *dept. name of organization (of Affiliation)*
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
ORCID: 0000-0003-3402-1494
halyna.shulha@vspu.edu.ua

Anna Khilya
Sistemas Microinformáticos y Redes IES IFACH,
Department of Primary Education
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Calp, Spaine
ORCID: 0000-0002-1287-2901
annkhi@alu.edu.gva.es

Irina Sarancha
Department of Psychology and Social Work
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
ORCID: 0000-0002-5715-6271
iryna.sarancha@vspu.edu.ua

***Abstract*— Neuroplasticity plays a crucial role in lifelong learning (LLL), particularly in supporting cognitive adaptability and resilience in older adults. The integration of digital learning tools has introduced new opportunities for enhancing memory, attention, and cognitive flexibility. This study explores the impact of gamification, adaptive learning platforms, and AI-driven education on neuroplasticity, emphasizing their role in maintaining cognitive functions and fostering engagement. The research examines how digital learning environments, including language apps (e.g., Duolingo), MOOCs (e.g., Coursera, Khan Academy), and virtual simulations, contribute to cognitive stimulation. While these tools provide increased accessibility and engagement, challenges such as digital stress, motivation fluctuations, and information overload remain key concerns. The study further investigates how self-regulation strategies and structured learning environments can optimize digital education for older learners. By analyzing expert insights, case studies, and existing research, this study proposes recommendations for improving digital learning experiences tailored to cognitive aging. The findings contribute to ongoing discussions on lifelong learning, offering strategies to support cognitive health and maximize the potential of digital education for an aging population.**

Keywords — adaptive learning; AI in education; digital learning tools; digital stress; gamification; lifelong learning; motivation; Neuroplasticity.

I. Introduction

In the field of medicine, social work and education today, there are challenges related to the interaction and support of social activity of older people and people with disabilities. These individuals experience various challenges, including physical, mental, social, emotional, cognitive, and visual impairments, as well as difficulties arising from personal and environmental factors, such as social and physical barriers [1].

Why do we include people with disabilities in our scientific review? Because, according to UNICEF's statistical analysis for 2021, there are about 240 million children with disabilities in the world [2]. This number is projected to grow steadily according to demographic trends. Some of these children are already of preschool age and receive financial support. In general, the issue of human ageing itself has a significant impact on the policy of each state, as cognitive ageing leads to an increase in requests for specific assistance and support. And according

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8599
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

to the Madrid Plan of Action, which aims to address the issue of ageing in the 21st century, we should focus on three areas:

- older people and development;
- preserving health and well-being in old age;
- ensuring a favourable and supportive environment [1].

Addressing these challenges requires attention, and in some cases, education rather than social or medical support provides the best solution. We believe that integrating digital technologies into lifelong learning projects is crucial for maintaining cognitive activity and adaptability in older people and individuals with disabilities. At the same time, it is worth noting that each country is making efforts in its own way to adapt existing laws, rights and regulations to ensure that a person with a disability (physical, mental, cognitive, sensory or emotional) or who is becoming an older person lives without discrimination and is treated as a normal person. This is to ensure that each of them has the opportunity to continue an active social and professional life.

Thus, in most cases today, disability is a general term for impairments, limitations of activity and participation, which refers to the negative aspects of the interaction between a person (for health reasons) and contextual factors (environmental and personal) [3]. Therefore, the search for specific technological solutions becomes a part of support, which includes

- medical services (research using smartwatches and other means of physical condition and neural activity);
- social services (creation of social, financial support and cultural interaction programmes based on the data obtained to involve older people in socially significant events, activities, clubs, physical activity, etc;)
- educational services, which include updating educational programmes, introducing specific courses to improve cognitive functions, introducing new technologies, etc.

While all aspects of inclusion are important, we argue that educational services should take priority. After all, education creates the preconditions for cognitive activity and stable functionality at any age. It allows a person not only to acquire knowledge and master certain skills, but also to form a constant interest and desire for self-development [4]. This, in turn, should ensure constant brain activity, which affects the functioning of the whole organism.

Thus, changes in the educational environment are necessary and inevitable. This is confirmed in UNESCO documents, as education is no longer limited to traditional schooling for children, but is expanding to include lifelong learning [5]. It promotes employability by retraining and upskilling workers in a changing world of work; enables people to master the digital revolution; enables students of all ages to take action to protect the climate; supports health and well-being in communities; helps countries respond to an ageing society, as the world's population aged 65 and over is expected to outnumber young people by 2050; and promotes tolerance and democratic values in the face of profound social and economic change [5].

This, in turn, directs scientists and practitioners to in-depth research into mental processes and phenomena that affect education and cognition processes that are directly related to inclusion and lifelong learning. That is why the purpose of this theoretical review is to model a basic algorithm for using digital learning platforms, gamification, and artificial intelligence-driven educational tools to stimulate neuroplasticity and maintain the cognitive health of older people.

II. Materials and Methods

The main objectives of this review are as follows:

- To analyse scientific research on the impact of neuroplasticity on cognitive ageing.
- To explore the main challenges and barriers to digital learning in older age, considering the potential of neuroplasticity.
- To identify the most effective digital tools for enhancing cognitive functionality among older adults.
- To propose a basic model for ICT-based learning tailored to the neuroplasticity-related needs of older adults.

To achieve these objectives, we employed the following research methods:

- Review of recent literature on neuroplasticity and digital learning.
- Analysis and generalisation of the effectiveness of digital solutions in enhancing cognitive functions.
- An expert survey involving speech therapists, cognitive therapists, and educators on the application of ICT in older adults' education.
- AI-assisted structuring was employed to improve coherence and organisation while preserving the integrity of the original content.

III. Results and Discussion

A. Neuroplasticity: Cognitive Challenges and Opportunities

Neuroplasticity, a science that has gone beyond biological or medical research (Fig. 1). Of course, one of the developmental questions that scientists are asking themselves is how the brain changes throughout our lives in terms of physiological and neurological indicators. But in the future, these data are proposed to be used to determine typical and atypical development for a certain age, as well as specific neurocognitive disorders and psychopathologies [6] that affect the ability to learn throughout life, maintain an active professional position and social engagement.

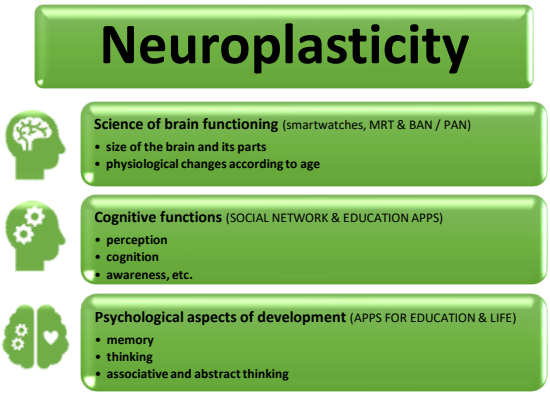


Fig. 1. Neuroplasticity as a scientific field.

The elements of cognitive science within the framework of neuroplasticity allow us to place emphasis on the competitiveness of the modern world. That is, those who have a smart competitive mind and are ready to adapt to complex new situations [7] are in a winning position. That is why we have various brain training programmes or traditional methods such as meditation that stimulate neuroplasticity. We also recognise that a person's effectiveness depends on their unique way of correlating with specific cognitive functions, including the speed of mastering digital skills. Depending on experience, culture, lifestyle, and many other variables, including biological and historical developmental factors [7], we have significant differences in brain functioning. As an example, we can look at how different nationalities and cultures approach the same mathematical problem differently, but we will discuss this in more detail in our next publications.

In general, today this particular part of neuroplasticity cognition includes the study of cognitive functions not only of an individual character, but also of interpersonal (emotion recognition, linguistic communication, etc.) and social (religion, morality, direct behaviour in conflict management, etc.) [7].

The next step in understanding neuroplasticity is the fundamental work of the nervous systems used to train AI today, which is the most important part of learning for the human brain – the association of the first stimulus with the next one that occurs at approximately the same time and the automatic reproduction of the second one when the first one appears [8]. What does this give us? We form neural connections through associations in the world around us, which we perceive. Based on these associations, our brain develops a certain algorithm of actions in a given situation, which becomes stable over time. These processes are easiest to understand through recall, which works even without a real object when there is a set of associations. But over time, this also leads to a decrease in new forms of interaction or algorithms for solving current tasks, both at home and at work. For example, an elderly person needs more time to master modern technologies, while a child born during the period of introduction of this technology seems to absorb intuitive and practical knowledge about its use with the «mother's milk».

Why does this happen? Because memory is mired in countless prejudices and distortions, and the original picture of the event we recorded was influenced by multiple factors. It may sound complicated, but the accumulation of outdated mechanisms for responding to new technological solutions hinders the development of a new algorithm for perceiving and responding to an «unexpected» element. In addition, it is worth remembering those elements that we specifically study or try to erase from our memory [9]. All of this increases the error in cognition and eventually narrows the channels of perception and information processing.

That is why the issue of neuroplasticity as a driving force for change in the focus of technology use allows us to approach the issue of cognitive ageing and the need to learn: to know, to do, to live together, to be [10]. Thus, learning becomes a panacea for overcoming various challenges caused by change. This includes lifelong learning, which is seen as a means of solving the problems of maintaining employability.

The proposed flexible learning is a so-called insider solution for deep transformations of modern society [11]. It can help to stimulate and preserve cognitive abilities, delay the decline in cognitive functions in older people [12]. In this aspect, changes for older people include:

- improvement of cognitive functions, as basic education develops an inquisitive open mind;
- career advancement, which helps to fully develop natural abilities;
- personal growth and fulfilment, enrichment of life related to self-realisation;
- social connections and community involvement, which helps us to make new friends and establish valuable relationships; supports us as active members of society;
- adaptability and resilience, which help us find meaning in our lives and adapt to change;
- opportunities to make the world a better place [12, 13].

B. Digital Tools for LLL

«In the state of flow "the sense of duration of time is altered; hours pass by in minutes, and minutes can stretch out to seem like hours» [13].

If we consider all the challenges facing older people's education, we must also take into account that lifelong learning is about providing a second chance to update basic skills and the opportunity to learn at higher levels [13]. In particular, the process of lifelong learning helps to maintain mental acuity and improve memory, stimulates and enables people to acquire the knowledge, values, skills and understanding they will need throughout their lives and apply them with confidence, creativity and enjoyment in all roles, circumstances and environments [13]. Within the framework of LLL, the following types of learning are distinguished:

- Formal learning, which takes place in an organised and structured context (formal education, apprenticeships) and can lead to formal recognition (diploma, certificate) [13];
- Non-formal learning is integrated into planned activities that are not explicitly defined as learning, but which contain an important element. For example, professional skills acquired in the workplace [13]. The defining characteristic of non-formal education is that it is a supplement, alternative or complement to formal education in the LLL process [15];
- Informal learning is the result of everyday life activities related to family, work or leisure. It is often referred to as experiential learning and is to some extent considered as incidental learning [13].
- Social learning is a relatively new format of learning that scholars have distinguished from informal and non-formal learning, based on the fact that interaction takes place online. In particular, this applies to independent learning activities on the Internet; sharing information and knowledge among peers through online interaction; searching for answers to everyday questions, downloading relevant files [16], watching video instructions or blogs that address these issues, and finding solutions to work issues. And this list, in our opinion, is constantly expanding and supplementing, in particular with the increasing participation and influence of generative AI and neural networks in general. In addition, in this case, students are involved in practices that require active construction of new knowledge and understanding of the processes taking place [11].

All these efforts are aimed at developing a new set of competencies that go beyond the obvious ICT literacy or DigComp: communication, collaboration, social and cultural skills, creativity, critical thinking, problem solving, productivity in a globalised world, learning skills, self-direction, planning, flexibility, risk-taking, conflict management, and a sense of initiative and entrepreneurship [14, 17].

Typically, the goal of modern education set by formal structures is to lay the foundation for lifelong learning and human development, on the basis of which education systems can then expand further educational opportunities [15]. Therefore, a basic learning offer uses:

- synchronous distance learning sessions using virtual classrooms equipped with electronic whiteboards;
- asynchronous sessions and Web 2.0 tools (podcasts, wikis, chats, forums, blogs, the use of which is also uneven depending on the territorial, economic, cultural or social situation) [11];
- massive open courses such as Coursera, Khan Academy, EdEra, Prometeus, EDX, Alison, etc.
- But this is only the first layer of modern technological solutions for education. After all, this type of education and interaction with the next generations of Web resources allow expanding the educational arsenal by
- virtual simulations or interaction environments (OpenSim, AltspaceVR) that promote cognitive stimulation [10, 18];
- language applications that also support cognitive activity (e.g. Duolingo);
- learning through blogs, podcasts, and video casts, which have changed the specifics of interaction platforms such as YouTube, Facebook, MySpace, and Instagram [11] by expanding services to provide certified or professional practical content on a particular highly specialised topic.

The next layer of digital education for LLL includes, in our opinion, a number of further and more complex forms of implementation. The first is GBL, or game-based learning, which is based on active user actions and provides a transition from serious games to gamification. The spectrum of GBL ranges from specially designed digital serious games that combine learning objectives in a game universe with some cognitive and visual immersion and gameplay, to gamification as 'the use of game design elements in non-game contexts' [14]. Here we can mention training for technical staff of steel mills; the use of simulators and car seats for driver training; online city tours around the world, etc.

The second is the use of artificial intelligence-based tools, taking into account possible risks, such as threats to privacy and security, but with an interest in improving the teaching and learning process [20].

The third, which few people write about and pay attention to, is contextual learning, which works like contextual advertising or «25-frame». That is, in an unobtrusive way, it provides knowledge on one or more subjects while reading fiction or entertainment, watching TV series or videos. The types of information presented can range from the hard sciences to historical facts, religious or cultural features. Of course, the quality of contextual learning often depends on the publisher and author of the content and material. Therefore, any information should be checked, and for this purpose, a person should have a developed algorithm for responding to fake information, i.e., searching for confirmation or refutation of the data received. Today, such a mechanism is being developed as part of media literacy.

Fourth, and in our opinion, in line with social learning, but still related to contextual learning, is the conscious comprehension of processes or events that take place in short entertaining sketches. We often see this type of material today in Facebook's Storify feed, YouTube shorts, or short sketches of various events and situations on TikTok. However, according to our observations and interviews, this type of digital education is used by a small percentage of viewers. An example of such use is watching videos of car accidents, which a driver watches to work out an algorithm of actions to avoid a collision. This method is psychologically based, because in this way the brain perceives a dangerous moment in the safest possible conditions. And, subject to repeated stimulation of such an algorithm for preparing for a non-standard situation, the

body automates the proven algorithm for reacting to events in real time with maximum efficiency.

An additional stimulus for any of the previously described areas of education is music and physical activity. Why? Movement is inseparable from consciousness or, perhaps, controls it, and in different age periods, these movements are different. In old age, movement stimulates oscillations in the hippocampus and cerebral cortex, which increase synaptic plasticity, improve communication between brain areas, and optimise brain function. In other words, the connection between the brain and the body is bidirectional: oscillatory rhythms in the brain control movement, and movement controls oscillatory rhythms. When the physical body tunes in to external (e.g., music) or internal (e.g., breathing) rhythms, these rhythms engage the brain areas associated with the external world (auditory and sensory) and subsequently engage other, more internally focused brain areas (motor, cognitive, and emotional) [21].

TABLE 1. DIGITAL TOOLS FOR LLL

DigComp level	**Essential digital tools**				
	Digital engagement and solutions			***Benefits***	***Challenges and barriers***
I	Formal learning	synchronous distance learning sessions using virtual classrooms	Zoom, Google Meet, To Go, Microsoft Team, etc	complex issues here and now, intuitive format of interaction (taking into account the number of years of adaptation and adjustment of the educational process to online education)	level of technical support, organisational readiness of the teacher
II	Non-formal learning and informal learning	asynchronous sessions	Moodle, MOOCs and other state-supported platforms that can be used both synchronously for classroom tasks and asynchronously	Choosing a highly specialised topic that meets the interests of the individual or the needs of the employer	Uneven provision depending on the territorial, economic, cultural or social situation
		Web 2.0 tools	Wiki, Blogs, e-mail and instant messengers, open source office applications in the cloud, file sharing, etc	Accessibility, relatively easy format of use	
		massive open courses (both narrowly focused on a particular speciality and with a wide range of topics and directions in various fields of science)	Coursera, Khan Academy, EdEra, Prometeus, EDX, Alison, etc.	Accessibility, wide range of topics, possibility of certification, reliable primary sources	Availability of appropriate digital competence, language barriers, technical implementation
		GBL (game-based learning)	Language applications or applications for the development of attention, memory and logic (duolingo, various mahjongs, go, chess, sudoku, tetris, etc.)	Accessibility, ease of implementation	Availability of appropriate digital competence
			simulators (sports, racing, flight simulators, workflow simulators ats4, etc.), OpenSim, Altspacevr	Authenticity of facts and proximity to reality	Complexity of implementation even with an intuitive interface
III	Social learning	Forums and specialised platforms	for example ReserchGate, Mendeley for scientists, GitHub for IT professionals, etc	Diversity, accessibility, choice of the best answer to a question	The inability to be sure of the reliability of information, even if it is a 'trusted' platform the need to seek confirmation of the reliability of facts and information
		Thematic Blogs, podcasts and video casts on YouTube, Facebook, MySpace and Instagram, video diaries etc			
IV	Learning based on AI models	ChatGPT, OpenAI, Copilot, generative AI from Adobe, various third-party applications based on them that supplement, change video, audio or other elements of audiovisual art		Ease and intuitive usability, accessibility	Threat to privacy and security, the need to verify information
V	Contextual learning	The 25th Frame. The Subliminal Message – presentation of subject knowledge in the format of fiction or entertainment, TV series or videos		Unobtrusivee format of material presentation, accessibility and interest of the individual due to the relevance of the basic information to his or her interests	Author's vision or publishing policy that requires verification of the information offered

This involvement creates increased synchrony (i.e., increased power and coherence) between brain areas, contributing to the enhancement of neurobehavioural effects in sensory, motor, cognitive, social, emotional, rhythmic and creative brain areas, which is one of the conditions for maintaining cognitive function and preserving brain neuroplasticity [21]. This, in turn, affects the brain's ability to learn and change itself according to the situation. These changes include: growing new neurons; changing the distribution and location of neurons; modifying new synaptic connections between existing neurons [22].

Below is a summarised list of the digital tools that we believe have the greatest impact on cognitive functioning and can be used for LLL.

Each proposed solution has both advantages and disadvantages for the organisation of LLL. However, the main advantages of each type of training to support the cognitive functioning of older people are

- accessibility, ease of use, intuitive interface;
- maximum approximation to the reality of the process of information assimilation;
- diversity, accessibility, the ability to choose the best answer to a question [23];

- the ability to solve complex issues here and now;
- personalisation and relevance to the interests of the individual or employer. Interest is a crucial motivator for adult learners, creating a desire to participate in learning activities without expecting any external rewards [24];
- formal courses ensure the reliability of facts and information;
- flexibility of learning and the ability to learn at one's own pace;
- in some cases, the possibility of obtaining certification;
- unobtrusive presentation format that stimulates interest;
- the use of adaptive algorithms for a personalised learning process.

Despite a number of advantages, we should note that each type of training offered to older people has its drawbacks. Namely:

- technical and organisational difficulties in providing the types of training offered for both teachers and students;
- low or no digital competence, and in some cases language barriers;
- lack of government initiatives to teach digital literacy to older people and/or insufficient support for younger generations in explaining complex technical aspects;
- the inability to be sure of the authenticity of information, especially on informal educational platforms, which leads to a constant need to verify it;
- the author's vision or publishing policy, which may distort the content and require additional analysis.

In some cases, privacy and security risks, including the possibility of personal data leakage or the use of unreliable platforms, are also a deterrent to organising LLL.

But the main message is: learning a new language or using a new app for communication or other purposes should be a solution for an older person to continue their social and professional life..

C. A Model of Neuroplasticity Stimulation by Digital Tools

According to our results, we can develop a model for stimulating neuroplasticity and maintaining the cognitive health of older people using modern technologies (ICT), which is presented below (Fig. 2).

We do not claim that this model is the only correct or sufficient for further development and refinement of the concept of lifelong learning. However, the proposed model allows us to consciously combine commonly accepted educational processes and integrate learning processes that arise under the influence of expanding technological solutions.

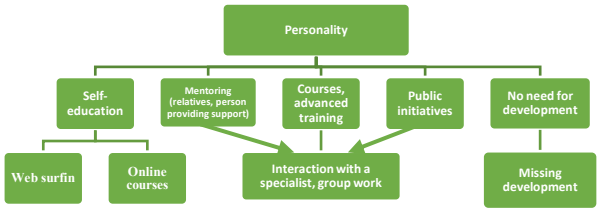


Fig. 2. A model of neuroplasticity stimulation by digital applications in the framework of LLL and personality interests.

In addition, this model will serve as a reminder of the need to adapt digital tools to the cognitive characteristics of older people. Taking into account the need to simplify and provide an intuitive interface of educational applications, platforms, materials for people with different levels of digital literacy. Also, ensure the availability of a facilitator, mentor, or training of family members in the basics of facilitating the acquisition of digital competencies by older family members. This will improve not only cognitive brain functions by providing the neuroplasticity necessary for an active life, but also reduce emotional, psychological and digital stress in the process of using ICTs.

IV. CONCLUSIONS

This paper considers the impact of neuroplasticity on cognitive ageing. We analysed the main benefits, challenges and barriers of digital learning environments for improving memory, attention and cognitive flexibility. We found that even though digital impact depends on the interpersonal and social communication characteristics of an older person, the most effective solutions include individual learning paths and interest-based digital tools. This has allowed us to create an ICT-based learning model that takes into account the adaptability of software to the cognitive needs of older people, provides optimal workload and minimises barriers to use.

In general, digital technologies implemented and complementing the process of lifelong learning are effective means of supporting the cognitive health of older people. Therefore, in our opinion, it is necessary to continue to introduce adaptive platforms that take into account the value of using and developing neuroplasticity, open access to learning resources for the development of digital skills in older people.

The results obtained may be useful for developers of various digital applications, teachers and curriculum developers, social workers, and researchers in the field of cognitive science and education.

REFERENCES

[1] Political declaration and Madrid international plan of action on ageing. Second World Asembly of Aging (2002). [Online]. Available: United Nations, https://www.un.org/esa/socdev/documents/ageing/MIPAA/political-declaration-en.pdf. [Accessed: Oct. 21, 2024].

[2] Around 240 million children with disabilities live in the world, according to UNICEF's most comprehensive statistical analysis (2021). Press release. [Online]. Available: UNICEF, https://www.unicef.org/ukraine/press-releases/copy-nearly-240-million-children-disabilities-around-world-unicefs-most. [Accessed: Feb. 26, 2022].

[3] W. L. Nonglait, Disabilities and their Classification. Modern Technological Intervention Advancements for the Physically Challenged and Disabled Population. Cambridge Scholars Publishing.2021. [Online]. Available: https://www.cambridgescholars.com/product/978-1-5275-7508-0. [Accessed: Nov. 08, 2021].

[4] A. Rauduvaitė and B. Sun, The Concept of Learning to Learn in the Context of Music Education. SOCIETY. INTEGRATION. EDUCATION. Proceedings of the International Scientific Conference, 1, 2023, pp. 476-490. [Online]. Available: https://journals.rta.lv/index.php/SIE/article/view/7077. [Accessed: Jul. 03, 2023]. https://doi.org/10.17770/sie2023vol1.7077.

[5] Lifelong learning. European Foundation for the Improvement of Living and Working Conditions, 2017. [Online]. Available: UNESCO, https://www.unesco.org/en/lifelong-learning/need-know. [Accessed: Feb. 13, 2025].

[6] W. J. Ray, Fundamentals of Brain and Behavior: An Introduction to Human Neuroscience. Taylor & Francis, 2024.[Online]. Available: https://www.taylorfrancis.com/books/mono/10.4324/9781003266426/fundamentals-brain-behavior-william-ray. [Accessed: Feb. 02, 2024]. https://doi.org/10.4324/9781003266426.

[7] R. K. Mishra, Cognitive Science: New Developments and Future Directions. Routledge India, 2022. [Online]. Available: https://www.taylorfrancis.com/books/mono/10.4324/9781003316053/cognitive-science-ramesh-kumar-mishra. [Accessed: Dec. 05, 2022]. https://doi.org/10.4324/9781003316053.

[8] E. T. Rolls, Brain computations and connectivity. Oxford University Press 2023 [Online]. Available: https://academic.oup.com/book/46855. [Accessed: Aug. 24, 2023]. https://doi.org/10.1093/oso/9780198887911.001.0001.

[9] C. R. Madan, Memories that matter: How we remember important things. Taylor & Francis. 2024. [Online]. Available: https://www.taylorfrancis.com/books/mono/10.4324/9780429032028/memories-matter-christopher-madan. [Accessed: March 28, 2024]. https://doi.org/10.4324/9780429032028.

[10] M. Laal and A. Laal, Challenges for lifelong learning. Procedia-social and behavioral sciences, 47, 2012, pp.1539-1544.

[11] G. Marzano, V. Lubkina and L. O. Siguencia, Key Issues in Adult Non Formal Participatory E-Learning. Society. Integration. Education. Proceedings of the International Scientific Conference, 4, 2016, pp.69-79. [Online]. Available: https://journals.ru.lv/index.php/SIE/article/view/1540. [Accessed: May. 26, 2016]. https://doi.org/10.17770/sie2016vol4.1540.

[12] X. Alla, Lifelong Learning. Interdisciplinary Journal of Research and Development, 11(1), 27, 2024. [Online]. Available: https://www.researchgate.net/publication/379231881_Lifelong_Learning. [Accessed: March 23, 2024]. https://doi.org/10.56345/ijrdv11n105.

[13] M. Laal and P. Salamati, Lifelong learning; why do we need it?. Procedia-Social and Behavioral Sciences, 31, 2012, pp. 399-403.

[14] M. Romero, Work, games and lifelong learning in the 21st century. Procedia-Social and Behavioral Sciences, 174, 2015, pp.115-121.

[15] Unesco. International standard classification of education (ISCED) 2011. 2012. UNESCO.

[16] G. Marzano and L. Ochoa-Siguencia. (2017). Challenges of Web-Based Participatory Learning. Society. Integration. Education. Proceedings of the International Scientific Conference, 2, 2017, pp. 458-467. [Online]. Available: https://journals.rta.lv/index.php/SIE/article/view/2395. [Accessed: May. 26, 2017]. https://doi.org/10.17770/sie2017vol2.2395.

[17] L. Ochoa Siguencia, Z. Gródek-Szostak, A. Niemczyk, A. Szeląg-Sikora, and E. Pagan Castano, Lifelong Learning for Talent Management and Professional Development of Employees. ETR, vol. 2, 2023, pp. 189–192. [Online]. Available: https://journals.rta.lv/index.php/ETR/article/view/7232. [Accessed: Jun. 13, 2023]. https://doi.org/10.17770/etr2023vol2.7232.

[18] A. Korol, I. Konovalchuk, O. Kolosova, N. Tarnavska, and A. Khilya. (2023). Organization of Distance Learning in the Ukrainian Practice of Inclusive Education. ETR, vol. 2, pp. 156–161. [Online]. Available: https://journals.rta.lv/index.php/ETR/article/view/7243. [Accessed: Jun. 13, 2023]. https://doi.org/10.17770/etr2023vol2.7243.

[19] A. Khilya, Basic Principles of Using Virtual and Augmented Reality Technologies in the Process of Teacher Training in Ukraine. ETR, vol. 2, 2023, pp. 141–144. [Online]. Available: https://journals.rta.lv/index.php/ETR/article/view/7268. [Accessed: Jun. 13, 2023]. https://doi.org/10.17770/etr2023vol2.7268.

[20] O. Vindaca, A. Abolina, and L. Danilane. Transforming Higher Education in the Era of Artificial Intelligence Chat Tools: Case Study. ETR, vol. 2, 2024, pp. 310–316. [Online]. Available: https://journals.rta.lv/index.php/ETR/article/view/8014. [Accessed: Jun. 22, 2024]. https://doi.org/10.17770/etr2024vol2.8014.

[21] J. C. Basso, M. K. Satyal and R. Rugh, Dance on the brain: enhancing intra-and inter-brain synchrony. Frontiers in human neuroscience, 14, 2021, 584312. [Online]. Available: https://www.frontiersin.org/journals/human-neuroscience/articles/10.3389/fnhum.2020.584312/full. [Accessed: Jan. 07, 2021]. https://doi.org/10.3389/fnhum.2020.584312.

[22] A. Zorins and P. Grabusts, Artificial Neural Networks and Human Brain: Survey of Improvement Possibilities of Learning. ETR, vol. 3,2015, pp. 228–231. [Online]. Available: https://journals.ru.lv/index.php/ETR/article/view/165. [Accessed: Jun. 16, 2015]. https://doi.org/10.17770/etr2015vol3.165.

[23] I. Gehtmane-Hofmane. (2022). Motivational Components of Adult Learning Within the Informal Educational Settings. Society. Integration. Education. Proceedings of the International Scientific Conference, 1, 2022, pp. 744-752. [Online]. Available: https://journals.rta.lv/index.php/SIE/article/view/6857. [Accessed: May. 19, 2022]. https://doi.org/10.17770/sie2022vol1.6857.

[24] A. Khilya, Value of Innovation in Lifelong Learning: Pedagogical and Social Context. Society. Integration. Education. Proceedings of the International Scientific Conference, 2, 2024, pp. 178-187. [Online]. Available: https://journals.rta.lv/index.php/SIE/article/view/7809. [Accessed: May. 22, 2024]. https://doi.org/10.17770/sie2024vol2.7809.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 265-270

Analyzing E-Commerce of Small and Medium-Sized Enterprises in the European Union: Dependencies and Trends in the Context of Digitalization

Simeonka Petrova
Department of Commerce
Tsenov Academy of Economics
Svishtov, Bulgaria
s.petrova@uni-svishtov.bg

Abstract- **The presented study analyses the implementation of e-commerce by small and medium-sized enterprises in the countries of the European Union. The main objective of the study is, based on analysing the sales of small and medium-sized enterprises in e-commerce by enterprise size and the relative share of turnover obtained from e-commerce, during the period 2013-2023, to identify the emerging dependencies, as well as to establish development trends. The importance of the digitalization of the business of small and medium-sized enterprises through e-commerce is emphasized. Development trends are established and the indicator for the average annual growth rate is determined. The adopted methodological framework for conducting the study includes the application of the IBM SPSS Statistics software product, the Excel program, as well as the use of the linear regression and correlation method. The respondents of the study are a set of small and medium-sized enterprises from the 27-member states of the European Union. The results of the analysis show that the relative share of SMEs in the countries studied that engage in e-commerce and the turnover generated by e-sales vary significantly over the period under analysis. Differences are identified across European countries. The business opportunities of SMEs to implement e-commerce in digital environments are interpreted. Such studies help to identify upcoming changes in the business models of European SMEs.**

Keywords- e-commerce, digitalization, small and medium-sized enterprises.

I. INTRODUCTION

Digital transformation has a significant contribution to the development of economies and societies. The introduction of new technologies and digital processes transforms the business models of small and medium-sized enterprises, changes consumer behaviour. In 2021, the European Commission identified the opportunities for digital transformation of Europe by 2030 [1]. The progress of the digital performance of the European Union member states is monitored through the Digital Economy and Society Index (DESI). In this context, existing challenges facing the digital transformation of small and medium-sized enterprises are outlined. The integration of digital technologies is determined as a priority area, covering two areas: business digitalization and e-commerce. Therefore, e-commerce is determined as an essential component of the index.

According to the World Bank, small and medium-sized enterprises account for a large proportion of the total number of enterprises in most economies, especially in developing countries [2]. They contribute to job creation and global economic development. They account for a significant portion of the Gross Domestic Product of each country. This makes these enterprises a high priority for individual countries, including those in the European Union.

In this context, the level of integration of small and medium-sized enterprises into digital transformation should be established. This creates opportunities for expansion and outlining strategies for business internationalization through digital platforms [3]. Small and medium-sized enterprises are embracing digital technologies to gain a competitive advantage over their competitors, creating additional value, increasing productivity and profitability. The implementation of cutting-edge technologies contributes to improving the production capabilities of small and medium-sized enterprises within the framework of Industry 4.0 [4].

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8615
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

Along with the opportunities, digital technologies create barriers for small and medium-sized enterprises in terms of available resources and limited size [5]. Studies show that their digitalization strategies primarily cover shorter time periods compared to large enterprises.

In the specialized literature, numerous studies focus on the main digital factors that ensure dynamic economic progress. For example, some of the studies are aimed at studying the impact of e-commerce on the economic development of countries, including the 27-member states of the European Union. The economic contribution of e-commerce, carried out by various businesses, in the creation and formation of the Gross Domestic Product is studied.

In the digital economy, e-commerce is becoming an essential technological tool, stimulating the innovation of small and medium-sized enterprises, changing their business models, as well as creating new consumer profiles [6]. E-commerce, as a modern innovative system, is determined as a factor of sales growth and an opportunity to participate in global markets [7]. It leads to an evolution of the commercial business. It changes the buying and selling of goods or services and improves the relationships and communication between customers and suppliers [8].

As confirmed in their scientific works by researchers F. Pantelimon, T. Georgescu and B. Posedaru, e-commerce is defined as an economic activity related to the purchase and sale of goods and services through online platforms [9]. Through e-commerce, the business carried out by small and medium-sized enterprises is expanded in an online environment. Thus, some studies consider e-commerce as one of the main conditions for the adoption of innovative marketing solutions, as well as for business development through the establishment of optimal customer relationships [10].

The adoption of e-commerce by SMEs is influenced by a number of internal and external determinants, including technological ones. At the enterprise level, e-commerce optimizes the structured supply chain, providing data on inventory, production, sales [11], [12]. Considering the operational efficiency of the business necessitates combining offline and online channels for marketing. Cross-border e-commerce creates conditions for reducing distribution costs.

Based on the aspects thus presented, it is considered appropriate for this study to focus on analysing the development of e-commerce at the level of small and medium-sized enterprises.

The main objective of the study is to identify the emerging dependencies and development trends, based on an analysis of the sales of small and medium-sized enterprises in e-commerce by enterprise size and the relative share of turnover obtained from e-commerce, during the period 2013-2023. At the same time, the research interest is to emphasize the importance of the digitalization of the business of small and medium-sized enterprises through e-commerce. In this regard, development trends are established and the indicator for the average annual growth rate is determined.

The analysis of e-commerce of small and medium-sized enterprises requires the following restrictive conditions to be introduced in this study: interpretation of trade type studies through empirical data relating to the 27-member states of the European Union during the period 2013-2023; study of the relationship between the total turnover of small and medium-sized enterprises from e-commerce sales and enterprises of the specified size whose website provides tracking of online orders. The study of the relationship between the selected variables allows reaching results reflecting a certain aspect of the development of e-commerce in Europe.

II. MATERIALS AND METHODS

This study aims to analyse more significant manifestations of the digitalization of small and medium-sized enterprises' business through e-commerce. In this context, the respondents of the study are small and medium-sized enterprises operating in the 27-member states of the European Union, carrying out e-commerce sales.

The analysis refers to data published by the European Statistical Office - Eurostat. This data has been collected and summarized using a methodology that allows for the analysis and evaluation of the e-commerce of the highlighted enterprises.

The methodological framework of the study includes measuring the emerging dependencies using the method of linear regression and correlation. In order to analyse and evaluate the sought dependencies, statistical software for computer processing is applied - IBM SPSS Statistics, as well as the capabilities of the Excel program. The analysis is carried out in two steps, ensuring logical consistency, namely:

- first step of the analysis – analysing and interpreting the status and dynamics of e-commerce sales by small and medium-sized enterprises from the 27-member states of the European Union, as well as calculating the growth rate and the average annual growth rate of the share of the surveyed small and medium-sized enterprises with e-sales;
- second step of the analysis – analysing and assessing the correlation between the dependent variable of the total turnover of small and medium-sized enterprises from e-commerce sales, and the independent variable of small and medium-sized enterprises with a website providing tracking of orders placed at the European level.

The outlined methodological framework helps to achieve the set objective of this study. This focus assumes that trends in e-commerce sales by enterprises from the 27-member states of the European Union are an important indicator of ongoing digitalization processes.

III. RESULTS AND DISCUSSION

Digitalization is transforming the business models of small and medium-sized enterprises. Available data on the various aspects of digitalization, including through e-commerce, of enterprises, including SMEs, at the European Union level allow for the analysis of the changes taking place in this area.

According to expert assessments, the use of digital technologies, including the possibilities of e-commerce, by small and medium-sized enterprises operating in the 27-member states of the European Union follows a trend of sustained and constant growth. [13]. The views held are supported by the available data published by the European Statistical Office – Eurostat [14].

According to the first step of the analysis, defined in this study, the status and dynamics of e-commerce sales by small and medium-sized enterprises operating in the 27-member states of the European Union are analyzed and assessed. According to Eurostat data for the ten-year period 2013-2023, in 2023 the relative weight of the enterprises in question reporting e-commerce sales turnover reaches 12.09%, which is 4.21 percentage points more than in the initial year of the period – 2013. The values reported in this way are favorably influenced by various factors, including: increasing application of information and communication technologies; electronic data exchange; use of websites, applications, marketplaces, online platforms and others.

The dynamics of change in the relative share of the total turnover of small and medium-sized enterprises from e-commerce sales, as well as the variation in the relative weight of small and medium-sized enterprises with a website providing tracking of orders placed, at the level of the 27-member states of the European Union, are illustrated by Fig. 1.

The reported changes in the relative share of the total turnover of small and medium-sized enterprises from e-commerce sales, as well as in the relative weight of small and medium-sized enterprises with a website providing tracking of orders placed at the level of the 27-member states of the European Union, allow us to conclude that both variables follow a favorable growth trend.

At the same time, the comparative analysis shows that certain countries report higher values compared to the average of 10.31% for the European Union for the share of the total turnover of small and medium-sized enterprises from e-commerce sales.

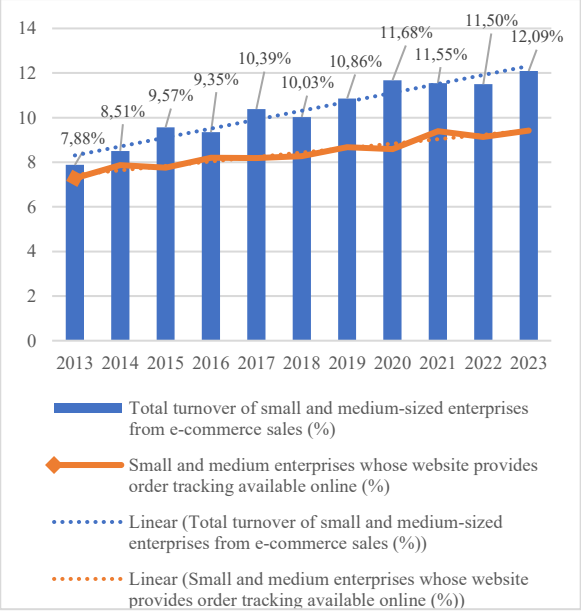


Fig. 1. Dynamics during the period 2013-2023 of the relative share of the total turnover of small and medium-sized enterprises from e-commerce sales and dynamics of the relative share of small and medium-sized enterprises with a website providing tracking of orders placed, at the level of the 27-member states of the EU.

Source: Eurostat data and author's calculations.

In 2023, the highest values, significantly exceeding the average, are as follows: Ireland - reporting a value of 21.13%; Czech Republic - 18.82% and Denmark 18.65%. Comparatively, countries such as Bulgaria and Romania have relatively lower values. At the same time, both countries report an increase and growth of the analyzed indicator in 2023 compared to the initial year of the study period - 2013, as follows: for Bulgaria the increase is more than 4 times, and for Romania - more than 2 times.

The use of a correlogram allows us to visualize the relationship between the total turnover of small and medium-sized enterprises from e-commerce sales and the functioning website that provides tracking of online orders. With the help of the following Fig. 2. the trend model is visualized, as well as the emerging regression line. The described regression line visualizes the relationship between the factor and the resulting quantitative value determined in this study.

As can be seen from the figure, during the period 2013-2023, there is an upward trend in the relative share of the analyzed enterprises with a website, varying between 7.28% and 9.42%. A similar favorable growth trend is observed for the other variable – its variation is between 7.88% and 12.09%, with the second value being reached at the end of the evaluated period. The same figure also shows that the coefficient of determination takes the value as follows: $R^2 = 0.8445$. Therefore, the value of the correlation coefficient is a positive number, which is closer to unity and indicates the presence of a stronger relationship.

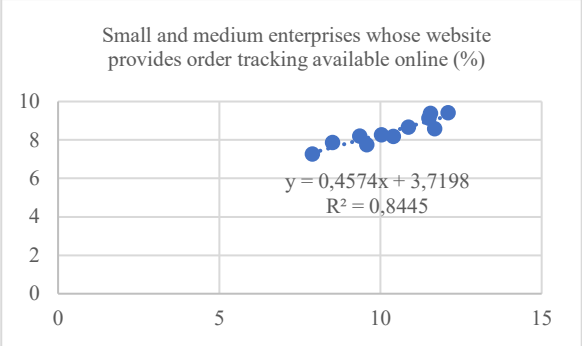


Fig. 2. Dynamics during the period 2013-2023 of the relative share of small and medium-sized enterprises with a website providing tracking of orders placed, in the 27-member states of the EU.

Source: Eurostat, https://ec.europa.eu/eurostat/databrowser/view/isoc_ec_esels/default/table?lang=en; author's calculations.

Within the same analytical step, the growth rate and the average annual growth rate of the share of surveyed small and medium-sized enterprises with e-sales are calculated. The values of both indicators are visualized in Table 1.

TABLE 1 CHANGE IN THE SHARE OF SMALL AND MEDIUM-SIZED ENTERPRISES FROM THE 27-MEMBER STATES OF THE EUROPEAN UNION WITH E-COMMERCE SALES DURING THE PERIOD 2013-2023

Region	**Indicators**	
	Growth rate (2023/2013)	***Average annual growth rate (2023/2013) Subhead***
EU-27	0.4065	1.0435

Source: Eurostat data and author's calculations.

As shown in Table 1, during the period 2013-2023, the growth rate of the relative share of small and medium-sized enterprises from the 27-member states of the European Union with e-commerce sales takes the value as follows: 0.4065. The resulting value expresses the speed of development of the variable under study over the selected long period of time. The average annual growth rate also reflects the average speed of development, and it should be noted that within the period 2013-2023, a positive increase in the measured relative share of the surveyed enterprises with e-commerce sales is achieved by 1.0435 times.

The second step of the analysis directs the research interest to interpret the correlation between the variable of total turnover of small and medium-sized enterprises from e-commerce sales, on the one hand, and the variable – small and medium-sized enterprises with a website providing tracking of orders placed, on the other hand. Determining the direction of the relationship between the two variables necessitates the conduct of a regression analysis.

The application of the linear regression and correlation method allows reaching certain research results, illustrated by the following tables. Table 2 illustrates the indicators of regression statistics.

TABLE 2 REGRESSION STATISTICS INDICATORS

№	**Regression Statistics**	
	Indicators	***Values***
1.	Multiple R	0.9189
2.	R Square	0.8445
3.	R Square	0.8272
4.	Standard Error	0.2851
5.	Observations	11

Source: Eurostat data and author's calculations.

According to the data visualized in Table 2, it is found that the linear regression coefficient, coinciding with the correlation coefficient, takes a positive value closer to unity. The considered coefficient measures the tightness of the linear correlation between the two variables. Since the condition that $0.7 < R = 0.9189 < 1$ is met, it is concluded that a strong single linear correlation is established between the two evaluated variables – the total turnover of small and medium-sized enterprises from e-commerce sales, and the variable – small and medium-sized enterprises with a website providing tracking of orders placed.

The second coefficient illustrated in Table 2 is the coefficient of determination. According to the data, its value is as follows: $R^2 = 0.8445$. The given value allows us to state that over 84% of the differences between small and medium-sized enterprises from the 27-member states of the European Union in terms of realized turnover from e-commerce sales are due to and explained by the differences between them in terms of a functioning website that provides tracking of orders placed. The data in the same table also shows the values of the specified coefficient of determination, assuming the favorable value of 0.8272, of the standard error, as well as of the eleven years surveyed in total, included in the analyzed period 2013-2023.

Table 3 presents values that help verify the adequacy of the regression model.

TABLE 3 ANOVA

Indicators	**Anova**		
	Sum of Squares	***Mean Square***	***F***
Regression	3.9749	3.9749	48.8945
Residual	0.7316	0.0812	
Total	4.7066		
Sig-significance F	0.0001		

Source: Eurostat data and author's calculations.

As can be seen from the data in Table 3, the verification method, i.e. F - the criterion, takes a value that amounts to: F = 48.8945. Provided that the risk of a first type error is 5% ($\alpha = 0.05$), it is established that the explained variance

of the dependent quantitative variable is over 48 times greater than the variance of the error. Since the significance level Significance F = 0.0001 < 00.5 = α, it is reasonable to conclude that there is a natural dependence of the variable - the total turnover of the studied small and medium-sized enterprises from e-commerce sales, on the built and functioning website, providing tracking of the orders placed. Therefore, the estimated regression model is adequate and can be used for further study of the dependence.

The data in the following Table 4 helps determine the type of linear regression equation.

TABLE 4 COEFFICIENTS

Indicators	**Coefficients**		
	Coefficients	***Standard Error***	***t Stat***
Intercept	3.7198	0.6798	5.4714
Total turnover of small and medium-sized enterprises from e-commerce sales	0.4574	0.0654	6.9924

Source: Eurostat data and author's calculations.

In this case, the linear regression equation takes the following form (1):

$$y = 0.4574 + 3.7198 \quad (1)$$

The resulting regression equation helps measure the average change in the outcome variable - the total turnover of small and medium-sized enterprises from e-commerce sales, with a unit increase in the factor variable - small and medium-sized enterprises with a website that provides tracking of orders placed.

Therefore, based on the data illustrated in both Fig. 2 and Table 4, the implementation of the relevant analysis allows us to reach the following conclusion: if the variable measuring the relative share of small and medium-sized enterprises from the 27-member states of the European Union with a website that provides tracking of online orders, changes by one unit, this will lead to a positive change in the direction of increasing the total turnover of the surveyed enterprises from e-commerce sales by an average of 3.7198 units.

The research results thus obtained provide grounds for reporting a high correlation or strong dependence between the two quantitative variables studied in the presented work. In addition, these results allow for a certain interpretation of the digital changes occurring in small and medium-sized enterprises from the 27 countries of the European Union. The specific focus placed on the website built, ensuring the tracking of online orders, allows for measuring its impact on the total turnover of sales realized in e-commerce.

In the research area thus outlined, there is an opportunity for discussion. It is relevant and practically useful to compare with the results obtained, published in the specialized literature by other researchers. For example, in scientific works dedicated to analyzing and interpreting the impact of digital technologies on the sustainable development of various economic sectors in the European Union, certain determinants are highlighted and corresponding business effects are measured [15]. In addition, significant findings are derived in the behavior of consumers, considered as counterparties in the process of making online purchases through a wide range of web-based tools [16]. The consideration of similar studies helps the process of directing research interest to the selected issue. In this area, econometric models are used that evaluate different groups of determinants of an economic, demographic and other nature. In this sense, the basic research position is the belief that the business of European small and medium-sized enterprises operating in various sectors of the economy is increasingly determined by the strength of the impact of a number of determinants, among which digitalization stands out, including the implementation of e-commerce and the application of website tools.

IV. CONCLUSIONS

This study, presenting theoretical and empirical aspects of the economic benefits of business digitalization for small and medium-sized enterprises from the 27-member states of the European Union, provides a basis for reaching certain conclusions and generalizations. The results obtained from the analysis show that during the ten-year period 2013-2023, the growth rate of the relative share of the surveyed European enterprises with e-commerce sales follows a favorable trend of growth by more than one time. The outlined trend of change is an important indicator of the ongoing processes of digitalization. The conclusion is drawn that over 84% of the differences between small and medium-sized enterprises from the 27-member states of the European Union in terms of realized turnover from e-commerce sales are due to and explained by the differences between them in terms of a functioning website that provides tracking of online orders. In this analytical direction, the increase by one unit in the relative share of the analyzed enterprises with a website affects the positive increase by an average of over 3.72 units in the turnover from realized sales in e-commerce. The comparative analysis also allows us to highlight that during the studied period within the European Union, progress is being made towards increasing the degree of digitalization of the business of small and medium-sized enterprises. These trends are most pronounced in countries such as Ireland, the Czech Republic and Denmark. In their entirety, the research results obtained in this way, reflecting a certain aspect of the development of e-commerce in Europe, can be useful for identifying the necessary transformations and stimulating the digitalization of small and medium-sized enterprises' businesses.

REFERENCES

[1] European Commission, “Europe's Digital Decade: Digital Targets for 2030,” Shaping Europe's Digital Future. The Digital Economy and Society Index (DESI). [Online]. Available:

https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/europes-digital-decade-digital-targets-2030_en [Accessed Jan. 05, 2025].

[2] World Bank, "Small and Medium Enterprises (SMEs) Finance-Improving SMEs," Access to Finance and Finding Innovative Solution to Unlock Sources of Capital, 2015. [Online]. Available: https://www.scirp.org/reference/referencespapers?referenceid=2397671 [Accessed Jan. 05, 2025].

[3] M. Stallkamp and A. Schotter, "Platforms without borders? The international strategies of digital platform firms," Glob. Strategy Journal, pp. 58-80, 2018. [Online]. Available: https://www.researchgate.net/publication/330252898_Platforms_without_borders_The_international_strategies_of_digital_platform_firms [Accessed Jan. 07, 2025].

[4] K. North, N. Aramburu and O. Lorenzo, "Promoting digitally enabled groth in SMEs: A framework proposal," Proceedings IFKAD Conference, Delft, pp. 197-214, July 4-6, 2018. [Online]. Available: https://www.researchgate.net/publication/326294819_Promoting_digitally_enabled_growth_in_SMEs_a_framework_proposal_-Part_I [Accessed Jan. 07, 2025].

[5] A. Bhatia and A. Thakur, "Corporate diversification and firm performance: An empirical investigation of causality," International Journal of Organizational Analysis, 26, pp. 202-225, Anal. 2018. https://www.researchgate.net/publication/324433385_Corporate_diversification_and_firm_performance_an_empirical_investigation_of_causality [Accessed Jan. 07, 2025].

[6] European Commission, "A Digital Single Market Strategy for Europe," 2015. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52015DC0192 [Accessed Jan. 07, 2025].

[7] M. Maki and T. Toivola, "Global Market Entry for Finnish SME eCommerce Companies," Technol. Innov. Manag. Rev, 11, pp. 11-21, 2021. [Online]. Available: https://www.researchgate.net/publication/349130426_Global_Market_Entry_for_Finnish_SME_eCommerce_Companies [Accessed Jan. 08, 2025].

[8] N. Volkova, I. Kuzmuk, N. Oliinyk, I. Klymenko and A. Dankanych, "Development trends of the digital economy: E-business, e-commerce,". Int. J. Comput. Sci. Netw. Secur., 21, pp. 186-198, 2021. [Online]. Available: https://www.researchgate.net/publication/382695771_DEVELOPMENT_TRENDS_OF_THE_DIGITAL_ECONOMY_E-BUSINESS_E-COMMERCE [Accessed Jan. 08, 2025].

[9] F. Pantelimon, T. Georgescu and B. Posedaru, "The impact of mobile e-commerce on GDP: A comparative analysis between Romania and Germany and how covid-19 influences the e-commerce activity worldwide," Inform, Econ, 24, pp. 27-41, 2020. [Online]. Available: https://www.researchgate.net/publication/342868068_The_Impact_of_Mobile_e-Commerce_on_GDP_A_Comparative_Analysis_between_Romania_and_Germany_and_how_Covid-19_Influences_the_e-Commerce_Activity_Worldwide [Accessed Jan. 09, 2025].

[10] K. Fouskas, O. Pachni-Tsitiridou and C. Chatziharistou, "A Systematic Literature Review on E-Commerce Success Factors," Strategic Innovative Marketing and Tourism, pp. 687-694, 2020. [Online]. Available: https://www.researchgate.net/publication/339807743_A_Systematic_Literature_Review_on_E-Commerce_Success_Factors [Accessed Jan. 10, 2025].

[11] S. Petrova, I. Marinov, Z. Ivanova and Y. Akhmedyarov, "Impacts of Sustainable Entrepreneurship and Income on Sustainable Food Consumption," Circular business management in sustainability, Book Series: Lecture Notes in Management and Industrial Engineering, DOI: 10.1007/978-3-031-23463-7_4, pp. 65-78, 2023. [Online]. Available: https://xreiss.efri.uniri.hr/Article_similar.php?id=70701 [Accessed Jan. 09, 2025].

[12] V. Blazheva, "Sustainable development of the European food system. – The membership of Bulgaria in the European union: sixteen years later,", Vol. 2, Papers presented in English language, Sofia, Sofia: Publishing complex - UNWE, pp. 307-312, 2023. [Online]. Available: https://www.ceeol.com/search/chapter-detail?id=1252301 [Accessed Jan. 11, 2025].

[13] S. Lone and J. Weltevreden, "European E-commerce Report 2023," Amsterdam/Brussels: University of Applied Sciences & E-commerce Europe, pp. 1-97, 2023. [Online]. Available: https://www.upu.int/UPU/media/wwwUpuIntUniversalPostalUnionAboutUpuBodiesConsultativeCommittee/2023EuropeanEcommerceReportEn.pdf [Accessed Jan. 11, 2025].

[14] Eurostat, "E-commerce sales of enterprises by size class of enterprise," 2025. [Online]. Available: https://ec.europa.eu/eurostat/databrowser/view/isoc_ec_esels/default/table?lang=en [Accessed Jan. 11, 2025].

[15] V. Blazheva, "Digital technologies for sustainable solutions in the agricultural sector," 100th International Scientific Conference on Economic and Social Development - "Economics, Management, Entrepreneurship and Innovations" - Svishtov, Economic and Social Development , Vol. 100, 4-6 October, pp. 83-92, 2023. [Online]. Available: https://www.esd-conference.com/upload/book_of_proceedings/Book_of_Proceedings_esdSvishtov2023_Online.pdf [Accessed Jan. 11, 2025].

[16] J. Sohn and J. Kim, "Factors that Influence Purchase Intentions in Social Commerce," Technology in Society, Vol. 63, p. 101365, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0160791X20303183 [Accessed Jan. 11, 2025].

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 271-276

Expanded Selecting Criteria of Research Databases for University Libraries

Mehriniso Qudratova
Information library systems department Tashkent University of Information Technologies named after Muhammad al-Khwarizmi
Tashkent, Uzbekistan
qudratovamehr@gmail.com

Marat Rakhmatullayev
Information library systems department Tashkent University of Information Technologies named after Muhammad al-Khwarizmi
Tashkent, Uzbekistan
marat56@mail.ru

Sherbek Normatov
Information library systems department Tashkent University of Information Technologies named after Muhammad al-Khwarizmi
Tashkent, Uzbekistan
shb.normatov@gmail.com

Laylo Sayfieva
Information library systems department Tashkent University of Information Technologies named after Muhammad al-Khwarizmi
Tashkent, Uzbekistan
sayfiyevalaylo05@gmail.com

Sarvinoz Berdibekova
Information library systems department Tashkent University of Information Technologies named after Muhammad al-Khwarizmi
Tashkent, Uzbekistan
sarvinozberdibekova@gmail.com

***Abstract*— Access to valuable scientific and educational resources is an important aspect of the effectiveness of the educational process. Depending on their financial capabilities, academic libraries subscribe to various databases of the world's leading publishers. It is very important to evaluate certain databases in order to select the necessary sources of information for educational and scientific activities. The purpose of the article is to determine the most important criteria for evaluating scientific and educational databases in academic libraries based on a survey conducted among teachers and students of technical universities of the Republic of Uzbekistan. The key criteria are content relevance, thematic coverage, usability, accessibility, technical specifications, licensing models, and scalability to meet future needs. The study emphasizes the importance of aligning database selection with institutional research priorities, user accessibility requirements, and emerging fields of study. Additionally, the role of open-access resources, interdisciplinary content, and vendor support in decision-making is analyzed. By developing a comprehensive framework for database evaluation, this article provides valuable insights for librarians and academic institutions seeking to optimize their resource offerings and support diverse research endeavors.**

***Keywords*— Selecting criteria, scientometric indicators, university library, Uzbekistan, world scientific database.**

I. Introduction

There are countless research databases available today, each offering unique collections of resources tailored to specific fields of study. Examples include interdisciplinary databases such as EBSCOhost, Springer, Francis Taylor, as well as the ProQuest dissertation database, specialized platforms such as PubMed for the medical sciences or IEEE Xplore for engineering and technology, and JSTOR for the humanities and social sciences. However, not all databases are equally relevant or suitable for every academic discipline or research purpose. However, not all databases are equally relevant or suitable for every academic discipline or research purpose.

While multidisciplinary databases provide broad coverage across various fields, they may lack the depth needed for specialized research. Conversely, highly focused databases excel in delivering in-depth resources for a single discipline but may fail to address interdisciplinary research needs. This diversity highlights the importance of carefully evaluating and selecting databases based on the specific requirements of researchers and institutions. The ideal database should align with the goals of the research, the scope of the subject, and the accessibility needs of its users [1].

Electronic databases are now necessary for research because they give researchers remote access to a wider range of relevant information. Emmasiegbu and Anaehobi expressed that the use of databases in the

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8593
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

academic setting had both direct and indirect effects on academic staff efficiency[2]. In addition to teaching and community service, academic staff members are expected to conduct high-quality research and impart ideas relevant to their areas of expertise. In the digital transformation, e-books, e-journals, e-databases, and e-magazines have replaced print books, magazines, and journals as knowledge centres[3].

TABLE 1 DATABASE SELECTING CRITERIA

Universities	Criteria
American Library Association (ALA)[4].	a. Relevance b. Suitability of physical form c. Suitability of subject and style d. Cost e. Importance timeliness f. Relation g. Attention (critics and reviewers) h. Potential i. Requests
University of Bath Library (United Kingdom) [5].	a. Relevance b. Geographical coverage c. Bias d. Quality e. Cost f. Licensing
Brown university Library (United States) [6].	a. Relevance b. Scope and content c. Depth d. Quality e. Currency and timeliness f. Bibliographic accessibility g. Price h. Language and country of origin
The Southern California online User Group (SCOUG)[7].	a. Consistency b. Coverage/Scope c. Timeliness d. Accuracy/Error rate e. Accessibility/Ease of Use f. Integration g. Output h. Documentation i. Customer Support and Training j. 10. Value-to-Cost Ratio
By authors	a. Relevance to the field of research being conducted b. Scope and content c. Price d. Potential e. Language and country of origin

When selecting online databases for a university library, you can consider things like:

- **Relevance:** What types of documents the database index
- **Suitability of physical form:** refers to how well the physical characteristics of an item (such as a book, journal, or digital resource) match its intended use and environment. This concept is important in library science, publishing, and information management.
- **Suitability of subject and style:** refers to how well the content and writing style of a resource (such as a book, article, or database) match the needs of its intended audience and purpose.
- **Importance timeliness:** refers to how crucial it is for information, content, or resources to be current, up-to-date, and relevant to the present time or situation. In the context of libraries, research, and publications, timeliness ensures that the materials being used or provided reflect the latest developments, trends, or data.
- **Relation:** refers to the connection or association between two or more things, concepts, or entities. In various contexts, it can describe how items are linked, how they influence one another, or how they are relevant to each other
- **Attention (critics and reviewers):** refers to the focus, consideration, or scrutiny given by critics and reviewers to a particular work, performance, or product, such as a book, movie, research article, or artwork. It highlights how the piece is evaluated, discussed, and analyzed by those who have expertise or influence in a particular field
- **Potential:** refer to the factors considered when evaluating the ability of a database to meet future needs and growth. In the context of database selection, "potential" often refers to the long-term value, scalability, and capacity of a database to adapt to evolving user demands and technological advancements.
- **Requests:** Refer to the specific factors or guidelines used when selecting a database to fulfill particular requests, whether for research, academic, or business purposes. When selecting a database, various criteria help ensure that it will meet the needs of users effectively and efficiently.
- **Depth:** refers to the extent and comprehensiveness of the content within a database, determining how much detailed, in-depth, or specialized information it offers on a specific subject or field. Depth assesses how thoroughly a database covers a particular topic, including the richness of its content and the ability to provide users with detailed insights.
- **Currency and timeliness:** in database selection criteria refer to the relevance of the database's content in terms of its up-to-date information, ensuring that it reflects the

latest developments, trends, research, and data. These criteria are crucial for ensuring that the database provides users with current and accurate materials that are relevant to ongoing research or decision-making.

- **Bibliographic accessibility:** in database selection criteria refers to the ease with which users can access, search, and retrieve bibliographic information (such as citations, references, and metadata) within a database. It focuses on the availability of structured, well-organized data that makes it simple for users to locate relevant materials and sources.
- **Language and country of origin:** in database selection criteria refer to the linguistic diversity and geographic relevance of the database's content. These factors ensure that users can access resources in their preferred language or relevant to their specific country or region.
- **Geographical coverage**: Whether the database covers a specific region
- **Bias**: Whether the database has any inherent bias in its coverage
- **Quality**: Whether the database provides high-quality resources
- **Cost**: Whether the database is affordable, especially if the library can get a consortial price
- **Licensing**: Whether the database has the correct licensing and license management[4][5][6].

Electronic database is a collection of structured data or information that can be searched and retrieved quickly using a computer system. Index/biblio- graphic databases (like Scopus, CiteSeerX, WorldCat, and Ulrichsweb) and full-text databases (e.g ScienceDirect, Springer, and EBSCOhost) make up the majority of these databases. There are additional types such as subject-based databases (like IEEE, Library and Information Science Source, Business Source Complete, AGORA, and PubMed/Medline). Meta-databases (such as ConsensusPathDB, Entrez, and Neuroscience Information Framework). Statistics/numeric databases (like Bureau of Labor Statistics, American Factfinder - US Census Bureau, and Balance of Payments Statistics - IMF eLibrary). Image/video databases (such as Pickup Image, 3D online action dataset and Audio-Visual Event (AVE) dataset). Subscription databases (e.g. IEEE, Emerald and ScienceDirect). Free/Low-cost databases (e.g. ScienceOpen, CORE, Eric, Jstor, HINARI and PLOS) [5].

Electronic databases can enhance academic work at the university. When faculty members become aware of the extensive use of these resources, it improves their teaching performance and other academic-related activities at the university [6].

Sivakami and Rajendran surveyed awareness, access, and sage of e-resources among faculty members in Arts and Science colleges in India. The findings revealed that both male and female users were aware of the availability of e-resources. The quality of research output by lecturers in the university community is assessed by their awareness of electronic databases. Even though other factors, such as training, availability, accessibility, and the skills of the user or computer literacy level, may positively or negatively influence the successful use of these databases, poor internet challenges may negatively influence it.[8]

Electronic databases have excellent potential for research, teaching, and learning, but many hindrances may tend to retard their usage in the library. A lack of training, poor infrastructure, and high usage costs hinder the full use of database resources [9].

A similar study was conducted in 2021 among four libraries in the state of Andhra Pradesh. Different types of electronic resources are either subscribed or purchased by the libraries of GITAM, KL and VU as per the requirement of various colleges, institutes and departments in the university. The found that majority of users are found to be using IEEE database, EBSCO database, DELNET Database, Springer, DELNET Database in libraries. Majority of users not using properly the following databases ASCE, ASME, ASTM, Emerald Database, Oxford University Press Database, Taylor & Francis Database, JGATE database, JSTOR Database, McGraw-Hill Access Engineering Database, NPTL & SONET Videos service. User Opinion about Effectiveness of electronic resources shows majority of users considered it as somewhat effective. The study observed the coverage of use of electronic resources especially online databases subscription is low in the libraries surveyed [10].

Furthermore, the study advised that the university libraries in South East Nigeria should enhance their financial plans to address the expenses of digital materials and for the education of personnel responsible for managing the digital collection growth. It also suggested that the libraries should undertake a bold strategy of obtaining digital resources via a consortium to benefit from the reduced rates linked with consortium membership [11].

In another research at central university libraries in Indea: in online databases, usability is heavily influenced by data retrieval features: the more efficient the techniques, the more likely it is that online databases will be used. In Project Muse, the usability percentage was highest followed by Emerald, JSTOR, and Elsevier. There is an efficient correlation between facilities and usability [12]. This trend suggests that users prioritize platforms with superior data retrieval capabilities, indicating a strong correlation between usability and efficient search functionalities. Consequently, online databases should

focus on enhancing these features to improve user engagement and satisfaction.

II. Materials and Methods

The purpose of the article is to determine the most important criteria for evaluating scientific and educational databases in academic libraries based on a survey conducted among teachers and students of technical universities of the Republic of Uzbekistan.

To achieve the goal, the following tasks are being implemented:

a) examine the extent of awareness of electronic databases for teaching and research by universities Uzbekistan;

b) identify the means through which awareness of electronic databases are created; and

c) determine the frequency at which universities in Uzbekisatan, use electronic databases.

The study adopted survey method. In this survey, bachelor's students, master's students, assistants, senior lecturers, associate professors, and professors participated, making up a total of 91 participants.

III. RESULTS AND DISCUSSION

The educational qualifications of those who participated in the survey were as follows: 28 students (bachelor), 31 students (master), 12 assistants, 11 senior lecturers, 2 associate professors, 1 professor, 6 others.

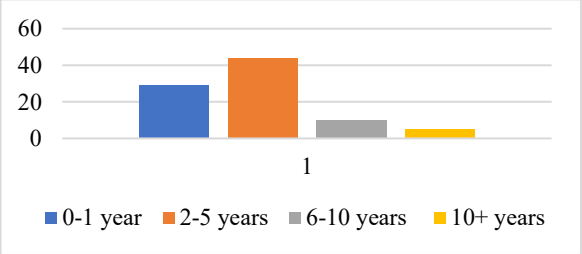


Fig 1 . Distribution of the respondents by years of work experience.

The following results were obtained regarding the years of work experience of the respondents: 29 participants had work experience between 0-1 year, 44 participants had experience between 2-5 years, 10 participants had experience between 6-10 years, and the remaining 5 participants had experience of more than 10 years.

In addition, it was determined how often the participants used the library of the organization in which they worked to meet their scientific needs. The majority of the participants said that they used the library of the organization in which they worked several times a week, which included 23 participants. 22 participants said that they used it several times a month. There were also participants who used the libraries regularly, that is, every day, and these participants amounted to 16 participants. It was found that 8 participants used it several times a year, 7 participants used it once a week, 7 participants did not use it at all, 5 participants used it once a month, and 3 participants used it once a year.

Table 2 Distribution of the Respondents Needs for Resources

Type of resources	Number of selected resources	Response rate
Collection of scientific articles	58	63,7 %
Dissertations	40	44 %
Fictions	32	35,2 %
Conference materials	25	27,5 %
Periodicals (newspapers and magazines)	20	22 %
Monographs	17	18,7%
Encyclopedias	11	12,1%
Other	1	1,1 %

Next, the information needs of the participants were determined. From the results, we can see that 58 participants (63.7%) have a great need for collections of scientific articles. 40 participants (44%) indicated a need for dissertations, 32 (35.2%) for fiction, 25 (27.5%), 20 (22%) for Periodicals (newspapers and magazines), 17 (18.7%) for Monographs, 11 (12.1%) for Encyclopedias and one participant indicated a need for other resources.

The majority of the survey participants (69.2%) consider scientific articles and research to be important for their scientific activities. In addition, we can find that scientific literature and textbooks (51.6%) and video tutorials and webinars (36.3%) are also important in meeting their needs. Some participants also considered technical documents and standards (16.5%) to be important, depending on their field.

In addition, when participants were asked which areas they would use to search for information in world databases, 40 (15.2%) of the participants said they needed information related to artificial intelligence. The remaining participants also chose areas related to various information technologies. The digital economy accounts for the largest share of these areas (11%).

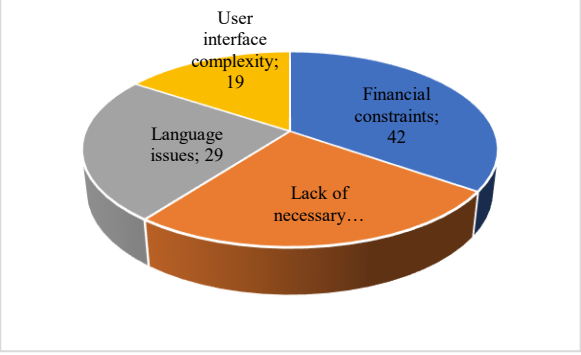


Fig 2. The main problems encountered in using world scientific databases.

When asked about the problems faced by the participants in using global scientific databases, 42 (34.7%) of them answered Financial constraints, 31

(25.6%) Lack of necessary resources, 29 (24%) Language issues and the remaining 19 (15.7%) User interface complexity. It is clear from this that financial problems are one of the most common problems in using world scientific databases.

We know that analytical systems are also important in the process of scientific activity. Therefore, we checked whether the participants had information about analytical systems. The question was asked about the importance of analytical systems in the process of scientific activity. We can see an analysis of this in Fig 3.

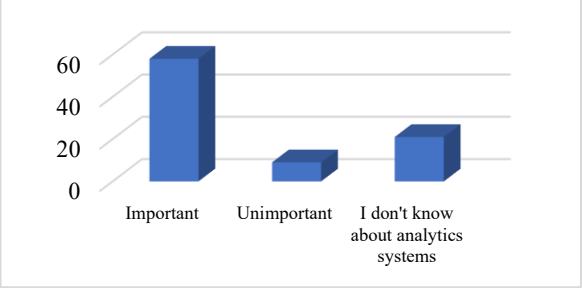


Fig 3. The importance of analytical systems in scientific activity.

When asked about analytical systems, 58 (65.9%) of the participants considered analytical systems to be important. 9 (10.2%) of the participants considered these systems to be unimportant. Unfortunately, the majority of the participants 21 (23.9%) said that they were not aware of these systems.

There are many indicators in analytical systems to assess scientific activity and identify changes (increase or decrease) in it. The participants' opinions on these indicators were also determined Fig 4.

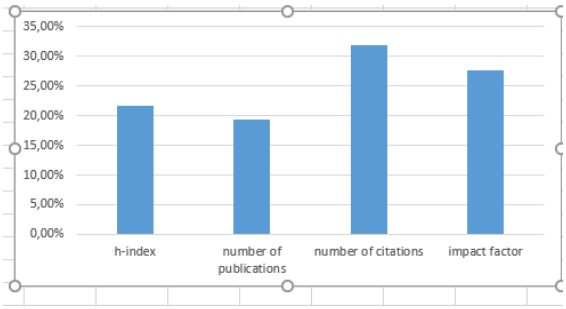


Fig 4. Scientometric indicators.

According to the participants, scientific metrics such as the number of citations to an article (31.8%), Journal Impact Factor (27.1%), h-index (21.7%), and number of published articles (19.4%) are considered important in conducting scientific activities.

At this point, the question may arise: what is the role of scientometric indicators in selecting global databases for universities? In fact, the main goal of selecting world scientific databases for universities is to increase the university's rating by improving the scientometric indicators of researchers conducting scientific activities.

TABLE 3 ANALYTICAL SYSTEMS FOR ANALYZING SCIENTOMETRIC INDICATORS

Analytical systems	Number of selected resources	Response rate
Web of Science	44	50%
Scopus	44	50%
GoogleScholar	44	50%
Researchgate	16	18,2%
SciVal	5	5,7%

It is clear from this that most of the participants use the most popular analytical systems to analyze their scientific activities. These are Web of Science (WoS), Scopus, and Google Scholar.

IV. CONCLUSION

The selection of research databases for university libraries requires a holistic approach that balances traditional criteria with emerging priorities. By incorporating factors such as accessibility, technical integration, and open-access content, libraries can better align their resource offerings with the diverse needs of their users. The expanded criteria proposed in this study provide a robust framework for evaluating databases and ensuring their relevance, usability, and cost-effectiveness in an evolving academic landscape. Future research should explore the application of these criteria in diverse institutional contexts to further refine and validate the framework.

In addition to the theoretical framework, this study included a survey conducted among university library users, including students, faculty, and researchers. The results revealed a strong and growing demand for access to global information resources, analytical platforms, and interactive database systems. These findings underscore the importance of not only maintaining core academic subscriptions but also expanding access to tools that support advanced data analysis and international scholarship.

By integrating user feedback with a strategic evaluation model, libraries can make more informed decisions that enhance the academic experience, support research productivity, and respond to the rapidly changing landscape of scholarly communication. As higher education institutions continue to digitize and diversify, the role of libraries in curating relevant, high-impact resources becomes increasingly vital.

REFERENCES

[1] S. Ameyaw, and F.K. Afua, The usage of Electronic Databases in Academic Libraries in Ghana. The Experience of Ghana Communication Technology University Library (GCTUL). International Journal of Knowledge Content Development & Technology, 14(2), 2024, pp. 7–27. [Online]. Available: https://journals.sfu.ca/ijkcdt/index.php/ijkcdt/article/view/875 [Accessed March 3, 2025].

[1] M. Emmasiegbu, and S. E. Anaehobi, Challenges to the use of electronic databases by lecturers in government-owned university libraries in Anambra State, Nigeria. Library Philosophy and Practice (e-journal), 5224. 2021. [Online]. Available: https://digitalcommons.unl.edu/libphilprac/5224 [Accessed March 3, 2025].

[2] U. Habiba, and S.Z. Ahmed, ICT infrastructure and access to online services: Determining the factors affecting faculty satisfaction with university-subscribed resources. International Information & Library Review, 53(2), 2020, pp. 112–130. doi: 10.1080/10572317.2020.1794204

[3] American Library Association (ALA). ALA Guidance on Selection Criteria. 2025. [Online]. Available: https://www.ala.org/tools/challengesupport/selectionpolicytoolkit/criteria [Accessed March 3, 2025].

[4] Bath University. How to do a Literature Search: Choosing a database, 2022. [Online]. Available: https://library.bath.ac.uk/literaturesearch/choosing-database [Accessed March 3, 2025].

[5] Brown University Library. (n.d.). Selection Criteria. Retrieved from https://library.brown.edu/colldev/criteria.php

[6] M. Manjunatha, Selection criteria for electronic resources. International Journal of Research in Library Science, 8, 2022, pp. 28–36. doi: 10.26761/ijrls.8.3.2022.1558

[7] R. Izuagbe, O.R. Olawoyin, C. Nkiko, P.I. Ilo, F. Yusuf, M. Iroaganachi, J. Ilogho, and G.I. Ifijeh, Impact analysis of e-databases' job relevance, output quality and result demonstrability on faculty research motivation. Library Hi Tech, 40(5), 2022. pp.1402–1421. https://doi.org/10.1108/LHT-03-2020-0050

[8] M.S. Ansari, Use and awareness of e-resources among research scholars of literature subjects at Banaras Hindu University. Library Philosophy and Practice (e-journal), 2020. [Online]. Available: https://digitalcommons.unl.edu/libphilprac/4667 [Accessed March 3, 2025].

[9] G.Rudraksha, R. Kona, and S. Chagari, S. (2021). Use of electronic resources in selected university libraries in Andhra Pradesh: A study, 2021. [Online]. Available: https://digitalcommons.unl.edu/libphilprac/5384/ [Accessed March 3, 2025].

[10] Okogwu, F., & Achebe, N. (2018). Selection and acquisition of electronic resources in university libraries in Southeast Nigeria: Challenges.

[11] P. Roy, S. Kumar and M. Satija. "Problems in Searching Online Databases: A Case Study of Select Central University Libraries in India," DESIDOC Journal of Library & Information Technology, 2022 32(1). https://doi.org/10.14429/djlit.32.1.1407

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 277-283

The Intersection of Artificial Intelligence and Employment Legal Relations: Balacing Employer Interests with Fundamental Rights in AI-Driven Employment Practices

Agnese Reine
Faculty of Social Sciences
Riga Stradiņš university
Riga, Latvia
agnese.reine@rsu.lv

***Abstract*— In the era of rapid technological advancement, artificial intelligence (hereinafter "AI") has profoundly transformed various sectors, notably employment. The integration of AI in employment practices represents a significant paradigm shift, enhancing efficiencies but also introducing substantial challenges. This integration poses complex legal issues, particularly in balancing employer interests with employees' fundamental rights, in particular to privacy. As of August 1, 2024, the European Artificial Intelligence Act (hereinafter "AI Act") was enacted. This legislation introduces a risk-based framework that mandates specific responsibilities for both providers and deployers of AI systems. Within the context of employment legal relationships and the integration of various AI systems therein, it is crucial to conduct a thorough analysis of the interplay between the General Data Protection Regulation and the stipulations of the AI Act. This article examines the legal frameworks that regulate rights to privacy and AI-driven employment practices, emphasizing the imperative to reconcile employer objectives—such as productivity and cost-efficiency—with employees' rights to privacy, non-discrimination, and equitable treatment. Through a detailed comparative analysis of extant legislation and case law, this study identifies deficiencies in current legal protections and advocates for a framework that ensures AI systems in employment conform to fairness and human rights principles. The article argues for a proactive legislative approach that not only addresses current challenges but also anticipates future ethical and legal issues arising from advancements in AI technology.**

Keywords*— *Artificial Intelligence, Business Objectives in Employment, Non-discrimination, Rights to Privacy

I. INTRODUCTION

In the century marked by rapid technological development, AI has assumed a significant role. Every day, the use of AI significantly increases across various sectors, including employment, providing opportunities to enhance employee efficiency, facilitate daily tasks, and monitor task performance etc. The use of AI must be analyzed in connection with its potential impacts on individuals, in particular in ensuring protection of privacy.

The European Council of October 2017 stated that to successfully build a Digital Europe, the EU needs in particular: [..] a sense of urgency to address emerging trends: this includes issues such as artificial intelligence and blockchain technologies, while at the same time ensuring a high level of data protection, digital rights and ethical standards. Also, the European Council invited the Commission to put forward a "European approach to artificial intelligence"[1]. Following this, European Commision stated: "The EU's approach to artificial intelligence centers on excellence and trust, aiming to boost research and industrial capacity while ensuring safety and fundamental rights. The way we approach AI will define the world we live in the future. To help build a resilient Europe for the Digital Decade, people and businesses should be able to enjoy the benefits of AI while feeling safe and protected [2]." Therefore, it is clearly stated, that artificial intelligence solutions should be implemented and used in processes around different areas, however it should be managed in a way, that ensures fundamental rights and freedoms.

The aim of this article is to analyze the interaction between legal framework of employment, artificial

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8571
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

intelligence and privacy protection, define the impact on the provision of fundamental rights and suggestions how to ensure balance between employers interests and employees rights to privacy in the rapid development of the artificial intelligence.

II. MATERIALS AND METHODS

This article utilizes interdisciplinary methods, such as analytical, descriptive, deductive and inductive methods, as well as following interpretative methods of legal acts: grammatical, historical, systemic, teleological. The mentioned methods will be used to analyse the legal regulations of employment relations and artificial intelligence, case law, scientific and other sources, to identify issues and their impact on the protection of fundamental rights.

III. RESULTS AND DISCUSSIONS

As of August 1, 2024, the European AI Act was enacted. This legislation introduces a risk-based framework that mandates specific responsibilities for both providers and users of AI systems, which are tailored according to the risk level associated with their deployment. Recital 1 of the AI Act states: "The purpose of this Regulation is to improve the functioning of the internal market by laying down a uniform legal framework in particular for the development, the placing on the market, the putting into service and the use of AI systems in the Union, in accordance with Union values, to promote the uptake of human centric and trustworthy AI while ensuring a high level of protection of health, safety, fundamental rights as enshrined in the Charter of Fundamental Rights of the European Union (the 'Charter')[..] [3]." Also recital 2 states: "This Regulation should be applied in accordance with the values of the Union enshrined as in the Charter, facilitating the protection of natural persons, undertakings, democracy, the rule of law and environmental protection, while boosting innovation and employment and making the Union a leader in the uptake of trustworthy AI [3]." Thus, the above clearly points to the main EU objective, i.e., boost innovation and employment while ensuring the fundamental rights and freedoms established in the Charter of Fundamental Rights of the European Union (hereinafter "the Charter"). Article 7 "Respect for private and family life" of the Charter states, that everyone has the right to respect for his or her private and family life, home and communications and Article 8 "Protection of personal data " states, that everyone has the right to the protection of personal data concerning him or her [4]. Therefore, the Charter states, that protection of privacy inlcuding data protection is one of the fundamental rights of individuals. Taking into account what is stated in Recitals 1 and 2 of the AI Act, it is clear that the implementation and use of AI must be aligned with the protection of fundamental rights, particularly data protection.

In addition to the previously mentioned scope of the Charter, it's also worth mentioning the European Convention on Human Rights, which in Article 8 stipulates the right to respect for private life[5]. In interpreting this Article 8 of the European Convention on Human Rights, the European Court of Human Rights (hereinafter "ECtHR") has recognized that the concept of "private life" has a broad scope. The acquisition and storage of personal data fall within the ambit of the right to respect for private life. In analyzing the interplay between employment legal relations and personal data protection, it should be noted that as early as December 16, 1992, in the case of "Niemietz v. Germany", the ECtHR clarified that it would be overly restrictive to apply the concept of private life only to the "inner circle" in which an individual can live his personal life as he chooses, and to completely exclude the outside world, which does not fall within this circle. Respect for private life also includes the rights to a certain extent to form and develop relationships with other people. Moreover, it seems there is no fundamental reason why this understanding of "private life" should exclude professional or business activities, as it is precisely in work life that most people have significant, if not the greatest, opportunities to develop relationships with the outside world. This observation by the ECtHR indicates a broad interpretation of the concept of private life, including its applicability to employment legal relations[6]. The regulation of personal data protection has evolved over the years into what is now known as the General Data Protection Regulation (hereinafter "GDPR").

Thus, the use of AI systems must be interpreted in conjunction with the GDPR [7], which has been applicable since May 25, 2018, regulating aspects of personal data protection in the EU.

Furthermore, it is necessary to analyze requirements set out in the AI Act and GDPR and assess their impact to the employment legal relationship.

The use of AI systems in recruitment and already established employment legal relationship, offers a significant opportunity to enhance employee performance, improve overall company performance and efficiency, and simplify and streamline various processes. Such use of AI is also in line with the EU's aforementioned position on AI development. However, it is essential to analyze, the risks associated with the use of AI systems in employment legal relationship, particulartly focusing on data protection as one of the fundamental rights, as well as analyze how to ensure a balance between the employer's interests and the employee's right to privacy.

Initially, it is essential to analyze the requirements governing the use of AI systems in employment relationships and subsequently examine these conditions in the context of GDPR compliance.

According to the Article 6 (2) of the AI Act and respective Annex III (4): "(a) AI systems intended to be

used for the recruitment or selection of natural persons, in particular to place targeted job advertisements, to analyse and filter job applications, and to evaluate candidates; (b) AI systems intended to be used to make decisions affecting terms of work-related relationships, the promotion or termination of work-related contractual relationships, to allocate tasks based on individual behaviour or personal traits or characteristics or to monitor and evaluate the performance and behaviour of persons in such relationships [3]", are considered as high-risk AI systems. Also Recital 57 of the AI Act explains, that: "AI systems used in employment, workers management and access to self-employment, in particular for the recruitment and selection of persons, for making decisions affecting terms of the work-related relationship, promotion and termination of work-related contractual relationships, for allocating tasks on the basis of individual behaviour, personal traits or characteristics and for monitoring or evaluation of persons in work-related contractual relationships, should also be classified as high-risk, since those systems may have an appreciable impact on future career prospects, livelihoods of those persons and workers' rights [3]. Therefore, in scope of this article, risks will be analyzed from the high-risk AI system perspective.

This article analyzes the use of AI systems, therefore the analyses is made from the *'deployer'* perspective in scope of definitions set out in the AI Act, i.e., from the perspective of the employer who uses AI systems under its authority. Requuirements towards the 'providers' are set out in the Section 2 of the Ai Act.

Article 26 of the AI Act sets out the obligations of deployers of high-risk AI systems, i.e. sets the requirements for the users of the AI systems. Deployers of high-risk AI systems shall 1) take appropriate technical and organisational measures to ensure they use such systems in accordance with the instructions for use accompanying the systems; 2) ensure that input data is relevant and sufficiently representative in view of the intended purpose of the high-risk AI system; 3) keep the logs automatically generated by that high-risk AI system to the extent such logs are under their control; 4) monitor the operation of the high-risk AI system on the basis of the instructions for use and, where relevant, inform providers (icl. In case of a high risk identified, incident and other situations defined in Article 16 (5)) [3]. Also, obligations include specific requirements towards the emploers, stating, that before putting into service or using a high-risk AI system at the workplace, deployers who are employers shall inform workers' representatives and the affected workers that they will be subject to the use of the high-risk AI system. Also Article 26 (11) states, that deployers of high-risk AI systems referred to in Annex III that make decisions or assist in making decisions related to natural persons shall inform the natural persons that they are subject to the use of the high-risk AI system [3]. Thus, this requirement is relevant for AI systems used in recruitment and employment as it is stated in Annex III of the AI Act.

In addition to the aforementioned obligations, Article 27 of the AI Act requires deployer to do the Fundamentas rights impact assessment for high-risk AI systems.

The aim of the fundamental rights impact assessment is for the deployer to identify the specific risks to the rights of individuals or groups of individuals likely to be affected, identify measures to be taken in the case of a materialisation of those risks [3].

However these requirements are not applicable to all high-risk AI systems, but only to those specified in Article 27 (1) of AI Act [3], that does not include high-risk employment, workers' management and access to self-employment systems. Respectively, if AI systems are used in recruitment or employment relationships, there is no requirement to conduct a Fundamental Rights Impact Assessment. However, it is important to note that according to the AI Act, EU member states are allowed to impose stricter requirements through national laws related to the governance of high-risk AI systems, therefore, the regulatory framework may differ in each EU country.

When analyzing high-risk AI systems in scope of employment, it is important to remember, that it is acknowledged that the employee is in a position of subordination to the employer, therefore, the incorrect use of AI systems can have significant consequences for the employee. Considering that an employee in a less protected position may not be able to fully defend their rights, there is a substantial risk that the employee's fundamental rights could be compromised. Therefore, it is crucial to conduct a thorough risk assessment of AI systems used in recruitment and employment to ensure compliance with fundamental rights such as data protection. While a Fundamental Rights Impact Assessment is not mandatory unless specified by national laws, all requisite measures related to the processing of personal data, such as the Data Protection Impact Assessment (DPIA), must be adhered to. Even though the Data Protection Impact Assessment (DPIA) is broadly focused on assessing all potential impacts on data subjects, it is the author's opinion that with the implementation of AI systems in daily operations, the DPIA should also be further developed to specifically address and assess the detailed risks of infringing fundamental rights.

Continuing to analyze the risks associated with the use of AI, particularly in ensuring the protection of personal data, this article will examine some of the most significant risk factors.

A significant amount of personal data is processed even before an employment legal relationship is established, notably during the recruitment process. With the advancement of AI technologies, companies are seeking to make recruitment more efficient and are therefore eager to exploit the opportunities provided by AI systems. Recruitment is a complex process that demands significant time and effort to evaluate and select

the most suitable candidate for a position. Employers are keen on streamlining this process to make it as quick and efficient as possible, thereby conserving the resources of HR personnel.

Artificial Intelligence (AI) significantly enhances recruitment efficiency by automating routine tasks, including screening resumes, parsing extensive data sets, and conducting preliminary candidate assessments. These systems are adept at analyzing large volumes of data to identify optimal candidates for specific roles. More than merely evaluating skills and experiences listed on resumes, AI can infer potential cultural fit by analyzing various data points that might be overlooked by human recruiters. Additionally, AI leverages historical data to predict outcomes such as job performance and candidate-job fit, offering a predictive approach to hiring decisions. AI systems also excel in managing large volumes of applications, which enables large organizations to scale their recruitment efforts effectively without the need for additional human resources. Furthermore, AI-driven chatbots and automated systems are able enhance the candidate experience by providing timely updates, feedback, and guidance throughout the recruitment process. These capabilities demonstrate AI's pivotal role in transforming recruitment processes, and explains the interests of the employer in using this kind of systems, however it is crucial to evaluate possibilities provided by the AI recruitment systems versus the GDPR requirements. The benefits of AI in recruitment, as outlined above, are indeed attractive to many company managements seeking efficiency and scalability. However, the implementation of these AI systems must be navigated carefully due to strict data protection regulations, notably the GDPR. GDPR imposes several key requirements that could limit the use of AI.

When analyzing the utilization of AI systems in established employment legal relationships, several objectives for deploying AI systems emerge. AI systems enable comprehensive monitoring of employee performance, analyzing data over time to discern trends, strengths, and areas needing improvement. Moreover, AI-driven platforms regularly assess employee satisfaction and engagement, utilizing data analytics to pinpoint potential issues or patterns throughout the organization. AI also enhances HR operations by processing extensive data from various activities, offering insights into workforce dynamics, productivity levels, and the overall effectiveness of HR policies. Additionally, AI automates routine administrative tasks such as timekeeping, scheduling, and compliance reporting. In certain cases, AI can even monitor the health and well-being of employees by analyzing metrics like work hours, physical activity levels, and self-reported mood scores. Each of these applications demonstrates AI's potential to transform traditional employment practices by providing more in-depth, data-driven insights and automating administrative processes, thereby optimizing workforce management and operational efficiency.

Taking into account various possibilities of using AI systems in recruitment and established employment relationships, it is crucial to address several aspects of the GDPR that are particularly pertinent. By highlighting these regulatory considerations, the article aims to balance the legal boundaries necessary to foster both technological advancement and privacy protection in employment practices.

Within the scope of this article, two crucial aspects from the data protection perspective will be analyzed: 1) the use of consent as a legal ground for processing personal data in AI systems; 2) automated decision-making, including potential biases and the ability for data subjects to exercise their rights.:

1) Consent – consent is one of the legal grounds stated in the GDPR that can be used as a legal basis for processing personal data. In scope of employment legal relationships, consent is not commonly used as a legal basis for processing personal data due to the dependent nature of the employee-employer relationship. This dependency may lead to consent that is not fully compliant with GDPR requirements. Conversely, in the recruitment process, consent is frequently utilized as a legal ground for processing data collected from the candidates. According to the GDPR, consent should be given by a clear affirmative act establishing a freely given, specific, informed and unambiguous indication of the data subject's agreement to the processing of personal data relating to him or her, such as by a written statement, including by electronic means, or an oral statement [7]. This includes, that clear and understandable information needs to be provided to the data subject, in this case employee about the consent that is beeing collected, i.e., what amount of personal data will be collected, for what exact purposes, etc. Therefore, when analyzing the requirements set out in the GDPR regarding consent, and in the AI Act, particularly the obligations for employers to inform affected workers of their exposure to high-risk AI systems, it can be concluded that this information should be provided at the very beginning of the recruitment process. This includes before collecting personal data and prior to its use in AI systems. Consequently, the information required for consent to be lawful and the information about the use of AI systems could be provided simultaneously.

However, prior to implementing such solutions for recruitment, employers should assess the impact of the solution on potential candidates, taking into account the data subjects' right to object at any time to the processing of personal data concerning them which is based on automated decision-making. This assessment should include the evaluation of possible alternatives, for

example, ensuring the possibility for candidates to opt out of the use of the AI system and proceed through the recruitment process in another manner. The aspects of the automated decision-making in scope of using AI systems are analyzed in the next section of the article.

2) Automated decision-making – if AI systems are used in recruitment process to screen resumes and to eliminate candidates, or in employment relationships – e.g., to analyze employee work efficiency in employment leading to termination of legal relationship, this is considered as automated decision-making according to the GDPR. Decisions made by automated means, in this case AI systems, without human envolvement grant employees ('data subjects' under GDPR) specific rights. These rights include requesting a manual review of the decision, involving human oversight. Article 22 (1) of the GDPR states, that the data subject shall have the right not to be subject to a decision based solely on automated processing, including profiling, which produces legal effects concerning him or her or similarly significantly affects him or her [7], thus, employers in scope of implementing use of AI systems in their processes need to ensure, that the candidates and employees are able to excersise their rights according to the GDPR and ask for human envolvement into the decisions made by the AI system.

However, the use of AI systems in automated decision-making is further complicated by the GDPR requirements for transparently defining the logic embedded within the decision-making process. GDPR states, that meaningful information about the logic involved, as well as the significance and the envisaged consequences of such processing that involved automated decision-making should be provided. Unlike other types of automated decision-making, where specific logic and criteria are clearly established to guide decisions, ensuring full compliance with these GDPR requirements is challenging with AI systems. To effectively utilize AI systems in such contexts, a common understanding of how information about the decision-making process should be communicated is necessary. In the author's opinion, the European Data Protection Board (hereinafter "EDPB") should establish guidelines or specific provisions to clarify the explanation of the logic used in automated decision-making involving AI systems. This would facilitate unifyed application and adherence to GDPR requirements. Otherwise, the lack of specific guidance from the EDPB might lead to varying interpretations of the requirements across the EU, potentially resulting in non-compliance with GDPR mandates.

Also, similarly, when utilizing AI systems in decision-making, it is crucial to ensure that these systems do not perpetuate discrimination in any aspect of decision-making. As stated in Recital 75 of the GDPR the risk to the rights and freedoms of natural persons, of varying likelihood and severity, may result from personal data processing which could lead to physical, material or non-material damage, in particular: where the processing may give rise to discrimination [..] [7]. Also as set out in the AI Act, it is necessary to analyze and prevent any biases using AI system, however due to different type of AI systems, processes how the AI is trained and how the information provided to the AI system is analyzed, it is still a risk, that AI systems could be biass in their decision making, that might lead to discrimination.

AI Act states, that diversity, non-discrimination and fairness means that AI systems are developed and used in a way that includes diverse actors and promotes equal access, gender equality and cultural diversity, while avoiding discriminatory impacts and unfair biases that are prohibited by Union or national law. Biases can for example be inherent in underlying data sets, especially when historical data is being used, or generated when the systems are implemented in real world settings. Results provided by AI systems could be influenced by such inherent biases that are inclined to gradually increase and thereby perpetuate and amplify existing discrimination, in particular for persons belonging to certain vulnerable groups, including racial or ethnic groups [3].

As research from the EU Agency for Fundamental Rights highlights, users of predictive algorithms need to assess the quality of training data and other sources that influence bias and may lead to discrimination. Such bias and potential discrimination may be developed or amplified over time, when data based on outputs of algorithmic systems become the basis for updated algorithms. Consequently, algorithms that are used to make or support decisions about people, such as predictive policing, need to be assessed before and regularly after deployment. Special attention needs to be paid to the use of machine learning algorithms and automated decision-making [8].

Analyzing different scientific researh papers, it is clear, that it remains a debatable issue whether a human or an AI system can exhibit more bias in decision-making processes. Human and AI biases can consequently create a feedback loop, with small initial biases increasing the risk of human error, according to the findings published in Nature Human Behaviour [9], [10]. Co-lead author Professor Tali Sharot (UCL Psychology & Language Sciences, Max Planck UCL Centre for Computational Psychiatry and Ageing Research, and Massachusetts Institute of Technology) said: "People are inherently biased, so when we train AI systems on sets of data that have been produced by people, the AI algorithms learn the human biases that are embedded in the data. AI then tends to exploit and

amplify these biases to improve its prediction accuracy. Professor Sharot added: "Algorithm developers have a great responsibility in designing AI systems; the influence of AI biases could have profound implications as AI becomes increasingly prevalent in many aspects of our lives." [9], [10]. Thus, even the responsibility for training an AI system—including ensuring that decisions made by it are unbiased —falls under the provider responsibility, the deployer should also analyze the decisions made by the AI system to ensure there is no discrimination.

IV. Conclusions

Overall, this article has highlighted several important aspects to consider when integrating AI systems into employee recruitment and employment relationships. While it addresses key points such as non-discrimination, transparency in automated decision-making, and the division of responsibilities between AI providers and deployers, it also acknowledges the limitations of its scope. There are many more aspects of AI system usage in employment contexts that merit attention but are beyond the breadth of this article.

Main conclusions:

1. **Alignment with EU Values:** The European Union aims to foster innovation and employment while safeguarding fundamental rights and freedoms. This entails that the development, marketing, implementation, and usage of AI systems within the Union must adhere to Union values. This approach ensures the promotion of human-centric and trustworthy AI, alongside a robust protection of fundamental rights.
2. **High-Risk AI Systems in Employment:** AI systems used for recruitment or employee management—such as those deployed to analyze and filter job applications, assess candidates, make decisions affecting employment terms, or monitor employee performance—are categorized as high-risk. This designation underscores the significant implications these systems can have on personal and professional aspects of individuals' lives.
3. **Duty to Inform:** Before deploying high-risk AI systems within the workplace, it is mandatory for employers (deployers) to inform both workers' representatives and the affected workers about the implementation of these systems. This transparency is crucial in maintaining trust and adherence to ethical standards in the deployment of AI technologies.
4. **Impact Assessments:** Although specific requirements for Fundamental Rights Impact Assessments are not mandated in the employment sector under current regulations, the importance of conducting thorough and high-quality assessments remains critical. This includes the utilization of Data Protection Impact Assessments (DPIAs) which should be expanded to also thoroughly evaluate the risks AI systems might pose to fundamental rights.
5. **Consent in Recruitment:** When using consent as the legal ground for processing personal data in the recruitment process, information about the use of AI systems should be provided simultaneously. There is no need for separate consent specifically for the use of AI systems, as long as the information provided covers all aspects of personal data processing, including the deployment of AI.
6. **Right to Object:** In scenarios where AI systems are utilized in recruitment and/or employment that result in automated decision-making, it is imperative to ensure that candidates or employees can exercise their right to object to such processing. This right is crucial in cases where decisions could significantly affect their professional life, ensuring compliance with GDPR provisions on automated decision-making.
7. **Challenges with Automated Decision-Making:** The use of AI in automated decision-making complicates compliance with GDPR requirements, which demand transparency in the logic used within the decision-making process. Unlike other automated systems where the decision-making criteria are clear, AI systems often involve complex algorithms that are not transparent. To effectively deploy AI in such contexts, there must be a common understanding of how details about the decision-making process are communicated.
8. **Non-Discrimination in AI Decision-Making:** When utilizing AI systems in decision-making processes, it is imperative to ensure that these systems do not perpetuate discrimination in any form. This involves rigorous testing and monitoring of AI algorithms to detect and mitigate any biases that may exist within the decision-making framework. Ensuring fairness and equity in automated decisions is not only a technical requirement but also a legal and ethical imperative to uphold the standards of justice and non-discrimination enshrined in both EU law and broader international human rights norms.

Acknowledgments

This study was funded by the project "RSU internal and RSU with LSPA external consolidation", No. 5.2.1.1.i.0/2/24/I/CFLA/005

References

[1] European Council, General Secretariat of the Council, "European Council meeting (19 October 2017) – Conclusions," EUCO 14/17, October 19, 2017. [Online]. Available: https://data.consilium.europa.eu/doc/document/ST-14-2017-INIT/en/pdf . [Accessed: Feb. 1, 2025].

[2] "European approach to artificial intelligence," Apr. 9, 2025. [Online]. Available: https://digital-

strategy.ec.europa.eu/en/policies/european-approach-artificial-intelligence. [Accessed: Apr. 17, 2025].

[3] "Regulation (EU) 2024/1689 of the European Parlianment and of the Council of 13 June 2024 laying down harmonised rules on artificial intelligence and amending Regulations (EC) No 300/2008, (EU) No 167/2013, (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1139 and (EU) 2019/2144 and Directives 2014/90/EU, (EU) 2016/797 and (EU) 2020/1828 (Artificial Intelligence Act)," Jul. 12, 2024. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401689. [Accessed: Feb. 1, 2025].

[4] "Charter of Fundamental Rights of the European Union, (2000/C 364/01), Official Journal of the European Communities," C364/1, Dec. 18, 2000. [Online]. Available: https://www.europarl.europa.eu/charter/pdf/text_en.pdf. [Accessed: Feb. 1, 2025].

[5] "European Convention on Human Rights, Council of Europe," Sep. 3, 1953. [Online]. Available: https://www.echr.coe.int/documents/d/echr/convention_ENG [Accessed: Feb. 20, 2025]

[6] European Court of Human Rights judgement, "Niemietz v. Germany," 13710/88, Dec. 16, 1992. [Online]. Available: https://hudoc.echr.coe.int/eng?i=001-57887. [Accessed: Feb.21, 2025]

[7] "Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation)," OJ L 119, May 4, 2016. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R0679. [Accessed: Feb.21, 2025]

[8] European Union Agency on Fundamental Rights, "Bias in Algorithms – Artificial Intellligence and Discrimination," 2022. [Online]. Available: https://fra.europa.eu/sites/default/files/fra_uploads/fra-2022-bias-in-algorithms_en.pdf. [Accessed: Feb. 20, 2025].

[9] "Bias in AI amplifies our own biases," Dec. 18, 2024. [Online]. Available: https://www.ucl.ac.uk/news/2024/dec/bias-ai-amplifies-our-own-biases#:~:text=Artificial%20intelligence%20(AI)%20systems%20tend,new%20study%20by%20UCL%20researchers. [Accessed: Feb. 23, 2025].

[10] M. Glickman and T. Sharot, "How human–AI feedback loops alter human perceptual, emotional and social judgements," Nature Humane Behaviour, vol. 9, no.2, p. 345, February 2025. Available: Nature Human Behaviour, https://www.nature.com/articles/s41562-024-02077-2 [Accessed: Feb. 23, 2025], https://doi.org/10.1038/s41562-024-02077-2

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference, 2025. Volume II, 285-291

Nuclear Weapons - Consequences for the Biosphere in Case of Their Potential Use

Stefko Burdzhiev
Department of Security and Safety
Varna Free University "Chernorizets Hrabar"
Varna, Bulgaria
stefko.burdzhiev@vfu.bg

Maria-Magdalena Burdzhieva
Faculty of Pharmacy
Medical University - Varna
Varna, Bulgaria
maria-m_burdzhieva@abv.bg

***Abstract*—The study aims to investigate nuclear weapons - consequences for the biosphere in the case of their potential use. Understanding the devastating impact of nuclear weapons on the surrounding biological world, infrastructure, and cultural and material values poses a significant challenge for scientists. Modern theories explaining the destructive factors of nuclear weapons do not provide completely satisfactory answers and remain incomplete. This report will examine the dangers associated with the detonation of nuclear munitions, their various types, and the resulting destructive effects on our surrounding environment, as well as some of the main methods of protection.**

Keywords*— *nuclear ionizing radiation, natural and artificial radioactivity, plants

I. INTRODUCTION

After the detonation of atomic bombs, radioactive fission products of heavy nuclei and part of the unfissioned nuclear fuel enter the atmosphere. The entry of U-235 and Pu-239 occurs because the utilization coefficient of nuclear fuel never reaches 100%.

With the explosion of a thermonuclear bomb, the amount of fission products increases proportionally to the bomb's power. In an air nuclear explosion, an interaction process occurs between atmospheric oxygen and nitrogen, forming nitrogen oxides. An atomic bomb with a TNT equivalent of 20 megatons can form 50,000 to 500,000 tons of nitrogen oxides, which create nitric acid and lower the pH (acidity, alkalinity) of rainwater, i.e., acidify it.

The speed of transport of radioactive products can be significant. For example, in the city of Troy (USA), located 3,450 km from the Nevada test site, a powerful hurricane occurred 36 hours after a nuclear explosion test [1], leaving a trail of radioactive material along its path. A. Zitkus [2] found that fission products from experimental explosions conducted in Nevada and the Marshall Islands reached Germany in 10-20 days. Fission products from the same explosion can appear in the same place several times after a significant interval.

The gravitational deposition of smaller particles is hindered by various laminar and turbulent air mass flows that exist in the atmosphere. The descent of particles of all sizes in the atmosphere is always accelerated in the precipitation zone. It has been established that the amount of radioactive substances falling on the soil significantly increases on rainy days. In the explosion of high-power bombs and in cases where explosions are carried out at high altitudes, a reservoir of long-lived radioactive isotopes is formed in the stratosphere.

The speed of transition of radioactive products from the stratosphere to the troposphere probably depends on the size of the particles and the height at which they were ejected. In mid-latitudes, the speed increases in spring. Another, albeit significantly smaller, source of environmental pollution is the waste released from nuclear industry enterprises. The disposal of this waste is a very important problem, the proper resolution of which will prevent a number of undesirable consequences. For example, the burial of radioactive waste in seas and oceans can cause gradual contamination of water, marine flora, and fauna.

The greatest danger is posed by long-lived isotopes strontium-90 (Sr-90), cesium-137 (Cs-137), cesium-144 (Cs-144), and to a lesser extent, ruthenium-106 (Ru-106). During nuclear explosion tests in the atmosphere, several tens of megatons of fission products were released. According to some data, by the end of 1958, the total amount of Sr-90 and Cs-137 formed was 9.2 and 16.5 MCi, respectively.

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8607
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

From the atmosphere, fission products enter the soil, marine, and freshwater bodies, from where they pass into plants and animals, eventually entering the human body, i.e., the so-called migration of radionuclides (fission products) occurs. The fission fragments that contaminate the Earth's surface not only increase the natural background but also differ in nature from the isotopes that create natural radiation. Currently, Sr-90 and Cs-137 have been found in the air, atmospheric precipitation, soil, water, many plants (including those used for human food), muscles, bones, and other organs of animals and humans. It has been established that Sr-90 is most similar in properties to calcium and is localized in bone tissue.

The somatic effect of fission products depends on their nature, the degree and duration of radioactive exposure, as well as the individual characteristics of the organism. A dose of 400 R (Roentgen) is considered lethal for 50% of irradiated individuals.

The localization of radioactive substances in the soil depends on the soil composition, groundwater level, vegetation type, etc. For example, soils poor in calcium salts may contain large amounts of Sr-90. The amount of Cs-137 retained in the soil is probably related to the content of humic acids, which form corresponding complex compounds with Cs.

The amount of deposited radioactive products depends on the geographical latitude of the regions. For example, in the northern hemisphere (between 30° and 50° north latitude), it is about 3-4 times greater than in the southern hemisphere. The entry of long-lived fission products into the human body depends on the type of consumed food and is a result of the migration of radionuclides. For example, people who primarily consume plant-based food receive relatively more Sr-90 than those whose main source of food is milk and dairy products. The uneven contamination of the Earth's surface complicates the assessment of the consequences of nuclear weapon tests. Experimental verification of the impact of low doses of ionizing radiation created by global deposits is difficult, as observations must be conducted over many years and must ensure the statistical reliability of the results.

Observations on the consequences of nuclear weapon tests have always pursued a number of tasks, such as:

- Studying the formation and spread of radioactive aerosols in the atmosphere.
- Clarifying the patterns of radioactive fallout on the Earth's surface.
- Determining the content (degree of contamination) of artificial radioactive isotopes in various external environmental objects.
- Studying the distribution and migration paths of radioactive substances (natural and artificial) in the biosphere.
- Determining the impact of fission products on plants, animal organisms, humans, and the entire global population.

Solving these tasks requires the application of many scientific disciplines - nuclear physics, radiochemistry, hydrochemistry, biology, medicine, meteorology, oceanology, and soil science.

Studying global deposits, characterized by low concentrations of radioactive substances, requires the use of very precise research methods. Radiochemical analysis is performed using precipitation extraction, chromatographic, and other methods. Recently, devices for complete gamma spectrometric analysis, multi-channel gamma spectrometers, and for alpha - and less frequently beta-active preparations - thick-layer photo emulsions - have been widely used to determine gamma-emitting isotopes. Low-background 4π counters and special alpha - counting chambers are used to measure radioactivity.

The aim of the study is to investigate Nuclear weapons - consequences for the biosphere in case of their potential use.

II. Materials and Methods

Research methods:

- Theoretical methods.
- Mathematical statistical method.

The research results are presented in the work using tables and text [3].

III. Results and Discussion

We distinguish between air, underground, and underwater nuclear explosions.

An air nuclear explosion is distinguished from other types by the fact that the luminous ball does not touch the Earth's surface. A cloud of dust and smoke forms at the site of the explosion, which rises after the spherical explosion cloud. The dust cloud generally does not merge with the radioactive cloud. In this type of explosion, the shock wave has the widest range of action, and light radiation can cause serious damage at great distances from the epicentre. The radioactive products formed in the explosion remain in the troposphere and stratosphere. The radioactive fallout on the ground in the first minutes, hours, and days creates a critical radiological situation mainly in the destruction zone and along the path of the radioactive cloud, but it is less severe than the situation that can be created by surface explosions.

A surface nuclear explosion occurs directly on the Earth's surface or at a height of several tens of meters above it. The fireball is shaped like a hemisphere or a truncated sphere lying on its base on the Earth's surface. In the area of contact between the fireball and the Earth's surface, the soil layer is crushed, melted, partially turned into vapor, evaporates, and mixes with radioactive products under the influence of high pressure and temperature. The molten soil turns into a glass-like, highly radioactive slag that covers the Earth's surface in the explosion zone after solidification.

Unlike an air nuclear explosion, a surface explosion generates a strong air flow, which forms a significantly larger dust cloud. This creates conditions for intense radioactive contamination of the area, both in the explosion zone and along the path of the radioactive cloud. In this

case, the shock wave and light radiation have a smaller range of action compared to the air explosion. The effect of penetrating radiation in surface and air nuclear explosions is similar.

The damage inflicted on agricultural crops in the Hiroshima and Nagasaki areas in 1945 by the use of nuclear weapons confirmed that vineyards and orchards, as well as their support structures, were the most sensitive to damage. The damage to orchards and their support structures was greater in areas that were positioned perpendicular to the direction of the shock wave. At a pressure of -0.3 kg/cm², 30% of the trees are destroyed; at a pressure of 0.3 to 0.5 kg/cm², 50% are destroyed; and at a pressure above 0.5 kg/cm², the damage is complete.

The degree of damage to different crops varies depending on the distance from the explosion's center or epicenter, the plant's phenological stage of development, the variety composition, the development and power of the root system, and other factors. The orientation of the rows of perennial crops relative to the propagation of the shock wave is also significant [4].

In cereal crops, at early phenological stages of development, the plants may lodge but subsequently recover, without significantly affecting yields. At later phenological stages (milk-wax and full maturity), the damage may cause plant breakage, resulting in improper grain filling or partial shedding of mature seeds, thereby reducing yields.

Significant losses from the shock wave's impact will occur in vegetable crops, particularly tomatoes when the fruits have formed. Losses will be substantial at technical maturity. There will also be noticeable losses in sunflowers, corn, and some crops at later stages of development.

Protection of Plants from the Shock Wave: Considering the damage from the shock wave on cultivated vegetation, it can be noted that its spatial nature is limited (a few kilometres), and for the current level of agricultural production development, the shock wave does not pose a significant danger.

Protection of Plants from the Shock Wave: Considering the damage from the shock wave on cultivated vegetation, it can be noted that its spatial nature is limited (a few kilometres), and for the current level of agricultural production development, the shock wave does not pose a significant danger:

- Cereal Crops - Growing short-stemmed, lodging-resistant varieties; using the retardant CCC (chlorocholine chloride) to increase stem strength, applying good and timely agro-support (fertilization, irrigation, herbicide treatment), including avoiding separate harvesting, which is known to reduce the degree of loss; creating good organization in harvesting considering the extreme situation that has arisen.
- Perennial Crops - For the espalier formations of fruit crops and high formations of vines, special attention needs to be paid to the type and method of constructing the wire structures. The preserved products, if they cannot be used for fresh consumption, can be processed into compotes, grape juice, wine, or other concentrated alcoholic beverages.

As the shock wave moves, it carries various mechanical impurities, which settle on nearby territories and cause varying degrees of contamination of cultivated fields, meadows, and pastures. These areas need mechanical cleaning through sprinkling using different types of sprinkling equipment. Bees, plant pollinators, pollinate flowering plants treated with pesticides [5] - [8], contaminate honey with pesticides and may also transfer deposited radioactive elements.

The shock wave can cause the complete destruction of forest massifs at a front pressure greater than 0.5 kg/cm². At this pressure, trees are uprooted, broken, and thrown aside, forming dense pile-ups. At a pressure of 0.3 to 0.5 kg/cm², about 50% of the trees are destroyed, and at up to 0.3 kg/cm²—30% of the massifs. Young trees are more resistant to the effect of the air shock wave than older ones.

A. Light radiation

Among the destructive factors of a nuclear explosion, light radiation occurs the fastest. About 30% of the explosion's energy is used to form it. The source of radiation is the unreacted parts of the nuclear munition (charge, body, etc.) that instantly vaporize in the surrounding air, which heats up to several million degrees. Light radiation travels in a straight line at the speed of light. During a nuclear explosion, the duration of the glow is a few seconds, and in a thermonuclear explosion, several tens of seconds. For example, for a nuclear munition with a TNT equivalent of 1 km, the light radiation duration is 0.8 seconds, and for a thermonuclear explosion, it is 16 seconds.

When the temperature of the fireball's surface is 6000°C, the spectral composition of the light radiation is as follows: [4]

- Ultraviolet radiation with energy 13%
- Visible light with energy 31%
- Infrared rays with energy 56% of the total radiation energy.

Ultraviolet rays act immediately after the explosion and have harmful biological effects on living organisms, damaging human vision. Infrared rays have a thermal effect and cause the most significant damage to living organisms by causing various degrees of burns and igniting different objects, structures, products, and other unprotected objects.

The primary indicator characterizing light radiation is the light impulse, which represents the amount of light energy that falls on a unit of stationary and unshielded surface (1 cm²), located perpendicular to the direction of the radiation spread throughout the glowing time. It is measured in joules per square meter (J/m²).

The destructive effect of light radiation is expressed in its thermal effect on plants and objects. The light energy absorbed by plants and objects is converted into heat, heating them to varying degrees. The heating depends primarily on the amount of energy absorbed during illumination and other conditions, such as colour, shape, size, position of the heated surface, heat capacity, thermal conductivity, and the temperature of plants and objects at the time of heating.

The influence of colour is such that light-coloured plants reflect a significant portion of the light rays. Light colour hinders rapid and intense heating, while dark-coloured plants absorb most of the light and heat more intensely. Regardless of colour, in most agricultural crops, the strength of light damage will depend largely on the phenological stage of the crop. For example, cereal crops—wheat, barley, rye, oats, etc., during ripening, cease photosynthesis and turn straw-yellow. Naturally, they are expected to be most resistant to light radiation at this stage. In practice, the opposite is true. Semi-dried plants are most vulnerable to light radiation effects.

The shape of plant leaves and fruits also matters. Plants with wider, slightly convex leaves, arranged horizontally or downward-facing, such as most vegetable crops, potatoes, sunflowers, cotton, sugar and fodder beets, pumpkins, watermelons, melons, etc., will be more affected as light rays cover a significant portion of the leaf surface. Plants with vertically upright, elongated, and pointed leaves, arranged at various angles to the horizontal cross-section of the stem and at a sharp angle to the vertical cross-section of the stem, will be less affected. In round fruits, such as apples, pears, watermelons, tomatoes, etc., the light rays will cover and damage more than half of their surface. This phenomenon is often observed in practice, especially in tomatoes grown in cultivation facilities. Under the influence of sunlight, even though the light and heat impulse reaching the ground is reduced thousands of times, in summer, on a clear and warm day, sunscalds form on exposed fruits within hours, deforming or killing them. Essentially, sunscalds are identical to burns caused by light radiation from a nuclear explosion since the sun is a specific thermonuclear reactor where a continuous chain reaction occurs, synthesizing potassium nuclei from hydrogen nuclei.

The thickness of stems and leaves also affects the degree of light damage. In the case of a short-term heat impulse, as in a nuclear explosion, plants with thicker stems and leaves will absorb more energy than thinner ones. Therefore, damage to plants with thicker leaves and stems will be greater. An example of this is again the sunscald on tomatoes. While the fruits have large, pronounced burns, the leaves, under the same sunlight, exhibit minor burns.

The light flux of an air atomic explosion falls vertically on the surface in the nearby zone within a radius of 300-400 m. As the distance from the explosion centre increases, the angle of the rays changes. Thus, different crop types, depending on habitus, type of planting, and row direction, will be affected by light radiation to varying degrees.[9] Plants in the nearby zone, where the rays fall vertically, regardless of habitus, planting type, and row direction, will be completely destroyed. As the distance from the explosion centre increases, the angle at which the rays fall becomes sharper. In this situation, in the distant zone, the light flux's effect will be greater on plants standing vertically or high above the soil surface (light radiation covers a larger plant surface). Orchards, vineyards, and field crops like corn, sunflower, cereals, etc., will be more affected than crops at the same distance from the explosion centre, like sugar beets, fodder beets, beans, peas, potatoes, etc. The propagation of light radiation at an angle allows for penetration and damage within the plantation. In this case, the planting type and row direction influence the degree of damage. Crops sown or planted at greater row spacing will be more affected by light radiation due to less shading. Conversely, densely planted crops have much more shading, providing natural self-protection (shielding). This also applies to row direction and row width. Crops with rows oriented towards the explosion centre will be more affected than those with rows arranged transversely. This explains the requirements for row orientation and direction when establishing new orchards and vineyards. In all cases where terrain configuration and prevailing winds do not interfere, rows are oriented north-south for optimal sunlight exposure.

The degree of light damage will also depend on terrain configuration. Crops and plantations in ravines, behind natural elevations, windbreaks, tall trees, and other obstacles crossing the light radiation rays will be naturally protected from its effect.

Meteorological conditions will influence the degree of light radiation. The more transparent the atmosphere, the further the light flux spreads. For example, the light impulse of a medium-calibre nuclear munition in good visibility at 1 km from the explosion site is about 30 (1 cal = 4.186 J). At the same distance, the light impulse in poor visibility is about 15 cal/cm², and in dense fog—515 cal/cm². In dense fog, light radiation decreases sixfold. In connection with the temperature of plants at the moment of light radiation, the time of day during which the nuclear explosion occurs affects the degree of damage. Damage will always be smaller at night and in the early morning hours.

TABLE 1 – PLANT DAMAGE AT DIFFERENT TYPES AND POWER OF EXPLOSION (IN KM)

Nature of the defeat	Blast Power			
	1 Mt		10 Mt	
	Air	Earth	Air	Earth
Grade I st - wilting (*Slight heat damage on plants*)	20	13	53	34
Grade II nd - partial burn (*Significant heat damage to plants*)	14,5	9	40	24
Grade III th - General Burning (*Burning of cereals, orchards and forests)*	13	6	24	14

In a surface atomic explosion, the radius of damage is much smaller because the light flux travels parallel to the Earth's surface. Along its path, in this type of explosion, the

light rays encounter many more obstacles compared to an air explosion. Additionally, a significant portion of the light energy is used to melt the soil around the explosion centre, heat the ground-level air layer, and the dust raised by the shock wave. The damage caused by light radiation is of two types: direct and indirect. Direct action occurs when the light flux directly affects plants, causing overheating (scorching) or premature ripening of cereal crops. Indirect action occurs when light radiation affects plants through heated air masses caused by the fireball and fires ignited by agricultural products or vegetation. [4]

B. Penetration radiation

As a result of the nuclear or thermonuclear reaction, a very powerful stream of gamma rays, alpha and beta particles, and neutrons is generated.

Penetrating radiation includes ONLY gamma rays and neutron streams because alpha and beta particles have low penetrating ability in air. About 10-15% of the explosion's energy is used to form penetrating radiation.

The radius of penetrating radiation in an air explosion with a power of 20 Kt can be distributed as follows: up to 300 m - 100% mortality in exposed people (dose 10,000 R - Roentgen); up to 1.2 km - 75% mortality (dose 1,000 R); up to 2 km - radiation sickness of the 1st degree (dose 500 R).

In a thermonuclear explosion, lethal damage can occur at a distance of 3-4 km from the explosion's epicentre. The main source of gamma radiation is the "fragments" of substances from the atomic explosion, found in the fireball and the radioactive cloud. The effect of gamma rays lasts 10-15 seconds.

The destructive effect of penetrating radiation is determined by the ability of gamma rays and neutrons to ionize the molecules of living tissues, resulting in stable radioactive isotopes. These, in turn, decay, emitting alpha and beta particles and gamma rays. Thus, under the influence of neutrons, induced or secondary radioactivity arises. The elements formed in soil and water with the highest secondary radioactivity include zinc, iron, manganese, aluminium, sodium, etc. Secondary radioactivity is also acquired by food products, fodder, organs, and tissues of living organisms, were radioactive isotopes of sodium, phosphorus, chlorine, potassium, etc., form. [10]

Penetrating radiation and secondary radioactivity can have harmful biological effects on living organisms. Under these factors, agricultural crops will be irradiated, disrupting their normal development or completely killing them.

The most sensitive to radiation are those parts of the plants whose cells are in the process of division at the moment of irradiation and through which the plants form new cells and grow (root tips, leaf tips, fruits, etc.). It has been established that the inhibition of cell division depends on the phase in which the division occurs. In the early phase, inhibition becomes an irreversible process, killing the cells and later the plant.

The unit of measurement for radioactivity in the International System of Units is the becquerel, named in honour of Henri Becquerel, with the designation Bq and dimension 1/s. One becquerel is defined as one transformation (or decay) per second.

When plants are exposed to lethal doses of radiation (LD100), they do not die immediately, but after 3 to 4 weeks as a result of damage to the plant's reproductive capacity. The most characteristic feature of irradiated plants is the absence of external symptoms by which the affected plants can be identified (turgor state and green colour of plants do not differ from the control). In irradiated plants, growth is halted. The plants remain "living specimens," not forming new leaves and branches. This is particularly characteristic of cereal crops affected at the tillering phase. In some cases, minimal growth is observed, due to cell elongation rather than division. In irradiated plants, meristematic tissue cells are mainly affected.

Sudden death of irradiated plants can occur, primarily near the explosion's epicentre within a radius of up to 500 m, where ultra-high doses are received. Thus, in wheat, death occurs immediately at 2,000,000 R, and in potatoes at 200,000 R. At small doses, radiostimulation is observed. Seeds of different plants vary in sensitivity to ionizing radiation, and accordingly, they are classified as radiosensitive—beans, corn, timothy, ryegrass, rye, wheat, etc.; moderately sensitive—peas, vetch, oats, barley, sunflower, etc.; and relatively resistant—peas, hemp, alfalfa, clover, tobacco, etc. Unlike vegetating plants, the resistance of seeds to radiation is several times higher and is directly proportional to their maturity level and storage duration.

When radiosensitive seeds are irradiated with a dose of 20,000 R, germination is hampered and growth is significantly reduced. In moderately sensitive seeds, this effect is observed at a dose of 90,000 - 100,000 R, and in relatively resistant seeds, the dose must be increased to 150,000 - 200,000 R [4].

In plants derived from seeds irradiated with high doses, morphological changes are observed—reduced height, shortened internodes and branches, thickened stem, reduced number and size of leaves. Slight colour changes are also noted—increased sterility and reduced yield. The shape of seeds obtained from irradiated plants does not change.

Depending on the radiation dose, various deformations occur, which can lead to malformations or valuable radiomorphoses—fasciations.

Unlike warm-blooded organisms, plants exhibit significantly higher radioresistance. In vegetating plants, the lethal dose varies within sensitive limits, allowing for the classification of three groups of plants based on their radiosensitivity. The first group includes those with an LD100 between 1,000 and 5,000 R—onion (kaba) 1,500 R,

oats 3,300 R, barley, rye, and wheat 4,500 R, corn 4,200 R, legumes about 5,000 R, peas 4,600 R, etc. The second group, with an LD100 of 5,000 to 10,000 R, includes apples and pears with radioresistance of 5,000 to 7,000 R, plums and peaches 6,000 to 10,000 R, onions and garlic 7,000 to 10,000 R. The third group, with an LD100 above 10,000 R, includes the following crops: cabbage with radioresistance of 12,300 R, tomatoes 12,400 R, eggplant 15,000 R, potatoes 12,600 R, sunflower 20,000 R, rice 19,600 R, flax and hemp 20,700 R, and others.

The radiosensitivity of plants will be influenced by cultivation techniques, the physiological state of the plants, and climatic factors.

The effect of ionizing radiation is also influenced by external environmental conditions. At low temperatures, the radiosensitivity of plants increases. When cooling occurs during the vegetation period, damage to irradiated plants increases. Precipitation (atmospheric and soil moisture) plays a certain role in the effect of radiation, with high moisture levels increasing the radiosensitivity of plants. However, it should not be forgotten that this is related to the plant's phenological phase of development. The gas environment (atmosphere) has a significant influence, primarily depending on the oxygen content. The so-called oxygen effect of radiation is manifested. With increased oxygen content in the atmosphere, the radioresistance of plants increases. The presence of carbon dioxide (CO2), hydrogen (H), and other elements inhibits the effect of ionizing radiation.

Abundant and prolonged illumination reduces the impact of ionizing radiation on plants. This shows that in determining the biological effects of radiation on plant organisms, all factors influencing its effect must be considered.

In the primary processes occurring in cells under the influence of radiation, ionization and related chemical changes play a key role in the observed biological effect. Under the influence of ionizing radiation, positive and negative ions from the molecules of the chemical components of the cell are formed in the building blocks and other constituents of the cell [10].

The predominant component of the living cell is water, which accounts for the highest percentage of interaction between its molecules and radiant energy. Two types of ions are formed—positive and negative. [11, 12, 13]

$$H_2O \text{ ionising radiation } H2O+ + e- \quad (1)$$

The ejected electron attaches to another electrically neutral water molecule, converting it into a negative ion:

$$H_2O + e- \quad H_2O - \quad (2)$$

The resulting ions have an unstable electron structure, quickly dissociating to form two free radicals - hydrogen (H+) and hydroxyl (OH-), and two stable ions (H+ and OH-) that recombine to form water molecules:

$$H_2O \ N^+ — HE- \quad (3)$$

$$H_2O- \ HE- — H \quad (4)$$

$$H + OH- \ H_2O \quad (5)$$

The resulting free radicals also undergo recombination, forming water, molecular hydrogen, or hydrogen peroxide:

$$H + OH \ H_2O; \quad (6)$$

$$H + H \ H_2. \quad (7)$$

$$OH + OH \ H_2O_2 \quad (8)$$

In the presence of oxygen in the environment where ionization occurs, other reactions are also possible:

$$H + 0_2 \ HO_2 \text{ (hydroperoxide)}; \quad (9)$$

$$HO_2 + H \ H_2O_2. \quad (10)$$

These recombination reactions occur in the presence of oxygen and form the basis of the oxygen effect of radiation.

Similar changes are observed in the molecules of other chemical components of the cell—proteins, carbohydrates, fats, etc. The formation of free radicals completes the primary impact of ionizing radiation. Subsequently, secondary processes occur in which free radicals, produced by the radiolysis of water, react with the substances dissolved in it. This highlights the important role of water as a material (transport) carrier of ionizing radiation. Modern theory of radiation damage to organisms is primarily based on the radiolysis of water (the property of radioactive radiation to ionize substances being its most characteristic feature). [10]

Supporting this claim is the rule that the radioresistance of biological objects increases with the decrease in relative water content. Ionizing radiation does not directly affect the bio-object but indirectly through the radiolysis of water.

It is assumed that chain reactions occur in cells after irradiation, indicating that ionization does not diminish but proceeds with varying intensity along the biological chain.

Under the influence of direct radiation and the products of water radiolysis, biologically important molecules of the cell's main components are irreversibly altered.

Changes also occur in nucleic acids (protein components of complex proteins—nucleoproteins), which contain ribose—ribonucleic acids (RNA), and those with a carbohydrate component—deoxyribonucleic acids (DNA). Changes in them under the influence of ionizing radiation are crucial (DNA is the material carrier of heredity). Usually, the negative biological effect is expressed through two groups of reactions:

- The first affects the genetic code;
- The second destroys the carbohydrate part (matrix) of DNA.

These changes usually lead to strong genetic mutations. Carbohydrates, which are biochemically active cell compounds (monosaccharides, disaccharides, and polysaccharides) and are an important energy source for cell and organism building blocks, undergo changes in the concentration of sugars in glucose and fructose solutions under the action of ionizing radiation. Fructose decreases, acidity increases, and formaldehyde and molecule

destruction appear in the solution, leading to their degradation. [10]

IV. Conclusions

In our opinion, these issues deserve special attention from both scientists and specialists involved in nuclear, chemical, biological, and environmental protection in the state management system, at the national, regional, and municipal levels, defence, and national security, as well as the activities of supervisory and control authorities in this regard.

Theoretical research and the development of necessary and effective practical measures in these areas conducted so far represent a significant contribution to improving and developing such important interdisciplinary fields of scientific knowledge and practical spheres, such as radiation, chemical protection, and environmental security. Nonetheless, it is undeniable that much more needs to be done in this regard.

References

[1] N. Clark, Science, 119, 619, 1954.

[2] A. Sitkus, Naturwissenschaften, 42, 478, 1955.

[3] Z. Goša, Statistika. Rīga: Latvijas Universitāte, 2007.

[4] G. Sengalevich and V. Koleshev, Plant Protection Against Weapons of Mass Destruction. Sofia, SCA, 1988.

[5] I. Justs, L. Poiša, T. Vīksna, V. Pole, K. Ivanova, J. Vīksna, and A. Skromulis, Characteristics of the Beekeeping Industry in the Latvia. Environment. Technology. Resources. Rezekne, Jun 2024, Latvia. Proceedings of the 15 th International Scientific and Practical Conference, vol. 1, pp. 182–188, Jun. 2024. https://doi.org/10.17770/etr2024vol1.7990

[6] N.T. Dolchinkov, and M.P. Pavlov, Influence of Meteorological Elements in Accidents in Enterprises with Radioactive Elements or Dangerous Chemical Substances in Bulgaria. Environment. Technology. Resources. Rezekne, Jun 2023, Latvia. Proceedings of the 14 th International Scientific and Practical Conference, vol. 1, pp. 49–54, 2023. DOI:https://doi.org/10.17770/etr2023vol1.7221.

[7] L. Poiša, A. Adamovičs, K. Ivanova, and L. Antypova. The significance of bees (*Apis mellifera* L.) in preserving the natural environment. Продовольча безпека України в умовах війни і післявоєнного відновлення: глобальні та національні виміри : тези доповідей учасників міжнародної науково-практичної конференції, м. Миколаїв, Україна, 30-31 травня 2024 р. / Міністерство освіти і науки України. Миколаївський національний аграрний університет - Миколаїв, 2024, pp. 121-123. DOI: https://doi.org/10.31521/978-617-7149-78-0-38.

[8] L.Poiša, A. Adamovičs and A.Teilans, "Honey production in Latvia", Sustainable Food Industry, 2025, pp. 38-46. https://doi.org/10.17770/sfi2025.1.1.8372

[9] V. Marinov, Agricultural Radiobiology. Sofia, Zemizdat, 1989.

[10] M.M. Ivanov, Strategic Objects: Legal Regulation and Paradoxes." Legal Compendium, Vol. XXIX, 2022.

[11] G. Naidenov, Biological Effects of Ionizing Radiation, Sofia University "St. Kliment Ohridski," Physics Days' , Sofia, April 2016, pp. 19-23.

[12] N.T.Dolchinkov, State of the population disclosure systems in the changing radiation situation in Bulgaria, Environment. Technology. Resources.. Rezekne, Jun 2019, Latvia. Proceedings of the 12th International Scienfic and Practical conference Vol 1, pp. 54-58, ISBN 1691-5402, DOI: 10.17770/etr2019vol1.4152

[13] N.T. Dolchinkov and N. Nichev, Gamma-background radiation control systems as a factor of Bulgaria's national security, Environment. Technology. Resources. Rezekne, Latvia, Proceedings of the 15th International Scientific and Practical Conference. Volume IV, Print ISSN 1691-5402, Online ISSN 2256-070X, https://doi.org/10.17770/etr2024vol4.8225, pp 83-88

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 293-298

Methodological Approaches to Using Artificial Intelligence to Develop Creative Skills in Future Designers

Bohdan Rozputnia
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
b.rozputnia@vspu.edu.ua

Lyudmila Shevchenko
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
shevchenko@vspu.edu.ua

Volodymyr Umanets
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
umanets@vspu.edu.ua

Serhii Yashchuk
Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University
Vinnytsia, Ukraine
serhii.yashchuk@vspu.edu.ua

Yuliia Sabadosh
Vinnitsya National Technical University
Vinnytsia, Ukraine
avataric87@gmail.con

***Abstract*-The article analyzes methodological approaches to leveraging artificial intelligence (AI) technologies to foster the creative abilities of future designers. This study is highly relevant in the context of rapid digital transformation and the pervasive integration of innovative digital technologies across all sectors of society. It underscores the urgent need to revise and update pedagogical approaches that nurture creativity—a fundamental competence for modern designers. The purpose of this study is to develop a methodological framework for the effective integration of artificial intelligence tools into the training process of future designers, aimed at enhancing their creative potential, critical thinking, and adaptability in the context of digital transformation. The authors examine the specific potential of using generative AI models, such as Leonardo.AI and Microsoft Copilot (with DALL-E 3 integration), which enable rapid concept generation, as well as language AI models like ChatGPT and Gemini that automate text processing, information retrieval, and idea generation. A comprehensive examination of both theoretical and practical ramifications of integrating these tools into vocational education (specialty A5) is presented. The integration of these AI tools has the potential to optimize the training process, enhance creative imagination, and develop analytical skills and adaptability required by today's competitive labor market. The research methodology is based on a comprehensive model that integrates elements of competency-based, systemic, and personality-oriented approaches to creativity development. A comparative analysis of traditional teaching methods and innovative AI-based approaches is provided, emphasizing the formation of flexible and non-standard thinking in students. The study's findings highlight the necessity of continuous monitoring of the impact of AI technologies on the educational process to enable timely adjustments in methodological solutions and to manage risks associated with the automation of creative tasks. Based on an extensive review of the literature and open-source data, the study identifies both the advantages and limitations of using AI in design education. The authors note risks such as overreliance on automated content generation and potential loss of traditional design skills. To address these challenges, the article proposes a series of recommendations for the phased introduction of AI technologies through introductory classes, practical projects, brainstorming sessions, and creative competitions. These measures are designed to support the comprehensive development of students' creative potential and to maintain a balance between digital automation and hands-on, traditional design skills. In conclusion, the results demonstrate the feasibility and necessity of integrating AI into design education to develop professional, innovative, and transferable skills among future designers, equipping them to effectively compete in the evolving digital economy.**

Keywords - Artificial Intelligence, creative skills, design education, digital transformation.

I. INTRODUCTION

The accelerated digital transformation and the pervasive integration of innovative digital technologies across all sectors of society have dramatically reshaped the professional landscape for designers. In particular, the professional training of future designers now demands a comprehensive update of pedagogical approaches to equip

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8596
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

students with the relevant knowledge and skills necessary for success in a highly competitive, technology-driven labour market. While traditional teaching methods have been found to be effective in cultivating foundational design skills, they have been shown to fall short in fostering the dynamic creative abilities and critical thinking required in today's digital era.

The advent of artificial intelligence (AI) has precipitated a paradigm shift within this domain. AI is defined as a specialised field of computer science focused on developing systems capable of performing tasks that typically require human intelligence, such as learning, pattern recognition, decision-making, and creative content generation [1]–[2]. Within the domain of design education, generative AI models, including Leonardo.AI and Microsoft Copilot (with integrated DALL-E 3), present novel opportunities for expeditious concept generation by automating the creation of graphic content, analysing compositional solutions, and proposing design alternatives based on user-defined parameters. Concurrently, language models such as ChatGPT and Gemini have demonstrated the capability to automate text processing, information retrieval, and the generation of ideas for presentations and explanatory materials, thereby streamlining various aspects of the creative process [3]–[4].

Notwithstanding these encouraging advancements, the incorporation of AI technologies into design education is accompanied by a number of challenges. Existing literature highlights the dual nature of AI's impact: while it has the potential to enhance creative capacities and optimise training processes, there is also a significant risk of overreliance on automated systems. Such dependence may inhibit the development of critical thinking and diminish the cultivation of traditional design skills, such as hand-drawing, composition, and manual digital modeling [3]. Furthermore, ethical and legal concerns, particularly those related to copyright issues, arise when generative models such as DALL-E and Leonardo.AI utilise vast datasets that include copyrighted material. These challenges necessitate the development of robust normative frameworks and ethical standards to guide the responsible use of AI in educational settings [1], [3].

A significant gap in current research is the lack of a clearly defined methodological framework for integrating AI into the professional training of designers. While numerous studies have confirmed the effectiveness of generative AI models in the creative process, there is insufficient guidance on how to harmoniously combine digital tools with traditional pedagogical practices to foster both creative and critical competencies. The present study aims to address this gap by developing and substantiating methodological approaches for the integration of AI technologies into design education, with the aim of enhancing students' creative potential, analytical skills, and adaptability.

The purpose of this study is to develop a methodological framework for the effective integration of AI tools into the training process of future designers. Achieving this objective involves a multifaceted approach: a critical review of existing AI applications in design education, an analysis of their pedagogical implications, and the formulation of evidence-based recommendations for their integration. The study's objective is to provide a balanced perspective that maximises the benefits of AI while mitigating its risks. This is to ensure that students not only gain exposure to advanced digital technologies but also retain and develop essential traditional design skills.

The study emphasises the importance of ongoing monitoring and adaptive management of AI's impact on education, emphasising the necessity of timely adjustments to methodological approaches. The findings of the study aim to serve as a foundation for the development of innovative educational programs that cultivate designers who are competitive, creative, and critically minded, and who are capable of thriving in the evolving digital economy.

II. MATERIALS AND METHODS

This study was conducted at the Vinnytsia State Pedagogical University named after Mykhailo Kotsiubynsky, specifically within the Department of Digital Technologies. The sample comprised 60 undergraduate students and 20 instructors involved in teaching design courses. The study was carried out over the course of one academic semester.

The investigation focused on the integration of various AI tools into the design education process. The primary AI programs employed in this study included generative models such as Leonardo.AI and Microsoft Copilot (with integrated DALL-E 3), which were used for rapid generation of visual concepts, and language models such as ChatGPT and Gemini, which facilitated the automation of text processing, idea generation, and content creation.

The data collection process encompassed a combination of qualitative and quantitative methodologies. An online questionnaire was administered to all participants before and after the intervention to assess changes in satisfaction levels, perceived creativity, and overall impact on the design process. Furthermore, practical design projects and case studies utilising the aforementioned AI tools were implemented in selected courses to evaluate their real-time impact on the creative process. The outputs from these projects, including visual concepts and text-based design proposals, were analysed to determine the effectiveness of the AI applications.

The experimental findings were contextualised within broader trends in AI integration in design education by means of a comprehensive review of open-source literature and available reports. The statistical analysis of the data was conducted in accordance with standard methodologies, encompassing the comparison of metrics before and after the intervention, including mean satisfaction scores, creative task performance, and the duration required to complete design projects.

III. RESULTS AND DISCUSSION

The integration of AI into the professional training of future designers is a relevant area of research. Modern generative and language models of AI open up new opportunities for developing creativity, automating creative processes, and improving teaching methods.Given the rapid development of technologies, special attention should be paid to analyzing their impact on the educational process, the effectiveness of their use, and the potential challenges that teachers and students may face.

To this end, the authors conducted a pedagogical experiment on the impact of AI technology integration on the educational process among 60 students of the Department of Digital Technologies and 20 teachers of Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University.

To facilitate a more detailed analysis of the changes that occurred after the introduction of AI, Table 1 shows the key indicators selected by the authors before and after the experiment. The findings reveal a substantial enhancement in the educational process, thereby substantiating the efficacy of AI in fostering students' creativity.

TABLE 1. COMPARATIVE ANALYSIS OF INDICATORS BEFORE AND AFTER AI IMPLEMENTATION

Index	Before AI implementation	After AI implementation	Changes (%)
The mean level of satisfaction (measured on a 5-point scale)	3.2 ± 0.4	4.1 ± 0.3	+28.1%
Average score for creative tasks (%)	68	82	+20.6%
Time to complete a creative task (hours)	4.5 ± 0.6	3.1 ± 0.5	-31.1%
Use of creative ideas (score/10)	5.6 ± 0.8	7.9 ± 0.6	+41.1%
Key terms using frequency (per 100 words)	2.3	3.8	+65.2%

The survey results indicated a notable increase in student satisfaction with the integration of AI methodologies. The mean score on a five-point scale increased from 3.2 ± 0.4 to 4.1 ± 0.3, suggesting a substantial rise in satisfaction levels. Concurrently, the mean score for creative tasks escalated from 68% to 82%, reflecting a significant enhancement in the quality of creative output. The following diagrams compare these indicators before and after the introduction of AI tools, demonstrating a significant improvement in the results of the educational process (see Fig. 1 and Fig. 2).

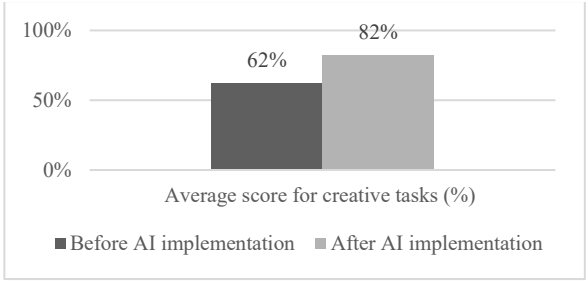


Fig. 1. Impact of AI Implementation on Creative Task Performance.

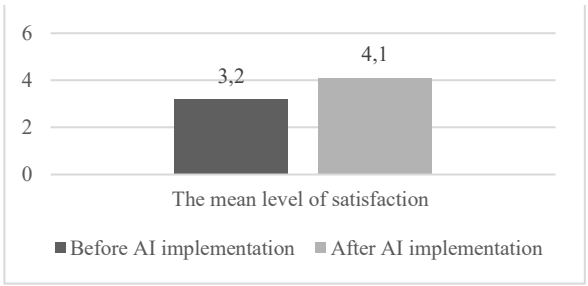


Fig. 2. Change in Satisfaction Levels After AI Implementation.

The examination of generative AI models draws on practical examples of integrating platforms such as Leonardo.AI and Microsoft Copilot with embedded DALL-E. These tools facilitate the creation of diverse, high-quality visual concepts, significantly streamlining the idea-generation process. For instance, the prompt *"Generate a modern, minimalist living room concept with Scandinavian-style furniture, large panoramic windows, soft natural lighting, and a neutral color palette. The design should include a cozy seating area with a coffee table and decorative indoor plants, following contemporary interior design trends."* yielded a comprehensive interior layout that illustrates how generative AI can assist in rapidly developing design concepts (Fig. 3).



Fig. 3. Result of generation in Leonardo.AI

Similarly, the prompt *"Create a futuristic, high-tech logo for an AI-driven startup. The logo should feature a sleek, abstract design with a combination of metallic blue and neon accents. The overall style should be minimalistic, professional, and suitable for a technology company."*

demonstrates the capacity of these platforms to generate distinctive brand elements (Fig. 4). The resulting images confirm the effectiveness of generative AI in supporting various design tasks.



Fig. 4. Result of generation in Microsoft Copilot (DALL·E)

As for the evaluation of AI language models, the results show a significant improvement in the quality of text content creation using ChatGPT and Gemini. The analysis of text generation indicators revealed that the frequency of key terms increased from 2.3 to 3.8 per 100 words on average, reflecting the increased structure and creativity of text descriptions. A graphical representation of these changes is shown in Fig. 5, which demonstrates the improvement in the quality of textual content compared to traditional methods.

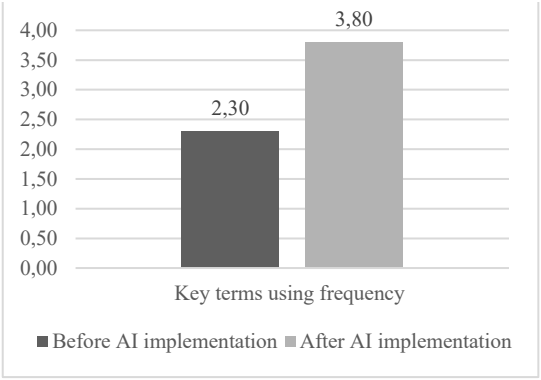


Fig. 5. Changes in key terms using frequency

The findings of the experiment substantiated the authors' hypothesis that the implementation of AI technologies exerts a favorable influence on the cultivation of creative aptitudes and professional competencies of prospective designers.Students who employed generative AI models during the execution of educational tasks exhibited a substantial enhancement in creative activity, as manifested by a 20.6% surge in creative task scores. Concurrently, a 31.1% reduction in the average time to complete tasks underscores the efficacy of automating specific design work stages, enabling students to prioritize the conceptual and analytical facets of the creative process.A comparison of the outcomes with prior studies [6-8] substantiates that they align with theoretical expectations. For instance, A. Jain and others [7] observe that generative models substantially accelerate the development of visual content, a finding that aligns with our observation of reduced task completion time. Furthermore, Crimaldi and Leonelli [8] substantiate that the integration of AI fosters experimentation with novel visual styles and amplifies the creative capacity of designers. Conversely, Kim and Lee [3] underscore the potential hazards of excessive automation, which might result in a diminution of autonomy in creative endeavors.In the present experiment, such risks did not materialize, likely attributable to the meticulous integration of AI tools into the educational milieu.

The analysis of the results indicates that generative models, such as DALL-E and Leonardo.AI, facilitate the identification of non-standard solutions and the development of visually appealing concepts, thereby obviating the necessity of extensive expertise in manual digital modeling tools. This development engenders novel opportunities for designers, who are thereby enabled to prioritize the conceptual underpinnings of a project, as opposed to the mere technical execution thereof.

Concurrently, the integration of language models such as ChatGPT and Gemini has been observed to enhance the structuring of creative ideas, facilitate the analysis of stylistic decisions, and broaden the semantic scope of projects.A comparative analysis of AI technologies and conventional teaching methods reveals both substantial advantages and limitations. The utilization of generative models has been shown to expedite the generation of visual concepts, enabling students to explore artistic styles and compositions with greater expediency.

For instance, the traditional approach necessitated several hours to develop sketches or conceptual solutions, whereas AI can accomplish this in mere minutes, enabling students to explore a broader spectrum of creative ideas. This finding aligns with studies [1]-[6], which demonstrate that automation of routine tasks enhances the efficiency of creative activity.However, it is important to note that the acceleration and simplification of the design process does have certain drawbacks. Specifically, an overreliance on AI can potentially diminish the significance of classical sketching, modeling, and manual detailing skills, which are still considered essential in the professional practice of design.Conversely, traditional teaching methods emphasize the cultivation of technical skills in conjunction with creative thinking. However, the employment of generative AI has the potential to redirect the emphasis from the technical execution of a project to its conceptual framework.

One of the advantages of AI is its capacity to personalize the learning process, a benefit that can be attributed to the implementation of adaptive algorithms. These algorithms enable language models to provide students with customized recommendations, including suggestions for enhancing their work, analyzing their

stylistic decisions, and proposing alternative approaches.In contrast, the conventional teaching method exhibits a notable lack of flexibility in this regard, as assessments and feedback are predominantly contingent on the subjective evaluation of the instructor.Notwithstanding the benefits inherent in the integration of AI into the educational milieu, it is imperative to acknowledge the potential implications, including the possibility of unifying creative products.

Given their reliance on data analysis for model training, generative models have the potential to produce solutions that bear similarities to existing samples, thereby diminishing the distinctiveness of student work. This underscores the necessity for cultivating an intentional approach to leveraging AI as an adjunct tool rather than a primary modality.A pivotal element in this paradigm is the automation of routine tasks, which enables students to allocate their attention toward more intricate phases of the creative process.

The utilization of ChatGPT and Gemini in the formulation of descriptions for design projects, the creation of structured concepts, and the analysis of stylistic solutions has the potential to streamline the development of teaching materials and presentations. This, in turn, can foster the development of professional communication skills, which are a vital component of students' future careers.

It is imperative to acknowledge the potential limitations and risks associated with the integration of AI into education, which should be given due consideration. A notable concern is the reliance on automated systems, as this can potentially diminish students' independent thinking skills [9]. The utilization of AI as the primary tool for content generation can hinder students' capacity to analyze and formulate creative solutions independently.

To mitigate this risk, it is imperative to integrate AI into the learning process as an auxiliary resource that supports, rather than replaces, students' individual skills.Another challenge pertains to the potential loss of traditional design skills, such as freehand drawing, composition, building without the use of algorithmic support, and understanding the basic principles of artistic modeling.

While AI facilitates the use of digital tools, students who depend exclusively on automated solutions may lose the capacity to generate designs from the ground up, underscoring the necessity to devise methodologies that integrate traditional methodologies with state-of-the-art digital technologies [10]. The practical ramifications of incorporating AI into the educational process demonstrate its capacity to enhance workflows, as evidenced by a reduction in the time required to complete creative tasks and an increase in student satisfaction [10]-[11].

The employment of language models has been shown to enhance the organization of creative ideas and the development of clear conceptual solutions. However, it is crucial to acknowledge the potential risks associated with reliance on automated systems, which have the potential to hinder the development of critical thinking and student autonomy [12].

It is imperative to exercise particular caution with regard to copyright concerns, as generative models such as DALL-E and Leonardo.AI generate visual concepts through the analysis of substantial data sets that may encompass copyrighted material. This practice gives rise to the potential for unwarranted utilization of protected works, thereby engendering ethical and legal dilemmas. To mitigate these challenges, there is a necessity to institute comprehensive regulations and ethical standards for the integration of AI in educational settings [6].

In light of the identified benefits and risks of incorporating artificial intelligence in the educational process of designers, it is recommended to adopt a comprehensive approach that will ensure the effective use of AI and minimize potential negative consequences. The following recommendations are proposed:

1. The integration of digital and traditional teaching methods is a subject that has been the focus of considerable scholarly attention. The development of integrated courses that combine traditional methods, such as manual sketching and composition, with the use of generative and language models of AI, is recommended. This approach is believed to ensure a balance between technical automation and the development of fundamental artistic skills.

2. The organization of introductory seminars and training sessions is imperative for the effective dissemination of knowledge in the field. Special seminars should be scheduled for educators and students to showcase the potential and constraints of artificial intelligence in design, while also addressing ethical considerations and copyright implications when utilizing automated systems.

3. The implementation of practical projects and creative competitions is a pedagogical strategy that has been demonstrated to foster creativity and critical thinking in students. The integration of practical tasks, brainstorming sessions, and creative competitions, in which students are tasked with applying artificial intelligence to solve real-world design problems, has been shown to be an effective method for achieving these educational objectives.

4. It is imperative to provide ethical and legal support to ensure the responsible integration of AI in creative processes. The development of methodologies and regulatory guidelines is crucial for guiding the ethical use of AI in such contexts, particularly with respect to copyright implications and the allocation of responsibility for the content generated. By addressing these issues, we can mitigate the risks associated with unauthorized use of protected works, fostering a secure and responsible environment for AI-driven creative endeavors.

The analysis confirms the significant potential of digital transformation in education. However, further improvement of methodological approaches requires additional research, taking into account the data obtained

from open sources. These results indicate the need for a balanced approach that allows for the use of AI technologies to optimize the creative process without depriving students of the opportunity to develop traditional design skills and critical thinking.

IV. Conclusions

The study demonstrated that integrating AI technologies into the professional training of designers can significantly enhance both the efficiency and quality of creative outputs. Specifically, the utilisation of generative models, such as DALL-E, Leonardo.AI, and Microsoft Copilot, led to an enhancement in student satisfaction (from 3.2 ± 0.4 to 4.1 ± 0.3 on a 5-point scale) and an improvement in creative task scores (from 68% to 82%), while concomitantly reducing the average time required to complete design tasks by 31.1%. In a similar vein, language models such as ChatGPT and Gemini have been shown to facilitate more structured conceptualisation, as evidenced by an increase in the frequency of key term usage from 2.3 to 3.8 per 100 words.

Notwithstanding these evident advantages, the study also identified specific challenges associated with the implementation of AI in design education. A salient concern pertains to the potential development of an overreliance on automated systems among students, which may potentially hinder the cultivation of independent creative thinking and traditional design skills—such as manual sketching and compositional analysis—that are indispensable components of a comprehensive design education. Furthermore, the utilisation of generative AI gives rise to significant copyright concerns, as these models have the capacity to generate content based on copyrighted datasets without appropriate attribution, thereby potentially infringing upon intellectual property rights.

The practical significance of this research lies in its formulation of targeted recommendations for the effective integration of AI into the design curriculum. It is recommended that the integration of AI technologies be implemented in a phased manner, commencing with introductory classes, practical projects, brainstorming sessions, and creative competitions. Furthermore, educational programmes should be designed to combine digital tools with traditional design techniques, ensuring that the benefits of technological automation do not come at the expense of fundamental artistic skills.

Future research should aim to refine the methodological framework for AI integration in design education, assess its long-term impact on students' cognitive and creative development, and develop robust strategies to mitigate the risks associated with excessive reliance on automated systems. The findings of this study substantiate the viability and necessity of integrating AI into design education, provided that its implementation is supported by rigorous methodological guidance that balances technological innovation with the preservation of traditional design competencies..

References

[1] N. Anantrasirichai and D. Bull, “Artificial intelligence in the creative industries: A review,” *arXiv:2007.12391*, Jul. 2020, doi: https://doi.org/10.48550/arXiv.2007.12391.

[2] L. Chen, S. Xiao, Y. Chen, L. Sun, P. R. N. Childs, and J. Han, “An artificial intelligence approach for interpreting creative combinational designs,” *arXiv:2405.04985*, May 2024, doi: https://doi.org/10.48550/arXiv.2405.04985.

[3] J. K. Kim and S. Lee, “Integrating artificial intelligence into design curricula: Opportunities and challenges,” *Journal of Engineering Education*, vol. 112, no. 4, pp. 789–810, 2023.

[4] F. Crimaldi and M. Leonelli, “Digital transformation in design education: The role of AI in developing creative competencies,” *IEEE Access*, vol. 12, pp. 4500–4515, 2023.

[5] L. S. Shevchenko, V. O. Umanets, and B. M. Rozputnia, “Applying generative AI to automate teacher tasks in vocational education,” *Open Educ. E-Environ. Mod. Univ.*, vol. 17, pp. 160–170, 2024, doi: https://doi.org/10.28925/2414-0325.2024.1711.

[6] L. S. Shevchenko, V. O. Umanets, and B. Rozputnia, “Use of artificial intelligence technologies in the educational process of professional designer training,” *OpenEdu*, no. 16, pp. 229–239, Apr. 2024, doi: https://doi.org/10.28925/2414-0325.2024.1615.

[7] A. Jain, A. Kerne, H. Fowler, J. Seo, G. Newman, N. Lupfer, and A. Perrine, “How could AI support design education? A study across fields fuels situating analytics,” arXiv:2404.17390, Apr. 2024, doi: https://doi.org/10.48550/arXiv.2404.17390.

[8] F. Crimaldi and M. Leonelli, “AI and the creative realm: A short review of current and future applications,” arXiv:2306.01795, Jun. 2023, doi: https://doi.org/10.48550/arXiv.2306.01795.

[9] A. Gabriel, D. Monticolo, M. Camargo, and M. Bourgault, “Creativity support systems: A systematic mapping study,” Thinking Skills and Creativity, vol. 20, pp. 1–15, 2016.

[10] S. Elmorshidy, A. Khalil, and D. Saunders, “The impact of artificial intelligence on the design process,” Design Management Review, vol. 32, no. 2, pp. 42–49, 2021.

[11] L. Umanets, L. Liubarska, and B. Rozputnia, “Enhancing creativity in design: Integrating AI technologies into the educational process,” in Proc. IEEE Conf. Innovation in Education, Feb. 2024, pp. 150–157.

[12] S. Colton, “Computational creativity: The state of the art,” AI Magazine, vol. 40, no. 3, pp. 39–49, 2019.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 299-306

On the Systematic Encoding of p-ary Reed-Solomon Codes with an Arbitrary Prime p

Zhaneta Savova
Computer Systems and Technologies Department
Faculty of Artillery, Air Defense and Communication and Information Systems,
National Military University
Shumen, Bulgaria
zh.savova@mail.bg

Antoniya Tasheva
Computer Systems Department
Faculty of Computer Systems and Technologies,
Technical University of Sofia
Sofia, Bulgaria
antoniya.tasheva@yahoo.com

Rosen Bogdanov
Communication Networks and Systems Department
Faculty of Artillery, Air Defense and Communication and Information Systems,
National Military University
Shumen, Bulgaria
r61@abv.bg

***Abstract*— The Reed-Solomon (RS) codes, which are a subset of error-correcting codes, are currently employed in a number of significant applications. The most notable of these are data recovery in storage systems, barcodes in management and advertising systems, and communication systems and networks. In the present technological era, RS codes over Galois fields GF(2^m) are frequently employed in the aforementioned applications, with GF(2^8) being the most prevalent. This enables the representation of all 256 values of a byte as a polynomial with eight binary coefficients over GF(2^8). The motivation for verifying and generalizing the idea of systematic encoding of RS codes in a field with a base p other than 2 stems from the fact that the mathematical dependencies in arbitrary field GF(p^m) are not only valid for GF(2^m), but also have wider applicability. Consequently, the article establishes the specific features of the systematic encoding of p-ary Reed-Solomon codes and LFSR-based systematic encoder, conceptualizing them as a class of cyclic codes over any field GF(p^m) whose base is a prime p other than 2.**

Keywords*—Reed-Solomon Codes, Systematic Encoding, LFSR-based pRS Encoder, Multilevel Sequences, PAM-3, PAM-5.

I. Introduction

The Reed-Solomon (RS) codes are non-binary cyclic (n, k) error correction codes of length n and size k, initially proposed by Irving Reed and Gustav Solomon in 1960 [1]. By incorporating additional symbols to check the data, the RS code is capable of detecting any combination of up to a maximum of $t = (n - k)/2$ erroneous symbols, correcting up to $\lfloor t/2 \rfloor$ symbols, or detecting and correcting combinations of errors and erasures. Here $\lfloor x \rfloor$ denotes the largest integer less than or equal to x. Furthermore, RS codes are well-suited for correcting burst errors.

The Reed-Solomon codes are a widely utilized method of error correction in practice, as evidenced by their numerous applications. The most significant of these are data recovery in storage systems [2], [3], [4] including hard drives, CDs, DVDs, BigTable, Google's GFS, and RAID 6, as well as in barcodes in management and advertising systems [5], such as QR Code, PDF-417, MaxiCode, Datamatrix, and Aztec Code.

Furthermore, RS codes are predominantly employed in communication systems. These include software-defined wireless networks [6], [7] telecommunication systems and networks [8], mobile wireless systems [9], digital video broadcasting (DVB-T) [10] and video-watermarking applications [11]. Furthermore, the applications of Reed-Solomon codes extend to code division multiple access in mobile phones [12], communication systems based on electrical power transmission lines [13], [14], ultra-wideband communications [15], reconfigurable electronic intelligent devices for smart energy [16], 802.11ad MIMO-OFDM transceivers [17], and other related fields.

The RS codes implementation can effectively enhance the characteristics of the communication system. For example, the performance of a RS-coded spectral-amplitude-encoding optical-code-division-multiplexing system [18] is evaluated in the presence of optical beating interference (OBI). It is observed that RS coding can effectively mitigate the impact of OBI, thereby enabling a doubling of the number of active users.

In the paper [19], the performance of the Satellite Downlink Transmitter that employs a Wavelet-based Filtered Multi-Tone (WFMT) modulation is examined. It is

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8568
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

demonstrated that error correction block codes, such as RS codes, can effectively enhance the Peak-to-Average Power Ratio characteristics of the communication system.

In their study [20], the authors examined the Bit Error Rate (BER) performance of tree models utilizing Hamming, BCH, and RS codes. Their findings indicate that the Reed-Solomon model demonstrates enhanced BER performance compared to the Hamming and BCH models, which demonstrate comparable outcomes.

In practical applications, Reed-Solomon codes use message symbols typically represented using a Galois Field with a base 2, i.e. GF(2^m). For example, the authors of the paper [21] propose a reconfigurable FEC system based on the Reed-Solomon codec for DVB and WiMax networks. The FEC system is based on the parameterisation approach of the RS encoder-decoder architecture, which is a key solution for software defined radio systems. The FPGA implementation of the advanced RS encoder-decoder uses only polynomials over GF(2^8).

The paper [22] presents a novel method for bit level shortening of a Reed Solomon (RS) code, resulting in only shortened BCH subcodes. Using a specific basis, an RS code over GF(2^m) is mapped to a binary image containing *m* concatenated BCH sub-codewords and some glue-vector code words.

To mitigate the effects of fading and inter symbol interference when WiMAX is used in the 2-11 GHz range, the time diversity by incorporating an outer Reed-Solomon block code concatenated with an inner convolutional code is used in WiMAX physical layer. The systematic RS(255, 239) which Galois Field elements are from GF(2^8) is applied [23].

In today's high-speed communication systems, multi-level signals and sequences are becoming a distinctive feature. New methods are being used for in-vehicle networking, such as the 4D PAM-7 [24], PWAM signaling scheme [25], and Automotive Ethernet [26]. These methods use four-dimensional five-level pulse amplitude modulation (4D-PAM-5), PAM-7 and PAM-3 symbols to improve data transfer rates compared to wired infrastructures.

In numerous research papers, the theoretical encoding of Reed-Solomon codes is presented over an arbitrary field GF(q) of q elements, where q is a power of a prime number. Despite this theoretical representation, the real applications and examples elucidating Reed-Solomon codes are over Galois fields GF(2^m) of base 2.

It is therefore evident that in order to guarantee the error correction features of new multi-level sequences, it is necessary to employ advanced methods of RS encoding that are capable of handling not only binary but also non-binary symbols over GF(p^n) of base which is arbitrary prime p.

The objective of this article is to present a comprehensive analysis of systematic *p*-ary Reed-Solomon (pRS) encoding as a family of codes over an arbitrary Galois field GF(p^m). Additionally, it elucidates the specific features of the encoding process and the encoding scheme, based on Linear Feedback Shift Register (LFSR), when a pRS code is employed over a finite field of base prime p, other than 2.

II. Materials and Methods

This section provides a concise overview of the problem formulation and the preliminary concepts employed in the solution.

In order to guarantee the error-correcting capabilities of multi-level sequences, such as PAM signals comprising 3, 5 or 7 levels, it is vital to determine the specific characteristics of the systematic pRS encoding and the circuits responsible for pRS encoding in instances where the message symbols are situated within a Galois field with an odd prime base.

First, we provide a concise overview of the two primary methods for representing Reed-Solomon codes and their special properties. We then present a brief introduction to the systematic RS encoding procedure. In the subsequent subsection, we examine the specific features of GF(p^m) calculations with an odd prime base p.

A. A Representation of Reed-Solomon Codes and Their Properties

There are two methods of representing Reed-Solomon codes. The first views the code word as a sequence of values, which was proposed in the original work of Reed and Solomon in 1960 [1]. Reed and Solomon propose a code E by which each k-tuple (a_0, a_1, …, a_{k-1}) of the field K of degree n over a field Z_2 of 2 elements is matched by a 2^n-tuple ($m(0)$, $m(\alpha)$, $m(\alpha^2)$, …, $m(1)$) of K. Here $m(x)$ is a polynomial of degree $k-1$

$$m(x) = a_0 + a_1 x + a_2 x^2 + \cdots + a_{k-1} x^{k-1}, \qquad (1)$$

where a_i, $\in K$, $k < 2^n$, and α is the primitive n–th unit root in K. The k-tuple is the input message and the 2^n-tuple is the transmitted message. The authors prove that, depending on whether k is an even or odd number, this code corrects either $(2^n - k)/2$ or $(2^n - k - 1)/2$ symbols.

The second method considers Reed-Solomon codes to be Bose-Chaudhuri-Hocquenghem (BCH) codes [27], in which the code word is represented as a sequence of coefficients. In this approach, instead of sending all the values of the message polynomial $m(x)$ (1), the transmitter calculates another polynomial $s(x)$

$$s(x) = m(x)g(x). \qquad (2)$$

of degree at most n - 1 and sends the n coefficients of this polynomial.

The generating polynomial $g(x)$ is defined as the polynomial whose roots are the elements α, α^2, …, α^{n-k} of the field K

$$\begin{aligned} g(x) = (x-\alpha)(x-\alpha^2)\ldots(x-\alpha^{n-k}) = \\ = g_0 + g_1 x + \cdots \\ + g_{n-k-1}x^{n-k-1} + x^{n-k}. \end{aligned} \qquad (3)$$

Reed-Solomon codes are Maximum Distance Separable (MDS) codes because their minimum Hamming distance is

$$d_{min} = n - k + 1. \quad (4)$$

Because RS codes are MDS codes, they have special properties. For example, any k positions in the block can be used as information and its weight distribution can be easily determined.

The RS code can correct up to a maximum of $t = (n - k)/2$ erroneous symbols or can correct up to $2t$ erasures if the error locations are known in advance, as defined by the erasure term. Moreover, the RS code is able to correct any combination of errors and erasures, provided they fall within its correction capability

$$2e + er \leq n - k, \quad (5)$$

where e is the number of errors and er is the number of erasures.

Given that GF(2^m) is a vector space of size m over GF(2), it follows that each element of GF(2^m) can be represented by m bits, with the element 0 being represented by a zero binary m-tuple (0, 0, 0, ..., 0). In this representation, the (n, k) RS code over GF(2^m) is transformed into a binary (mn, mk) code with a minimum distance d'_{min} that is at least as large as the minimum distance d_{min} of the RS code. Binary (mn, mk) codes with equivalent properties are useful for their ability to correct bursts of errors. Each burst of errors, defined as $(t - 1)\, m + 1$ or fewer consecutive bits, will appear as at most t errors in the GF(2^m) symbols. As a result, RS codes are ideal for correcting bursts of errors [28] due to their largest possible d_{min}.

B. Systematic Encoding of Reed-Solomon Codes

The RS encoding (3), which considers RS codes as a subset of BCH codes, is a well-established approach for all linear codes. However, it does not satisfy the requirement of the systematic encoding procedure that the message is contained unchanged in the transmitted codeword.

To satisfy the requirement of systematic encoding, the message polynomial $m(x)$ is relocated to the k most significant positions of the codeword register. The parity polynomial $t(x)$ is then concatenated to the right of $m(x)$ in the n - k least significant positions. This rule, which is applicable to any RS code with base 2, can be found in any work on the subject and any textbook on data transmission or information theory.

The mathematical description of these operations is as follows [29]. The rightmost shift of the polynomial $m(x)$ is represented by multiplying $m(x)$ by x^{n-k}. The product $m(x).x^{n-k}$ is then divided by the generating polynomial $g(x)$, yielding the quotient $q(x)$ and the remainder $t(x)$.

$$x^{n-k}.m(x) = \mathrm{g}(x).q(x) + t(x). \quad (6)$$

In a manner analogous to the classical binary encoding procedure, the remainder is the parity polynomial, which, as indicated in (5), can be represented as follows:

$$t(x) = x^{n-k}.m(x) \bmod \mathrm{g}(x). \quad (7)$$

The resulting polynomial of the codeword in binary case is

$$c(x) = x^{n-k}.m(x) + t(x). \quad (8)$$

For an example of systematic encoding for a (7, 3) RS code one can see [29].

C. Some Specific Features of GF(p^n) Calculations with Odd Base p

The field GF(q) can be considered an extension of the Galois field GF(p) with a power of m, provided that the order of GF(q) can be expressed as a power of the prime p ($q = p^m$), where m is a positive integer with $m \geq 2$. In such cases, the notation Extended Galois Field GF(p^m) is used.

The elements of the field GF(p^m) are polynomials of degree $m - 1$, which belong to the ring GF(p)[x] and have coefficients in GF(p)

$$GF(p^m) = \{a_{m-1}\alpha^{m-1} + \cdots + a_1\alpha + a_0 \mid a_i \in GF(p)\}. \quad (9)$$

The arithmetic in GF(p) is computed using integer arithmetic modulo p and the arithmetic in GF(p^m) involves polynomial arithmetic modulo the irreducible polynomial $p(x)$ over GF(p) with degree m [30].

In their analysis, the authors in [31] identify two specific features for p-ary Reed-Solomon code construction by considering them as a family of codes over any Galois field GF(p^m) whose base is a prime p other than 2. These features are as follows:

Specific Feature 1. Every nonzero element a has an additive inverse element $-a = p - a$ in a Galois Field GF(p).

Specific Feature 2. The subtraction operations must be performed due to the difference between addition and subtraction operations for fields GF(p^n) with base $p > 2$.

III. Results and Discussion

This section looks at the specific features of p-ary Reed-Solomon encoding and an LFSR-based circuit for encoding non-binary symbols in GF(p^m) with an arbitrary prime p. Examples of systematic encoding and polynomial division are also given, as well as an LFSR-based encoder for an (8, 4) 3RS code over the field GF(3^2).

A. Systematic Encoding of p-ary Reed-Solomon Codes

As demonstrated in Section 2.2, in the systematic encoding, the codeword is constituted of k message symbols, followed by $n - k$ parity symbols.

In this section, the codeword polynomial will be considered from a slightly different perspective, taking into account the differences in addition and subtraction operations in GF(p^m). Let $f(x)$ be a polynomial in which the leading k coefficients represent the message symbols, and the coefficients in front of powers less than $n - k$ are set to zero, i.e.

$$f(x) = a_{k-1}x^{n-1} + \cdots a_1 x^{n-k+1} + a_0 x^{n-k} = x^{n-k}.m(x). \quad (10)$$

In accordance with Euclidian's division algorithm

$$f(x) = g(x).q(x) + t(x), \quad (11)$$

where the degree of the remainder $t(x)$ is less than the degree $n - k$ of the generating polynomial $g(x)$.

Hence

$$f(x) - t(x) = g(x).q(x), \quad (12)$$

and thus, the codeword is $c(x) = f(x) - t(x)$.

In the aforementioned context, in order to obtain the resulting polynomial of the codeword $c(x)$ from the encoding procedure with pRS codes with a base $p \neq 2$, it is necessary to subtract the remainder $t(x)$ from the product $x^{n-k}.m(x)$, i.e.

$$c(x) = x^{n-k}.m(x) - t(x). \quad (13)$$

This is the third significant distinction in encoding a pRS code with an arbitrary base $p \neq 2$. Here, the check symbols in the codeword $c(x)$ are the additive inverse of the coefficients of the remainder $t(x)$. The following specific feature will present the fundamental rule that governs systematic encoding procedure in pRS codes.

Specific Feature 3. In systematic encoding of pRS codes, the message polynomial $m(x)$ is shifted to the k most significant positions of the codeword register and then the additive inverse of each coefficient of the parity polynomial $t(x)$ is written to the $n - k$ lowest positions of the register.

Example 1. Consider an (8, 4) 3RS code over the field GF(3^2) with the generating polynomial $g(x)$

$g(x) = 12 + 20x + 12x^2 + 11x^3 + 10x^4 =$

$= \alpha^2 + \alpha^4 x + \alpha^2 x^2 + \alpha^7 x^3 + \alpha^0 x^4.$

Let the input be 10 11 12 22. It is therefore represented by the message polynomial $m(x)$

$m(x) = 10 + 11x + 12x^2 + 22x^3 =$

$= \alpha^0 + \alpha^7 x + \alpha^2 x^2 + \alpha^3 x^3.$

The first calculation in systematic encoding is

$x^{n-k}.m(x) = x^4.m(x) =$

$= 10x^4 + 11x^5 + 12x^6 + 22x^7 =$

$= \alpha^0 x^4 + \alpha^7 x^5 + \alpha^2 x^6 + \alpha^3 x^7.$

Then dividing the polynomial $x^4.m(x)$ by the generating polynomial $g(x)$ gives a quotient $q(x)$ and a remainder $t(x)$:

$q(x) = 01 + 12x + 22x^3 = \alpha^1 + \alpha^2 x + \alpha^3 x^3;$

$t(x) = 11 + 11x + 20x^2 + 01x^3 =$

$= \alpha^7 + \alpha^7 x + \alpha^4 x^2 + \alpha^1 x^3.$

The inverse additive polynomial is found as follows:

$- t(x) = - (11 + 11x + 20x^2 + 01x^3) =$

$= 22 + 22x + 10x^2 + 02x^3 =$

$= \alpha^3 + \alpha^3 x + \alpha^0 x^2 + \alpha^5 x^3.$

The codeword is obtained according to (13)

$c(x) = x^4.m(x) + (- t(x)) = 22 + 22x +$

$= + 10x^2 + 02x^3 + 10x^4 + 11x^5 + 12x^6 + 22x^7 =$

$= \alpha^3 + \alpha^3 x + \alpha^0 x^2 + \alpha^5 x^3 + \alpha^0 x^4 + \alpha^7 x^5 + \alpha^2 x^6 + \alpha^3 x^7.$

If the code word is represented only by the coefficients of the polynomial $c(x)$, it is obtained by concatenating the inverse additive elements of the coefficients of the remainder $t(x)$ to the right of the input symbols of the message polynomial $m(x)$

$$c(x) = \begin{matrix}(10\ 11\ 12\ 22) \\ m(x)\end{matrix} \quad \begin{matrix}(22\ 22\ 10\ 02) \\ -t(x)\end{matrix}.$$

B. LFSR Encoder for pRS Codes

As well as obtaining an output p-ary pseudorandom sequence with a pLFSR register [32], the systematic encoding of $(n, k) = (p^m - 1, k)$ pRS codes can be achieved through a linear feedback shift register. As demonstrated in the preceding paragraphs, the elements of the input sequence, $m(x)$, and the code sequence, $c(x)$, respectively, are the elements of a Galois field extension, GF(p^m). This will determine the characteristics of the elements of the pLFSR register operating in the Galois field GF(p^m). Each of its elements must be a non-binary register comprising m elements, each of which can store integers from 0 to $p - 1$. The elements $\oplus$ implement the addition operation in the field GF(p^m), and $\otimes$ implements the multiplication operation in the field GF(p^m). The feedback coefficients g_1, g_2, …, g_L are determined by the coefficients of the generator polynomial $g(x)$ of the pRS code (3).

It should be noted that the generating polynomial $g(x)$ is not always a primitive polynomial so that some transformations can be applied to determine the feedback coefficients. Therefore, it is necessary to implement a hardware scheme for the polynomial division operation. Such a scheme was proposed by Peterson and Weldon in their book [33].

This section presents the specific characteristics of the aforementioned scheme when applied to an arbitrary field GF(p^m) with a base p that differs from 2. To illustrate this process, we will initially consider the example of performing polynomial division on the input sequence $x^{n-k}.m(x) = x^4.m(x)$ with the generator polynomial $g(x)$.

Example 2. Polynomial division of the input message sequence with the generator polynomial $g(x)$.

In the case of the (8, 4) 3RS code with generator polynomial $g(x) = 12 + 20x + 12x^2 + 11x^3 + 10x^4 = \alpha^2 + \alpha^4 x$

$+ \alpha^2x^2 + \alpha^7x^3 + \alpha^0x^4$ and input message 10 11 12 22, it is necessary to perform the division of $x^4.m(x) = 10x^4 + 11x^5 + 12x^6 + 22x^7 = \alpha^0x^4 + \alpha^7x^5 + \alpha^2x^6 + \alpha^3x^7$ by $g(x)$.

The steps of the actual polynomial division are shown in Fig. 1. For a more compact representation of the polynomial division, the powers of x in the dividend and divisor are omitted, and only the coefficients of the polynomials are recorded. Here, $q(x)$ is a quotient and $t(x)$ – remainder.

$$
\begin{array}{rl}
g(x) = & \qquad\qquad\qquad\qquad \alpha^3\ 0\ \alpha^2\ \alpha^1 = q(x) \\
\alpha^0\ \alpha^7\ \alpha^2\ \alpha^4\ \alpha^2 \ \big| & \overline{\alpha^3\ \alpha^2\ \alpha^7\ \alpha^0\ \ 0\ \ 0\ \ 0\ \ 0 = x^4.m(x)} \\
& \underline{\alpha^3\ \alpha^2\ \alpha^5\ \alpha^7\ \alpha^5} \\
& \ \ 0\ \ 0\ \ \alpha^2\ \alpha^5\ \alpha^1\ 0\ \ 0 \\
& \qquad \underline{\alpha^2\ \alpha^1\ \alpha^4\ \alpha^6\ \alpha^4} \\
& \qquad\ \ 0\ \ \alpha^1\ \alpha^7\ \alpha^2\ \alpha^0\ 0 \\
& \qquad\qquad \underline{\alpha^1\ \alpha^0\ \alpha^3\ \alpha^5\ \alpha^3} \\
& \qquad\qquad\ \ 0\ \ \alpha^1\ \alpha^4\ \alpha^7\ \alpha^7 = t(x)
\end{array}
$$

Fig. 1. Example of polynomial division.

As can be seen from Fig. 1, at each step the value of the product of $g(x)$ with the current input symbol is subtracted from the state of the current dividend. This operation can be implemented with a linear feedback shift register. Because it operates in an extension of a Galois field, it will be called GF(p^m) LFSR

Table captions and titles should always be right aligned and placed above the tables. Tables are numbered consecutively with Roman numerals and have reference in the main text.

The Galois architecture of the GF(p^m) LFSR will be considered because it directly corresponds to the real polynomial division algorithm shown in Fig. 1. The scheme of a GF(p^m) LFSR register with Galois architecture (Fig. 2) implementing systematic encoding of p-ary Reed-Solomon codes consists of a register ***R*** with $n - k$ number of elements, each of which can store one element of the extension GF(p^m), and with linear feedbacks defined by the generator polynomial $g(x)$, an inverter ***I*** that outputs additive inverse element $-a_0$ in the GF(p^m) field, and two keys $\boldsymbol{K_1}$ and $\boldsymbol{K_2}$.

The operation of the scheme is as follows:

1. The information symbols *ms*, which are k in number, arrive sequentially in the register ***R*** and appear at the output ***c***. For this purpose, the key $\boldsymbol{K_1}$ is in the upper position and the key $\boldsymbol{K_2}$ is closed.
2. The register ***R*** continues to clock for $n - k$ more clock cycles, with no new symbols *ms* fed to its input. This computes the remainder $t(x)$ of the polynomial division, which resides in register ***R***. No symbols are output to the output ***c***. For this purpose, key $\boldsymbol{K_1}$ is in the middle position and key $\boldsymbol{K_2}$ is closed.
3. The register ***R*** continues to clock for $n - k$ more clock cycles, with no new symbols *ms* fed to its input. At this, the already obtained remainder $t(x)$ is output through the inverter ***I*** to the output ***c***. Key $\boldsymbol{K_1}$ is in the down position and key $\boldsymbol{K_2}$ is open.

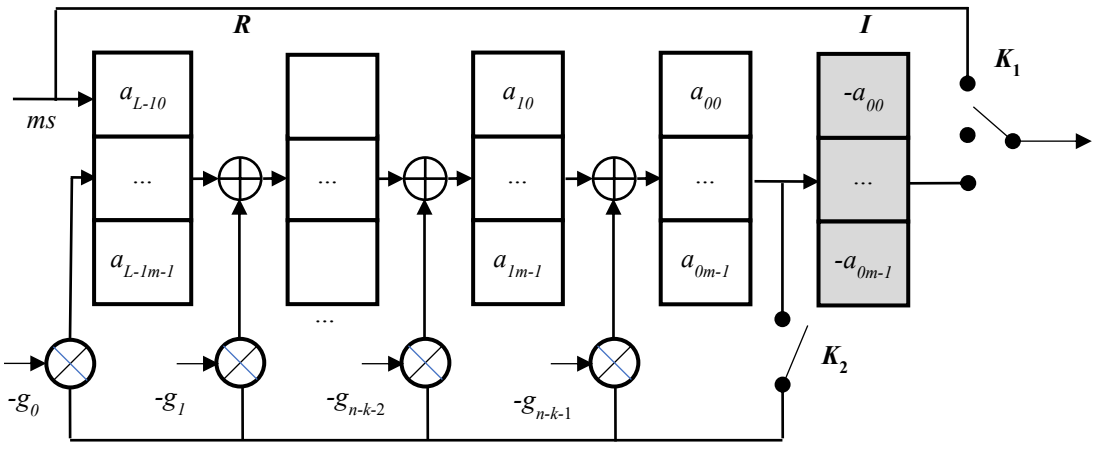


Fig. 2. Galois architecture of the GF(p^m) LFSR

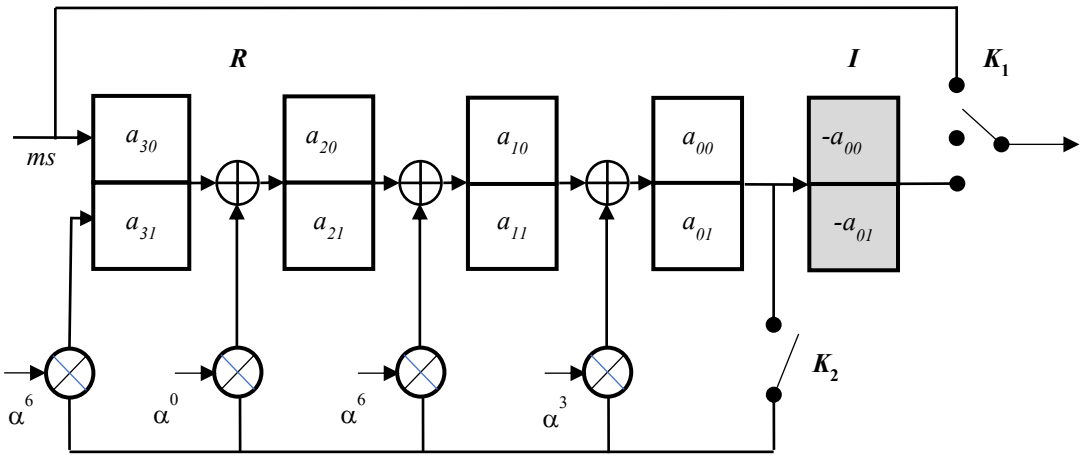


Fig. 3. GF(3^2) LFSR with generator polynomial $g(x) = \alpha^2 + \alpha^4 x + \alpha^2 x^2 + \alpha^7 x^3 + \alpha^0 x^4$

C. *Example of Systematic Encoding with GF(p^m) LFSR register*

The operation of the scheme of Fig. 2 will be explained with the example which actual polynomial division is shown in Fig. 1.

Example 3. The cyclic code under consideration is an (8, 4) 3RS code. The register ***R***, therefore, consists of four elements, each of length $m = 2$. The feedback coefficients are calculated from the generator polynomial $g(x) = 12 + 20x + 12x^2 + 11x^3 + 10x^4 = \alpha^2 + \alpha^4 x + \alpha^2 x^2 + \alpha^7 x^3 + \alpha^0 x^4$ as shown below

$$\begin{aligned} -g_0 &= -\alpha^2 = -12 = 21 = \alpha^6 \\ -g_1 &= -\alpha^4 = -20 = 10 = \alpha^0 \\ -g_2 &= -\alpha^2 = -12 = 21 = \alpha^6 \\ -g_3 &= -\alpha^7 = -11 = 22 = \alpha^3 \end{aligned} \qquad (14)$$

Therefore, the GF(3^2) LFSR register scheme with Galois architecture has the form shown in Fig. 3. The sequential operation of the scheme is shown in Table 1.

In the initial state, all four elements of the GF(3^2) LFSR register, which encodes an (8, 4) 3RS code, are in a zero state. For the next four clocks, key K_1 is in the upper position and key K_2 is closed. Therefore, the information symbols *ms* arrive sequentially in register ***R*** and simultaneously appear at output ***c***.

For the next four clocks, key K_1 is in the middle position and key K_2 is closed. No more symbols *ms* are passed to its input and no symbols are produced at the output ***c***. The computation of the states of the elements of the register **R** when the linear feedbacks are operating is performed as follows:

Clock 5. $a_0 = \alpha^3 . \alpha^3 + \alpha^2 = \alpha^6 + \alpha^2 = 21 + 12 =$

$= 00 = 0$

$a_1 = \alpha^3 . \alpha^6 + \alpha^7 = \alpha^1 + \alpha^7 = 01 + 11 = 12 = \alpha^2$

$a_2 = \alpha^3 . \alpha^0 + \alpha^0 = \alpha^3 + \alpha^0 = 22 + 10 = 02 = \alpha^5$

$a_3 = \alpha^3 . \alpha^6 = \alpha^1$

TABLE 1 SEQUENTIAL OPERATION OF THE GF(32) LFSR REGISTER FROM EXAMPLE 3

Clock	Input ms	Register R				Output c
		a_3	a_2	a_1	a_0	
0	-	0	0	0	0	
1	α^3	α^3	0	0	0	α^3
2	α^2	α^2	α^3	0	0	α^2
3	α^7	α^7	α^2	α^3	0	α^7
4	α^0	α^0	α^7	α^2	α^3	α^0
5	0	α^1	α^5	α^2	0	-
6	0	0	α^1	α^5	α^2	-
7	0	α^0	α^2	α^7	α^1	-
8	0	α^7	α^7	α^4	α^1	-
9	0	0	α^7	α^7	α^4	$-\alpha^1 = \alpha^5$
10	0	0	0	α^7	α^7	$-\alpha^4 = \alpha^0$
11	0	0	0	0	α^7	$-\alpha^7 = \alpha^3$
12	0	0	0	0	0	$-\alpha^7 = \alpha^3$

Clock 6. $a_0 = 0 . \alpha^3 + \alpha^2 = \alpha^2$

$a_1 = 0 . \alpha^6 + \alpha^5 = \alpha^5$

$a_2 = 0 . \alpha^0 + \alpha^1 = \alpha^1$

$a_3 = 0 . \alpha^6 = 0$

Clock 7. $a_0 = \alpha^2 . \alpha^3 + \alpha^5 = \alpha^5 + \alpha^5 = 02 + 02 =$

$= 01 = \alpha^1$

$a_1 = \alpha^2 . \alpha^6 + \alpha^1 = \alpha^0 + \alpha^1 = 10 + 01 = 11 = \alpha^7$

$a_2 = \alpha^2 . \alpha^0 + 0 = \alpha^2$

$a_3 = \alpha^2 . \alpha^6 = \alpha^0$

Clock 8. $a_0 = \alpha^1 . \alpha^3 + \alpha^7 = \alpha^4 + \alpha^7 = 20 + 11 =$

$= 01 = \alpha^1$

$a_1 = \alpha^1 . \alpha^6 + \alpha^2 = \alpha^7 + \alpha^2 = 11 + 12 = 20 = \alpha^4$

$a_2 = \alpha^1 . \alpha^0 + \alpha^0 = \alpha^1 + \alpha^0 = 01 + 10 = 11 = \alpha^7$

$a_3 = \alpha^1 . \alpha^6 = \alpha^7$

In the last four cocks, key $\boldsymbol{K_1}$ is in the down position and key $\boldsymbol{K_2}$ is open. The remainder is sent through the inverter $\boldsymbol{I}$ to the output $\boldsymbol{c}$.

From Table 1, it can be seen that after the 12th clock, the scheme is in the initial zero state and it can start encoding the next k number of information symbols from the field GF(p^m).

IV. Conclusion and Feature Work

The article proposes an approach to implement a systematic p-ary Reed-Solomon encoding with input information symbols in a Galois field GF(p^m) with an arbitrary prime p.

This article presents a detailed derivation of the special features involved in determining the coefficients of the parity polynomial $t(x)$. It is demonstrated that the additive inverse of each coefficient of the parity polynomial $t(x)$ must be written to the $n - k$ lowest positions of the codeword. Furthermore, the article examines the process of encoding non-binary symbols in GF(p^m) with an arbitrary prime p using a LFSR-based circuit. It also gives some examples of systematic encoding and polynomial division, as well as an LFSR-based encoder for an (8, 4) 3RS code over the field GF(3^2).

Nevertheless, the proposed approach presents certain theoretical and practical issues that require further examination. From a theoretical standpoint, a comprehensive analysis is necessary to elucidate the distinctive characteristics that emerge when employing a GF(p^m) field comprising an odd prime base p in the p-ary Reed-Solomon codes decoding process.

From a practical standpoint, it is necessary to design the Field Programmable Gate Arrays (FPGAs) [34], [35] or Application Specific Integrated Circuits (ASICs) [36], [37] hardware implementation of the proposed approach, which will facilitate the acceleration of algebraic operations in the Galois field GF(p) and Galois Extension GF(p^m) for p = 3, 5 or 7. Such an approach is well-suited to the analysis of multi-level sequences, including PAM-3, PAM-5, and PAM-7 signals.

Acknowledgments:

The article was prepared with the financial support of the National Scientific Program “Security and Defence”, funded by the Ministry of Education and Science of the Republic of Bulgaria, in implementation of Decision № 731 of 21.10.2021 of the Council of Ministers of the Republic of Bulgaria.

The authors would like to thank the reviewers for their helpful comments.

References

[1] I. S. Reed and G. Solomon, “Polynomial codes over certain finite fields,” Journal of the Society for Industrial & Applied Mathematics 8, No. 2, 1960, pp. 300-304.

[2] X. Liu, H. Jia and C. Ma, “Error-Correction codes For Optical Disc Storage, ” Advances in Optical Data Storage Technology, Proceedings of SPIE Vol. 5643, 2005, pp. 342-347.

[3] T. N. Hewage, M. N. Halgamuge, A. Syed, and G. Ekici, “Big data techniques of Google, Amazon, Facebook and Twitter, ” Journal of Communications, Vol. 13, No. 2, 2018, pp. 94-100.

[4] A. Chiniah and A. Mungur, “On the Adoption of Erasure Code for Cloud Storage by Major Distributed Storage Systems, ” EAI Endorsed Transactions on Cloud Systems, 7(21), e1-e11, 2022.

[5] J. A. Lin and C. S. Fuh, “2D Barcode Image Decoding, ” Mathematical Problems in Engineering, Article ID 848276, 10 pages, 2013. https://doi.org/10.1155/2013/848276.

[6] S. K. Moorthy, N. Mastronarde, E. S. Bentley, M. Medley, and Z. Guan, “OSWireless: Hiding specification complexity for zero-touch software-defined wireless networks, ” Computer Networks, *237*: 110076, 2023.

[7] S. K. Moorthy, Z. Guan, N. Mastronarde, E. S. Bentley, and M. Medley, OSWireless: Enhancing automation for optimizing intent-driven software-defined wireless networks, 19th International Conference on Mobile Ad Hoc and Smart Systems (MASS), IEEE, 2022, pp. 202-210.

[8] M. Almaz and B. Sevinj, “Estimation of the Noise Immunity Characteristics of Telecommunication Network, ” *WSEAS Transactions on Communications*, 22, 2023, pp. 192-198.

[9] J. Malhotra, “Investigation of channel coding techniques for high data rate mobile wireless systems, ” *International Journal of Computer Applications*, 115:3, 2015.

[10] E. Mohamed, W. Azeddine, M. Omar, and A. Hadjoudja, Development and Validation of an optimized syndromes block for Reed Solomon decoder. ITM Web of Conferences, Vol. 52, EDP Sciences. 2023, p. 03008.

[11] J. Wassermann and A. Dziech, “Multidimensional Enhanced Hadamard Error Correcting Code in Comparison with Reed-Solomon Code in Video-Watermarking Applications, ” WSEAS transactions on signal processing, Vol. 13, 2017, pp. 196-207.

[12] V. Riznyk, “Designs of Electronic Devices using Combinatorial Optimization, ” WSEAS Transactions on Electronics, Vol. 14, 2023, pp. 122-128.

[13] A. Ndolo and İ. H. Çavdar, “Current state of communication systems based on electrical power transmission lines, ” Journal of Electrical Systems and Information Technology, Vol. 8, 2021, pp. 1-10.

[14] C. F. Fontana, C. A. Sakurai, C. L. Marte, J. R. Cardoso, and A. D. S. Andrade, “Power Line Communication as Alternative for Data Communication Channel for BRT, ” Earth sciences and human constructions, Vol. 2, 2022, pp. 60-67.

[15] X. Gao and L. Huai, “Modern ultra-wideband communications: recent overview and future prospects, ” International Journal of Ultra Wideband Communications and Systems, *4*(2), 2020, pp. 57-67.

[16] C. Sandoval-Ruiz, “LFSR-fractal ANN model applied in R-IEDs for smart energy, ” IEEE Latin America Transactions, 18(04), 2020, pp. 677-686.

[17] G. Kiokes, “Hardware Implementation of 802.11 ad MIMO-OFDM Transceiver, ” WSEAS transactions on communications, Vol. 18, 2019, pp. 71-77.

[18] A. Pham and H. Yashima, Performance analysis of Reed-Solomon coded spectral amplitude encoding OCDM system. Proceedings of the 4th WSEAS International Conference on Electronics, Hardware, Wireless and Optical Communications, 2005, pp. 1-5.

[19] R. M. Vitenberg, A WFMT downlink transmitter for low earth orbit satellite. Proceedings of the 4th WSEAS Int. Conference on Electromagnetics, Wireless and Optical Communications, 2006, pp. 53-58.

[20] D. Dannan, K. Kabalan, and A. Chehab, "Performance comparison for serial concatenated block convolutional codes when sequentially and iteratively decoded, " WSEAS Transactions on Information Science and Applications, 4(6), 2007, pp. 1236-1244.

[21] L. Chaari, M. Fourati, N. Masmoudi, and L. Kamoun, "A reconfigurable FEC system based on Reed-Solomon codec for DVB and 802.16 network, " WSEAS transactions on circuits and systems, 8(8), 2009, pp. 729-744.

[22] T. H. Hu and M. H. Chang, "Decoding shortened Reed Solomon codes at bit level, " WSEAS Transactions on Communications, 9(11), 2010, pp. 695-707.

[23] A. Abderrahmane, M. Merouane, and B. Messaoud, "Diversity Techniques to combat fading in WiMAX, " WSEAS transactions on communications, 7, 2008, pp. 43-51.

[24] N. Stojanović, C. Prodaniuc, Z. Liang, J. Wei, S. Calabró, T. Rahman, C. Xie, "4D PAM-7 Trellis Coded Modulation for Data Centers, " IEEE Photonics Technology Letters, Vol. 31, No. 5, pp. 369-372, 1 March 2019, doi 10.1109/LPT.2019.2895686.

[25] H.-U. Kim and J.-K. Kang, High-speed Serial Interface using PWAM Signaling Scheme, 2022 19th International SoC Design Conference (ISOCC), Gangneungsi, Korea, Republic of, 2022, pp. 255-256, doi: 10.1109/ISOCC56007.2022.10031330.

[26] K. Matheus and T. Königseder. Automotive Ethernet. Cambridge University Press, 2021.

[27] R. C. Bose and D.K. Ray-Chaudhuri. "On a class of error correcting binary group codes, " Information and Control, Vol. 3, Issue 1, March 1960, pp. 68–79.

[28] N. G. Bardis, O. Markovskyi, and N. Doukas, Efficient burst error correction method for application in low frequency channels and data storage units, 17th International Conference on Digital Signal Processing (DSP), 2011, IEEE pp. 1-6.

[29] B. Sklar, Digital Communications: Fundamentals and Applications, Second Edition, Prentice-Hall, 2001.

[30] A. Beletsky. "An Effective Algorithm for the Synthesis of Irreducible Polynomials over a Galois Fields of Arbitrary Characteristics, " WSEAS Transactions on Mathematics, 20, 2021, pp. 508-519.

[31] Z. Savova and R. Bogdanov, Some Specific Features in the Construction of p-ary Reed-Solomon Codes for an Arbitrary Prime p. Proceedings of the 15th International Scientific and Practical Conference. Environment. Technology. Resources. Rezekne, Latvia, Vol. 4, 2024, pp. 237-243.

[32] M. Goresky, A. Klapper, "Fibonacci and Galois Representations of Feedback-With-Carry Shift Registers, " IEEE Trans. on Inform. Theory, vol. 48, pp. 2826−2836, November 2002.

[33] W. W. Peterson and E. J. Weldon, Error-correcting codes. Cambridge, MA: MIT Press 1972.

[34] P. Balasubramanian and N.E., Mastorakis, "FPGA based implementation of distributed minority and majority voting based redundancy for mission and safety-critical applications, " International Journal of Circuits and Electronics, 2016. *arXiv preprint arXiv: 1611.09446*.

[35] H. Shiyang, L. Hui, L. Qingwen, and L.Fenghua, "A Time-Area-Efficient and Compact ECSM Processor over GF (p), " Chinese Journal of Electronics, *32*(6), 2023, pp. 1355-1366.

[36] P. Balasubramanian and N.E. Mastorakis, "ASIC-based implementation of synchronous section-carry based carry lookahead adders, " Recent Advances in Circuits, Systems, Signal Processing and Communications, 2016, *arXiv preprint arXiv: 1603.07961*.

[37] N. D. Patwari, A. Srivastav, M. Kabra, P. Jonna, and M. Rao, Design and evaluation of finite field multipliers using fast XNOR cells. In Proceedings of the Great Lakes Symposium on VLSI 2023, 2023, pp. 163-166.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 307-311

Assessing the Need and Possibility of Using Recommender Systems in University Libraries

Laylo Sayfieva
Library information systems department Tashkent University of Information Technologies named after Muhammad al-Khwarizmi
Tashkent, Uzbekistan
sayfiyevalaylo05@gmail.com

Sherbek Normatov
Library information systems department Tashkent University of Information Technologies named after Muhammad al-Khwarizmi
Tashkent, Uzbekistan
shb.normatov@gmail.com

Mekhriniso Qudratova
Library information systems department Tashkent University of Information Technologies named after Muhammad al-Khwarizmi Tashkent,
Tashkent, Uzbekistan
qudratovamehr@gmail.com

Sarvinoz Berdibekova
Library information systems department Tashkent University of Information Technologies named after Muhammad al-Khwarizmi Tashkent
Tashkent, Uzbekistan
sarvinozberdibekova@gmail.com

Temur Khudayberganov
Information security department Urgench Branch of Tashkent University of Information Technologies named after Muhammad al-Khwarizmi
Urgench, Uzbekistan
doctordrebek@gmail.com

***Abstract*— Despite the growing number of scientific and technical information sources, traditional library search systems cannot fully meet the dynamically changing needs of users. Therefore, the implementation of personalized user-oriented services has become one of the main tasks of modern libraries. Recommender systems can be used in academic libraries not only to provide information resources that meet the interests and needs of users, but also to replenish the library collection with relevant sources of information. However, in practice, the creation of a recommender system for academic libraries requires taking into account the features of the library infrastructure and information resources, as well as its users. The purpose of the article is to analyze the need and possibilities of creating recommender systems in academic libraries based on the results of a survey conducted among the faculty and students of universities in Uzbekistan. Based on the results of the analysis, the authors developed recommendations for the creation of recommender systems in the context of the transformation of academic libraries in Uzbekistan. These recommendations can serve as important information for decision-making by university and library administrators, developers and researchers in this field who seek to improve user-oriented services in academic libraries.**

Keywords*— *Library Resource Discovery, Personalized Suggestions, Recommendation System, University Library, User Behavior Analysis.

I. Introduction

University lifffbraries are often equipped with advanced IT infrastructure, which allows them to collect and store large amounts of usage data. Compared with public libraries, university libraries have two unique characteristics: they have extensive collections of specialized scientific materials, especially in science and engineering, and their users usually have extensive experience in their respective fields. At the same time, the rapid growth of knowledge has led to a constant expansion of library collections.

A recommender system is a tool designed to provide users with suggestions tailored to their needs or requests. Its main task is to predict resources that are suitable for users' needs by analyzing the history of their use, profiles and interactions, including the queries, searches and content created or expressed. Since the emergence of the Internet, its rapid growth and development have created many opportunities for users to share knowledge, information and ideas. This evolution has had a significant impact on the development of social networks and commercial platforms such as Facebook and Amazon. Today, these advances allow authors to share their innovative ideas with millions of users worldwide.

Traditionally, search engines have been the primary means of finding resources or books in library collections. However, this process often involves iteratively entering

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8604
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

keywords to refine search results. A user who is skilled at formulating precise queries, especially those that are tailored to the preferences of the search engine, is more likely to achieve their goals easily. Despite the system's ability to track borrowing records-to determine which users have used which books at specific times-the knowledge gained from individual users' choices rarely benefits other users with similar needs. Thus, relying on traditional search engines may not be sufficient for users to effectively find the materials they need. This limitation highlights the need for a more intelligent recommendation system that can take advantage of user interactions and preferences.

A systematic approach was used to collect data on user preferences and usage patterns, allowing for an evidence-based assessment of their needs. The study includes a review of the survey results to identify key insights and contributions to the field. These results inform the need, requirements, and implementation strategies for integrating recommendation systems into academic library infrastructures. The focus is on developing a solution that is consistent with user-centered principles, offers optimized resource discovery, and enhances user satisfaction. Taking into account the unique requirements of the university library environment, this study contributes to the broader debate on improving the efficiency of library services through technological innovation. The proposed system of recommendations aims to bridge the gap between library resources and users, ensure efficient use of resources, and provide a superior library experience.

The growing interest in integrating recommender systems into university libraries has led to a wide range of studies examining their development, implementation, and impact on user satisfaction. Some studies provide a basic understanding of how open-source platforms can offer cost-effective solutions, especially for smaller institutions [1]. Others demonstrate the technical evolution of recommender systems by using advanced machine learning algorithms to optimize recommendations for larger and more diverse collections [2]. The importance of localization has been emphasized, and systems have been adapted to specific cultural and institutional contexts to enhance user engagement [3]. Hybrid approaches that combine collaborative filtering and content-based methods have also been explored to serve a broader and more diverse user base [4]. Systematic reviews provide insights into the general trends, challenges, and future directions of educational recommender systems. These reviews identify shortcomings in existing systems and highlight opportunities for adapting technological developments to academic needs [5], [6]. Metadata analysis has been investigated for its potential to improve academic outcomes through personalized recommendations [7]. Furthermore, studies highlight the role of user satisfaction and feedback mechanisms in informing iterative system improvements [8], [9]. A data-driven approach using historical lending data has proven effective in increasing the visibility and accessibility of resources within libraries [10]. Furthermore, studies have identified challenges and proposed strategies to overcome the limitations of existing systems [11]. Future library services are expected to move towards the integration of intelligent technologies such as recommendation systems, which will enhance the importance of personalized and data-driven approaches in modern academic libraries [12]. Taken together, these studies provide a holistic perspective on the field, encompassing the technical, user-centered, and strategic aspects of library recommendation systems. Some emphasize technical methodologies such as deep learning [2] or hybrid filtering approaches [4], while others focus on user engagement [8], [9] and systemic issues [6], [11]. The vision of integrating advanced technologies supports the feasibility and necessity of implementing recommender systems tailored to the specific needs of university libraries, bridging the gap between traditional resource management and effectively meeting modern user demands.

This study aims to assess the need and feasibility of introducing recommendation systems in university libraries by assessing the main criteria for evaluating scientific and educational databases.

II. Materials And Methods

The study focuses on the level of awareness, accessibility, and frequency of use of library electronic databases among faculty members and students of the Tashkent University of Information Technologies named after Muhammad al-Khwarizmi.

To achieve these goals, the following research tasks were carried out:

a) To study the level of awareness of electronic databases used for academic and research purposes at the university.

b) To identify the main channels of information about electronic databases among students and faculty members.

c) To determine the frequency and necessity of using electronic databases at the university.

The study used a survey methodology to collect relevant data. A structured questionnaire was designed to gather insights into users' experiences and perceptions of electronic databases in academic libraries. The survey covered aspects such as awareness, access, usage patterns, and potential interest in recommender systems for library resources. In this survey, bachelor's students, master's students, assistants, senior lecturers, associate professors, and professors participated, making up a total of 112 participants.

III. Results and Discussion

University libraries are an integral part of modern education systems, providing access to important academic resources and knowledge for students and researchers. However, a persistent challenge is to effectively tailor library services to the specific needs and preferences of users. Addressing this challenge is particularly important to enhance digital transformation in education.

This study explores these challenges by analyzing data collected through user surveys to develop practical recommendations for implementing a personalized recommendation system in university libraries. An analysis conducted among students of the Tashkent University of Information Technologies named after Muhammad al-Khwarizmi provides key insights into user behaviors and requirements. Using these findings, the study aims to propose strategies that increase resource accessibility and improve the overall user experience in academic libraries.

A. Analysis of Survey Questions and Objectives

The survey questions were designed with the following objectives:

- Understanding User Engagement with Library Services:
  Question: "How often do you visit the library?"
  Objective: To measure the frequency of library visits and adjust service offerings accordingly.
- Identifying Preferred Library Usage Modes:
  Question: "Do you use a traditional library or an electronic library?"
  Objective: To evaluate the demand for digital resources and services.
- Evaluating Feedback on Current Services:
  Question: "Is the library search system user-friendly?"
  Objective: To identify areas for improvement in search functionalities.
- Assessing Interest in Technological Enhancements:
  Question: "Do you think recommendation systems like those on YouTube or Instagram are necessary for libraries?"
  Objective: To gauge interest in integrating personalized recommendation systems in library services.

B. Analysis of Results

The study results revealed the following trends:

Library Usage Frequency: 70.4% of respondents reported visiting the library more than once a week, indicating high engagement with library resources.

Digital Resource Adoption: 65% of respondents indicated a preference for electronic libraries, demonstrating a growing demand for digital solutions.

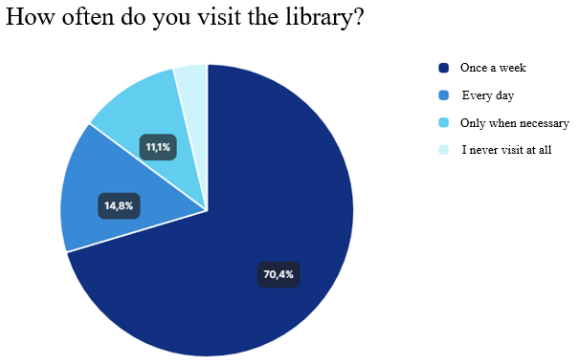


Fig. 1. Diagram of users' library visits.

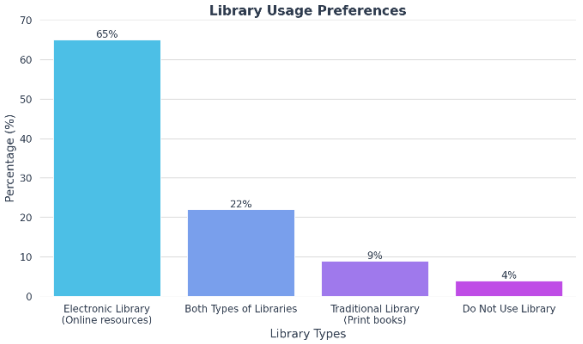


Fig. 2. Library usage preferences.

Search System Feedback: While 58% of users found the search system efficient, 30% identified areas for improvement, highlighting the need for an optimized user experience.

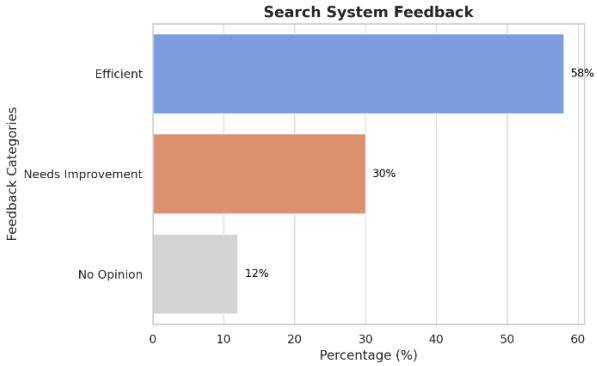


Fig. 3. Search system feedback data

Recommendation Systems: 78% of respondents believed that implementing recommendation systems would enhance library services by improving resource accessibility and personalization.

Developing a recommendation system for university libraries offers several advantages. It provides personalized services by tailoring recommendations based on user preferences and learning goals, thereby improving resource discovery. In addition, it improves search efficiency by automating the recommendation process, saving users time and effort in finding relevant materials.

The system also contributes to optimal resource utilization by providing visibility into underused resources through targeted recommendations. Furthermore, the integration of advanced technologies such as artificial intelligence and machine learning allows libraries to offer modern services that are in line with current technological trends, enhancing the overall user experience and academic engagement.

Below is a summary of survey responses:

TABLE 1 SUMMARY OF SURVEY RESPONSES

Question	Responses		
	Yes (%)	*No (%)*	*Undecided (%)*
Is a recommendation system needed?	78	15	7
Do you use electronic libraries?	65	25	10

The review findings indicate a strong demand for recommendation systems in university libraries. Such systems can enhance user experience, optimize service delivery, and support academic goals by providing personalized, efficient, and technology-driven solutions.

Surveys play an important role in shaping services by providing insights directly from users. For university libraries, a study that focuses on user preferences, technological needs, and service performance provides an opportunity to adapt offerings to the evolving academic and technological landscape. The analysis under consideration provides important information that informs strategies that can be implemented to improve library performance and user satisfaction.

University libraries benefit significantly from data-driven decision-making, as empirical evidence helps administrators optimize services based on user behavior. For example, 70.4 % of respondents believe that understanding library traffic can help better allocate services during peak hours, while 65 % say that a preference for electronic resources is a necessity to invest in digital infrastructure. Improved user experience is another benefit, as 30 % of users who identified inefficiencies in their search engine will guide necessary technical updates, ensuring libraries address specific pain points such as search inefficiencies or limited access to relevant resources. In addition, the integration of emerging technologies is made possible by strong user support, with 78 % of respondents expressing interest in AI-based recommender systems. This readiness allows libraries to prioritize technological improvements that personalize the user experience and help them find resources more efficiently. In addition, better utilization of resources can be achieved through library surveys, which identify underutilized materials, allowing recommendation systems to promote these resources and more balanced distribution of library assets. Finally, aligning library services with institutional goals strengthens the university's commitment to scholarly achievement and technological innovation by creating an environment conducive to research and learning.

Surveying university libraries is critical to understanding the changing needs of users, as academic environments are dynamic, influenced by technological advances and changing learning practices. Regular surveys ensure that library services are responsive to these shifts, and remain relevant and effective. In addition, surveys provide a competitive advantage by helping libraries keep pace with digital resources and online platforms such as YouTube and Instagram, identifying which features, such as recommendation systems, can improve their services and fill the gap. Cost-effectiveness is another important advantage, as survey results help institutions allocate resources more effectively, avoiding unnecessary investments in redundant services and directing funds to high-impact areas that users find valuable. Additionally, actively seeking user feedback increases engagement by demonstrating the library's responsiveness and building trust, which in turn encourages greater user participation and use of available resources.

The survey offers a foundation for university libraries to innovate and adapt in response to user needs. By leveraging the findings, libraries can enhance service delivery, integrate advanced technologies, and align their operations with modern academic requirements. This proactive approach ensures that libraries remain indispensable in the academic ecosystem.

IV. CONCULISIONS

The study confirms that the integration of recommendation systems in university libraries is both necessary and feasible. In theory, these systems will contribute to the evolution of digital library science by improving personalized information retrieval models and improving resource discoverability. The findings are consistent with the existing literature on AI-driven library management and reinforce the importance of adaptive learning algorithms in academic settings.

From a practical perspective, the survey results highlight the growing demand for intelligent recommendation systems among students and faculty. The data suggest that universities in Uzbekistan can improve research efficiency and educational outcomes by implementing AI-based recommendation tools tailored to the needs of their users. These systems not only simplify access to academic resources, but also optimize library management through data-driven decision-making. Institutions should invest in regular needs assessments to adapt recommendation algorithms to changing academic needs. By leveraging advanced technologies, university libraries can move from traditional resource management models to dynamic, user-centered academic support systems.

The implementation of recommendation systems represents a strategic advance in library innovation, ensures long-term sustainability, and enhances academic engagement. Future research should focus on developing

localized AI-based solutions, addressing language and content diversity, and optimizing system performance for different academic disciplines.

ACKNOWLEDGEMENTS

I would like to extend my sincere appreciation to the administration and faculty members of my university for their continuous support and professional guidance throughout the course of this research. In particular, I am profoundly grateful to my scientific supervisor, Mr. Normatov Sh. B., for his expert supervision, valuable recommendations, and constructive feedback, which played a significant role in the successful completion of this study. I also acknowledge the support and encouragement provided by my classmates and colleagues, whose collaboration contributed to a productive and motivating research environment.

REFERENCES

[1] K. Puritat, and K. Intawong, "Development of an Open Source Automated Library System with Book Recommendation System for Small Libraries." *Journal of Library Innovation*, 2022, pp. 45–60. http://dx.doi.org/10.1109/ECTIDAMTNCON48261.2020.9090753

[2] T. Xu, W. Xianqing and L. Tingting, "Research on Personalized Recommendation System of Library Collection Based on Deep Learning," *Digital Libraries Research*, 2022, pp. 78–90. http://dx.doi.org/10.1155/2022/3087623

[3] H. Zhang, Y. Xiao and Z. Bu, "Personalized Book Recommender System Based on Chinese Library Classification," *Library Systems and Services*, 2023, pp. 250–265. http://dx.doi.org/10.1109/WISA.2017.42

[4] T. Pan, "Personalized Recommendation Service in University Libraries Using Hybrid Collaborative Filtering Recommendation System," *Journal of Academic Libraries*, 2021, pp. 205–220.

[5] N. Kamal, F. Sarkar, A. Rahman, S. Hossain and K. Mamun, "Recommender System in Academic Choices of Higher Education: A Systematic Review," *International Journal of Educational Technology*, 2021, pp. 120–135. http://dx.doi.org/10.1109/ACCESS.2024.3368058

[6] F. L. da Silva, B. K. Slodkowski, K. K. Araújo da Silva and S.C.Cazella, "A Systematic Literature Review on Educational Recommender Systems for Teaching and Learning: Research Trends, Limitations, and Opportunities," *Educational Technology Research and Development*, 202371(2),123–145. https://doi.org/10.1007/s10639-022-11341-9

[7] M. J. Holmes, "Recommender Systems in Higher Education: The Effectiveness of Meta-Data Analysis in Predicting Academic Success" *Higher Education Technology Journal*, 2022, pp. 35–50.

[8] J. Miller, "Analysis of User Satisfaction of Academic Digital Library: An Empirical Model with Mediating Effects," *Journal of Information Systems in Education*, 2020, pp. 215–230. http://dx.doi.org/10.6007/IJARBSS/v13-i12/20030

[9] R. Johnson, "Evaluating User Satisfaction with Digital Library Services: A Study of Academic Libraries in Higher Education Institutions," *Higher Education Digital Resources Journal*, 2022, pp. 90–110.

[10] M. Garcia, "The Book Recommendation System Using Library Loan Records," *Library and Information Systems Journal*, 2021, pp. 55–72.

[11] T. Brown, "Book Recommendation System: A Systematic Review and Research Issues," *International Journal of Library Science and Research*, 2020, pp. 120–138.

[12] E. Thompson, "The Future of Libraries: Adapting to User Needs," *Library Management Review*, 2021, pp. 12–28.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 313-320

The Method of Complete Bifurcation Analysis for Predicting the Behavior of Complex Systems

Igor Schukin
Daugavpils Study and Science Centre
Riga Technical University
Daugavpils, Latvia
igors.scukins @rtu.lv

Raisa Smirnova
Daugavpils Study and Science Centre
Riga Technical University
Daugavpils, Latvia
raisa.smirnova@rtu.lv

Abstract- **Numerous studies of nonlinear dynamical systems have revealed a wide variety of dynamic behaviors. Nonlinear effects that occur when the initial conditions and parameters change can appear in different and sometimes unexpected ways. This work focuses on studying how complex dynamics arise in nonlinear systems. A bilinear oscillator is used as an example to show how the behavior of the system changes as its parameters vary. The study is based on a systems approach and uses the method of complete bifurcation groups. To investigate nonlinear effects, analog simulation or the direct scanning method is usually employed. However, these methods are somewhat limited in their ability to predict many dynamic characteristics, including bifurcations that lead to unstable, rare, and chaotic solutions. The paper is devoted to the parametrical analysis of periodic and chaotic oscillations in non-linear dynamic systems. The description of the regular approach to construction of bifurcation diagrams is offered to your attention. This approach allows building complete bifurcation diagrams constructing into consideration regimes the analysis of which is inaccessible by traditional methods. For example, regimes with a very small area of existence are identified as rare attractors. Such approach is used in a method of complete bifurcation groups and realized in software SPRING that developing in the Riga Technical University under guidance of Professor Mikhail Zakrzhevsky. The description of this approach and results of its application are presented in this report. The object of the research is a dynamical system whose behavior is described by the second order ordinary differential equation or a system of such equations. The dynamical system state at any time moment is characterized by the values of its phase coordinates and behavior – by variation of the phase coordinates in time. The behavior of a determinate dynamical system is uniquely defined by its initial state and the fixed parameters. The initial state is given by the values of the phase coordinates at the start. In the system behavior we can distinguish a transient process, which ends by a stationary state or regime. The stationary regime can be periodic with a period equal to the mapping period, subharmonic with a period multiple to the mapping period, almost periodic and chaotic. This method is effective for scientific research because it allows a systematic study of the main scenarios of birth and conditions for the formation of chaotic and rare attractors, which depend on parameters defined by engineering systems. Applications of this method include the simulation and analysis of nonlinear dynamic systems, the prediction of technical disasters, and the development of new vibration technologies and other technical systems.**

Keywords- complete bifurcation diagram, rare attractor, chaos.

I. INTRODUCTION

The study of nonlinear dynamical systems is an important task in science and engineering, as their behavior can change in complex and sometimes unexpected ways when parameters or initial conditions vary [1] – [2]. Traditional analysis methods, such as analog simulation and direct scanning, have limited capabilities in predicting rare and chaotic regimes [3] – [6]. Therefore, the development and application of the method of complete bifurcation groups [7] – [9] is a relevant scientific challenge, allowing for a more detailed investigation of the mechanisms behind the emergence of complex dynamics.

The purpose of this study is to investigate the processes of complex dynamical regime formation in nonlinear systems using a bilinear oscillator as an example. This research relies on the method of complete bifurcation groups [10] – [12], which allows for the construction of bifurcation diagrams containing both stable and unstable periodic regimes, as well as the systematic identification of dynamic regimes inaccessible to traditional analysis methods. These diagrams will be referred to as “complete bifurcation diagrams”. The obtained results can be applied in the simulation and analysis of nonlinear systems to predict their behavior, prevent technical disasters, and develop new vibration technologies and other engineering systems.

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8595
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

The object of the research is a dynamical system whose behavior is described by the second order ordinary differential equation or a system of such equations. The dynamical system state at any time moment is characterized by the values of its phase coordinates and behavior – by variation of the phase coordinates in time (time history). The behavior of a determinate dynamical system is uniquely determined by the initial state (the value of the phase coordinates at the initial time) and by the values of fixed parameters. Traditionally a system behavior is represented in the form of a continuous phase trajectory, but for some researches only points of discrete mapping of this trajectory can be used, as suggested by French mathematician Poincaré. In this case only certain points can be retained from continuous phase trajectory, located at equal time intervals, which can be called a period of mapping. In the non-autonomous systems with periodic excitation the mapping period is chosen to be equal to the period of driving force. This method of mapping is called Poincaré mapping or T-mapping.

In the system behavior we can distinguish a transient process, which ends by a stationary state or regime. The stationary regime can be periodic with a period equal to the mapping period (P1), subharmonic with a period multiple to the mapping period (P2, P3…), almost periodic (PA) and chaotic (Cha). In the case of periodic and subharmonic state the discrete mapping points are repeated, forming fixed points in Poincaré map. In the case of non-periodic steady state, the discrete mapping points fill a fixed region of phase space, not going beyond its borders.

The general characteristics of a steady state do not change over time. For example, phase coordinates of fixed points, phase portraits, amplitude of oscillations, amplitude spectrum, etc. A set of such characteristics we call a passport of steady state.

Characteristics in passport of steady state are unchanged in time, but will change with the variation of system parameters. For example, the amplitude of oscillations may be dependent on the frequency of the driving force or the stiffness of the elastic coupling. The study of such dependencies is the purpose of a parametric or bifurcation analysis. Typically, the bifurcation analysis results are presented in the form of bifurcation diagrams, which show the change of the characteristics of the stationary state when changing one or more system parameters. For example, the frequency response is the bifurcation diagram showing a dependency of the stationary oscillations amplitude on the forcing frequency.

Thus, the purpose of this paper is to present the method of bifurcation analysis and to describe the typical topology of bifurcation diagrams of forced dynamical systems.

This method is applied to investigate fundamental scenarios of attractor formation and the conditions for the emergence of chaotic and rare attractors, depending on parameters determined by engineering systems. The practical applications of this method include the analysis and simulation of nonlinear dynamical systems, the prediction of technical failures, the development of novel vibration-based technologies, and various other engineering applications.

II. Materials and Methods

In this study, a bilinear oscillator was analyzed to investigate the formation of complex dynamic regimes in nonlinear systems. The method of complete bifurcation groups was employed to construct comprehensive bifurcation diagrams, facilitating the systematic identification of dynamic regimes that are often undetectable by traditional analysis methods. This approach enables a deeper understanding of the mechanisms underlying complex dynamics in nonlinear systems.

A. Researched model

The results of bifurcation analysis of forced oscillations in the dynamical system with bilinear elastic force are considered in this paper. The scheme of this model is shown in Fig. 1.

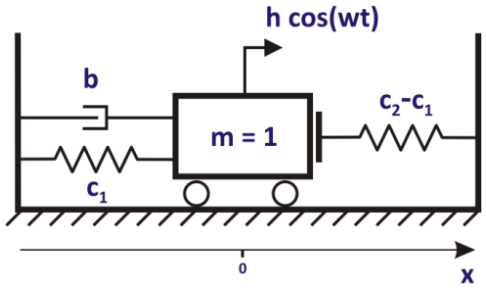


Fig. 1. Forced dynamical system with bilinear elastic force and viscous friction.

The behavior of the researched dynamical system is described by the second order differential equation (1).

$$m\ddot{x} + F_v(\dot{x}) + F_x(x) = F_t(t) \quad (1)$$

The dynamical system contains three forces (Fig.2): bilinear restitution force $F_x(x)$, harmonical excitation force $F_t(t)$ and linear dissipative force $F_v(\dot{x})$.

$$F_x(x) = \begin{cases} c_1 x, & x < 0 \\ c_2 x, & x \geq 0 \end{cases} \quad (2)$$

$$F_t(t) = h\cos(wt) \quad (3)$$

$$F_v(\dot{x}) = b\dot{x} \quad (4)$$

The parameters of the dynamical system are: m = 1 – body mass, b = 0.05 – coefficient of linear dissipative force, $c_1 = 1$ and $c_2 = 16$ – stiffness of elastic couples, h = 1 and w = 0.5…8.5 – amplitude and frequency of external harmonical excitation.

The detailed description of the forced dynamical system—with its bilinear elastic force, viscous friction and harmonical excitation — along with the robust numerical methods employed to solve its governing equation, provides a solid foundation for analyzing its dynamic behavior.

With the model and experimental procedures clearly defined, the discussion shifts to the intricate patterns that emerge as system parameters vary.

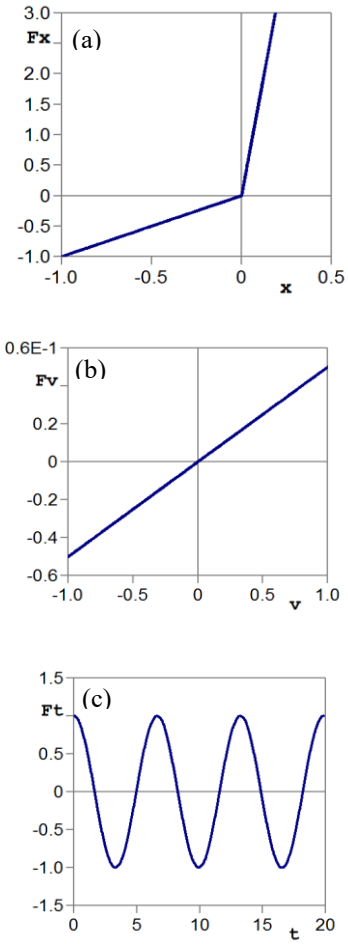


Fig. 2. The graphs of researched model's forces: (a) bilinear elastic force Fx(x), (b) linear dissipative force Fv(x˙) and (c) harmonical excitation force Ft(t).

The next section delves into the construction of complete bifurcation diagrams, which capture the evolution of periodic and chaotic regimes, offering deeper insights into the underlying mechanisms driving these complex dynamics.

B. Methods of research

The given research is based on the numerical solution of the Cauchy problem for the differential equation (1) from given initial condition at fixed parameters values. The resulting time history, obtained using the numerical integration by the Runge-Kutta method, is separated into transitional process and stationary state. For example, Fig. 3 shows time history that can be realized in the considered system at excitation frequency w = 0.88. Time history, phase portrait and Poincaré mapping illustrate the transitional process that ended by periodic steady state with the period of excitation force. Such periodic attractors we call P1. On the phase plane this periodic regime corresponds to the limit circle, on the Poincaré map – to the fixed point.

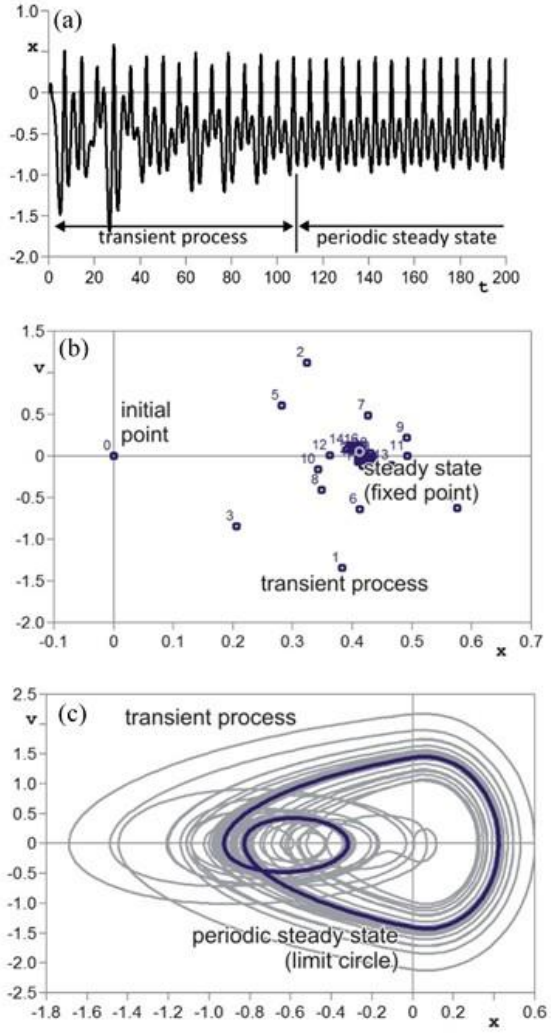


Fig. 3. Time history (a), phase portrait (b) and discrete mapping points (c) of transient process and stationary periodic regime P1. For bilinear system (1) at parameters m=1, c_1=1, c_2=16, b=0.05, h=1, w=0.88. Initial conditions x_0=0, v_0=0.

It is more convenient to solve the problem of periodic regimes searching for the discrete equation obtained from the original differential equation on the basis of the Poincaré map. For this, it is necessary to substitute a continuous system described by the differential equation (1) with a discrete system described by the discrete mapping operator D, which defines the change in the state of the system over one period of the investigated regime (5) [13], [14].

$$X(t + T) = D(X(t)), \qquad (5)$$

where X(t) is the system time history, T is the mapping period, for the considered non-autonomous system it's equal to the period of the driving force $T = \frac{2\pi}{w}$, D is discrete mapping operator, describing the variations of the system state via the mapping period.

For most systems obtaining of the discrete mapping operator analytically is impossible. In this research for the considered system the discrete mapping operator is constructed algorithmically based on the numerical integration of the original differential equation (1) over the mapping period T.

To find the periodic solution P1 of the original differential equation (1) it is necessary to solve the discrete equation (6).

$$X = D(X) \qquad (6)$$

Roots of the equation (6) will be fixed points of the discrete mapping or initial conditions of periodic regimes P1. To find periodic solutions with longer periods (P2, P3…) it is enough to apply the discrete mapping operator in equation (6) appropriate number of times. For example, for regimes P2 – two times (7).

$$X = D(D\,X) \qquad (7)$$

For the considered system equations (6) and (7) can be solved only numerically, e.g., using Newton's method.

The roots of the equations (6) and (7) correspond to the initial conditions of periodic regimes. We call the set of basic characteristics of such regimes the regime's passport. For example, the passport of the periodic regime may include: order, amplitude and period, phase portrait and limit values of phase coordinates, coordinates of fixed points, characteristics of stability, results of spectral analysis, etc. Passport of stable first order periodic regime P1 that exists in considered system at excitation frequency w = 0.88 is shown in Fig. 4.

The obtained solutions correspond to both stable and unstable periodic regimes. Evaluation of the periodic regime's stability is based on the Floquet theory [15], according to which the periodic solution is stable if all roots λ of the characteristic equation of monodromy matrix (Floquet multipliers) (8), calculated for the discrete mapping operator (5) at a fixed point, will be less than one in absolute value.

$$det\left[\frac{dD(X)}{dX} - \lambda E\right] = 0 \qquad (8)$$

For example, the regime in Fig. 4 is stable, since the absolute values of both multipliers are less than one. This is easily seen on the argand diagram, where the unit circle and the complex roots of the monodromy matrix are mapped.

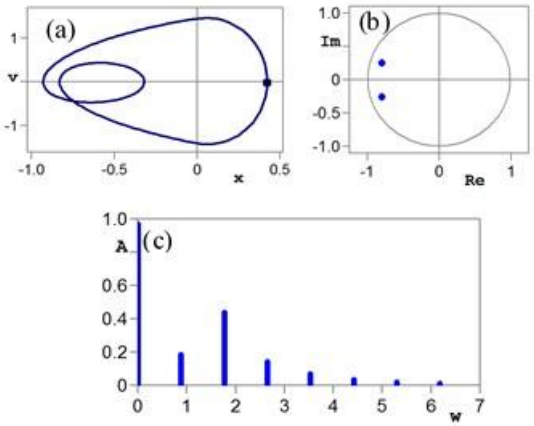


Fig. 4. Passport of the periodic regime P1. For bilinear system (1) at parameters m=1, c_1=1, c_2=16, b=0.05, h=1, w=0.88.
(a) Initial conditions: t0 = 0; x0 = 0.421642; v0 = -0.029472.
(b) Floquet multipliers: λ1 = -0.79736 + 0.252962i;
λ2 = -0.79736 - 0.252962i
(c) Spectrum: main harmonics (A > 0.1)

To perform parametric analysis and to construct bifurcation diagrams we used the method of complete bifurcation groups [7]-[9], which is based on the method of parameter continuation for the stable and unstable periodic solutions.

The graphs, describing changes of the system steady state when one of its parameters is changed, are called one-parameter bifurcation diagrams. The diagram may present changes of the fixed point's phase coordinates (x, $\dot{x} = v$) or the periodic regime's amplitude (Ax) when changing a system parameter. Practically the construction of such diagrams means the solution of equations (6) and (7) for different values of the variable parameter. This method is known as the method of parameter continuation. Its application allows one to represent points corresponding to both stable and unstable periodic regimes on the complete bifurcation diagrams [12].

For example, the bifurcation diagram for regime P1, whose passport is shown in Fig. 4, is shown in Fig. 5. This diagram shows the change of the regime amplitude when the frequency of the driving force varies from 0.8 to 1.9. In the diagram a resonance peak, which for the system under consideration is at the frequency w = 1.6, is clearly allocated. The diagram shows the amplitudes of both the stable and unstable regimes for which the Floquet multipliers are greater than one. The points, at which the stability of the regime changes, are called bifurcation points. At these points in addition to changing the stability other oscillation regimes are born, for which the own branches of the bifurcation diagram can be constructed. The bifurcation diagram, which contains branches for all stable and unstable oscillation regimes realized in the system, can be called a complete bifurcation diagram.

On the complete bifurcation diagram particular importance is given to the bifurcation points in which a qualitative change of the regime's stability occurs. For example, the period-doubling bifurcation at stability loss of regime P1 leads to the birth of stable regime P2.

Sequence of period-doubling bifurcations is one of the possible scenarios for the birth of chaos [7], [16], [17], known as the Feigenbaum scenario [18]. The cascade of period-doubling bifurcations leads to appearance of an infinite number of unstable periodic solutions (e.g. P1, P2, P4, P8...). Such structure will be called as unstable periodic infinitium (UPI). Presence of UPI in the system determines the existence of a stationary or transient chaos [7].

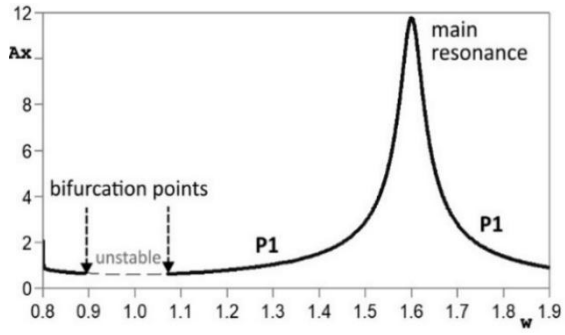


Fig. 5. Bifurcation diagram of periodic regime P1 shows the changes of regime amplitude Ax at variation of excitation frequency w. Diagram contains fragments, corresponding to stable and unstable solutions. For bilinear system (1) at parameters m=1, c_1=1, c_2=16, b=0.05, h=1, w=0.88…1.9.

On the plane of the two parameters a two-parameter bifurcation diagram can be constructed. This diagram consists of bifurcation boundaries, every point of which corresponds to the bifurcation point on the one-parameter diagram. Bifurcation boundaries corresponding to the bifurcation of period-doubling cascade limit in the two-parameter diagram regions of parameters at which UPI exists. In these regions chaotic behaviour of the system is possible. To construct a two-parameter bifurcation diagrams a method of movement on the bifurcation boundary can be used.

The following section delves into the construction of complete bifurcation diagrams, which capture the evolution of periodic and chaotic regimes, offering deeper insights into the underlying mechanisms driving these complex dynamics.

C. Complete bifurcation diagram

The construction of a complete bifurcation diagram begins with the search of all possible periodic regimes at fixed parameters values. It is important to find not only stable, but also unstable periodic solutions. For this discrete equations similar to (6) and (7) need to be solved. As initial conditions for the iterative processes of numerical solutions, points from a certain region of the phase plane are chosen. As we shall see hereinafter, it is important to find at least one regime from each bifurcation group. The remaining regimes will be found when constructing the complete bifurcation diagram by the method of parameter continuation.

Passports of all found regimes form a periodic skeleton. It is the basis for constructing a complete bifurcation diagram. An example of a periodic skeleton for the system under consideration is shown in Fig. 6. It contains three periodic regimes, two of which are unstable.

Applying the method of parameter continuation and the hypothesis about the continuity of the bifurcation diagrams branch, it is possible to construct a branch of the bifurcation diagram for each regime from the periodic skeleton. In the bifurcation points of the branch, new periodic regimes can be born, which will be the starting points for constructing new branches. The set of branches of the bifurcation diagram obtained in this way is called the bifurcation group. The order of the bifurcation group is determined by the regime with the lowest order. The bifurcation branch of this regime is either infinite in the direction of decreasing and increasing the parameter (this is characteristic of the basic regime P1), or it is closed to itself. Closed groups are called island-type bifurcation groups or islands.

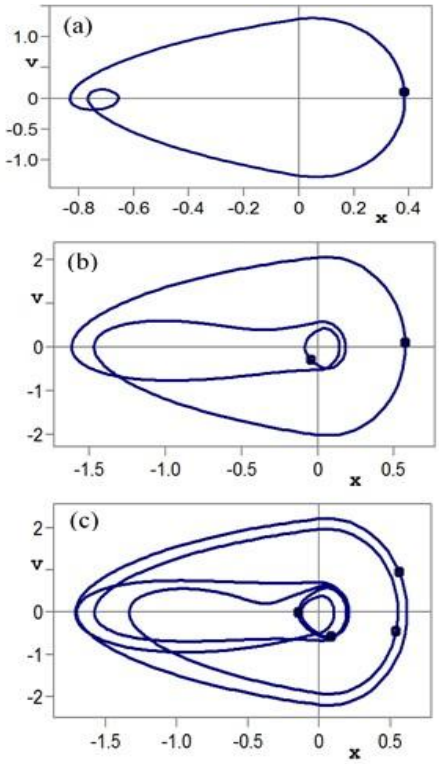


Fig. 6. **P**eriodic skeleton – the passports of all possible periodic regimes (P1,P2 and P4) at given fixed parameters values:
(a) unstable periodic regime P1;
(b) unstable periodic regime P2;
(c) stable periodic regime P4.
For bilinear system (1) at parameters m=1, c_1=1, c_2=16, b=0.05, h=1, w=1.01.

An example of a complete bifurcation diagram for the system under consideration is shown in Fig. 7. The diagram contains one bifurcation group of order P1. It includes stable and unstable branches for periodic solutions P1, P2, P4 and P8. Moreover, solutions of higher orders are produced at bifurcation points of lower-order solutions, when the latter lose their stability. The sequence

of such period doubling bifurcations (of which only the first three are shown in the diagram) leads to the creation of an infinite number of unstable solutions branches. We call this structure UPI (Unstable Periodic Infinitium). It is the cause of the chaotic behavior of the system, which can be expressed either in a chaotic attractor or in a chaotic transient process. An example of the discrete mapping of the chaotic stationary regime from the UPI region of the bifurcation diagram of Fig. 7 is shown in Fig. 8.

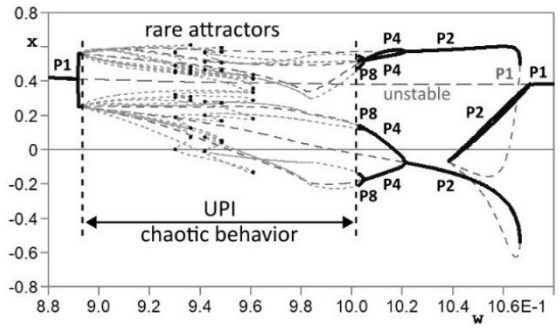


Fig. 7. Complete bifurcation diagram of bifurcation group P1 shows the changes of the fixed points coordinates x at variation of excitation frequency w in low frequency region.
For bilinear system (1) at parameters m=1, c_1=1, c_2=16, b=0.05, h=1, w=0.88…1.08.

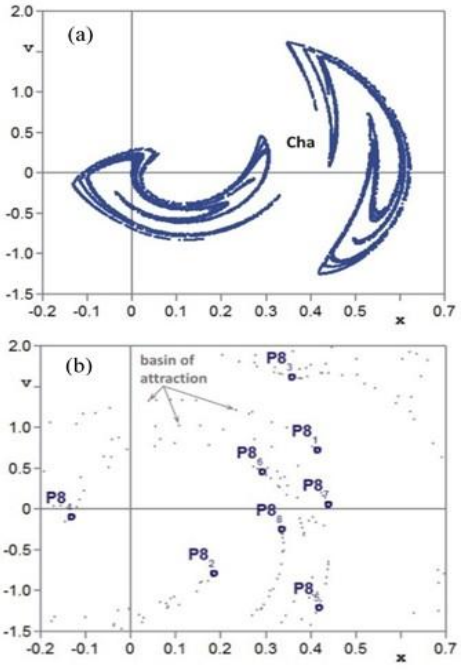


Fig. 8. Poincaré mapping of chaotic attractor (a) contains 10 000 points from initial condition $x_0 = 0$, $v_0 = 0$ and fixed points (b) of coexisted periodic rare attractor P8 (Fig. 9) with very narrow basin of attraction. For bilinear system (1) at parameters m=1, c_1=1, c_2=16, b=0.05, h=1, w=0.9608.

The bifurcation diagram in Fig. 7 illustrates one more phenomenon, which is revealed with the help of complete bifurcation diagrams – these are rare attractors. On the unstable branch of the P8 regime of this diagram small regions of stability are seen. In these areas, the P8 regime is stable in very narrow parameter ranges. We call such narrow regions of stability as rare attractors. Fig.7 shows five rare attractors that are stable at the values of the parameter w showing in Table 1.

TABLE 1 PARAMETER VALUES FOR RARE ATTRACTORS P8

Rare attractor	Minimal w value	Maximal w value
RA_1	0.93013	0.93014
RA_2	0.93617	0.93618
RA_3	0.94175	0.94176
RA_4	0.94839	0.94840
RA_5	0.96079	0.96082

The passport of one of these rare attractors (at w = 0.96080) is shown in Fig. 9. Due to the fact that this rare attractor is in the UPI region, it coexists with a chaotic regime, the discrete mapping of which is shown in Fig. 8. A rare attractor has a very small region of attraction, which also complicates its detection. Practically it can be found only with the help of a complete bifurcation diagram.

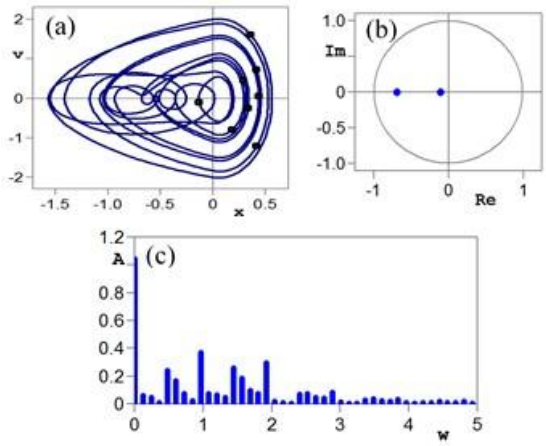


Fig. 9. Passport of the rare attractor P8 that is stable at very narrow diapason of excitation frequency w=0.96079…0.96082. For bilinear system (1) at parameters m=1, c1=1, c2=16, b=0.05, h=1, w=0.96080.
(a) Initial conditions: t0 = 0; x0 = 0.413051; v0 = 0.728654.
(b) Floquet multipliers: λ1 = -0.107133 + 0i;
λ2 = -0.687102 + 0i.
(c) Spectrum: main harmonics (A > 0.2)

To construct bifurcation diagrams of other bifurcation groups it is necessary to construct periodic skeletons for other values of the parameter and, starting from the periodic regimes of these skeletons, construct branches of other bifurcation groups. Fig. 10 shows a complete bifurcation diagram containing all bifurcation groups of orders from 1 to 5 over a wide range of frequencies of the driving force.

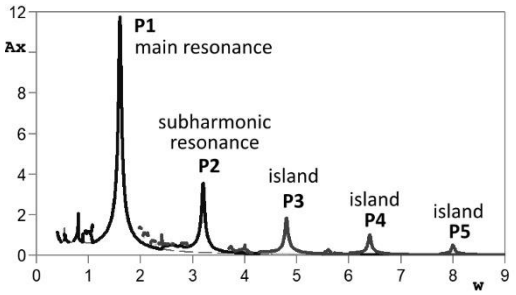


Fig. 10. Complete bifurcation diagram shows the changes of the periodic regimes amplitudes Ax at changing of excitation frequency w. For bilinear system (1) at parameters m=1, c_1=1, c_2=16, b=0.05, h=1, w=0.5…8.5.

Thus, the construction of a complete bifurcation diagram provides a comprehensive representation of the system's dynamic behavior, capturing both stable and unstable periodic solutions. The identification of bifurcation groups and their hierarchical structure allows for a deeper understanding of the transitions between periodic and chaotic regimes. Moreover, the discovery of rare attractors highlights the necessity of this approach, as such regimes are difficult to detect with conventional methods. The complete bifurcation analysis not only enhances our theoretical understanding of nonlinear dynamics but also has significant practical implications for the control and prediction of complex systems.

III. Results and Discussion

The research presented in this paper demonstrates the effectiveness of the complete bifurcation analysis method in predicting the behavior of nonlinear dynamical systems. By constructing complete bifurcation diagrams, including stable and unstable periodic solutions, we gain deeper insights into the system's behavior beyond traditional bifurcation analysis. The method reveals fundamental mechanisms of attractor formation, chaotic transitions, and rare attractor existence, significantly improving the accuracy of dynamical system simulation.

The bifurcation diagrams constructed for a bilinear elastic force system illustrate the transition from periodic oscillations to chaotic behavior via the period-doubling cascade, confirming the Feigenbaum scenario. Additionally, the study highlights the concept of Unstable Periodic Infinitium (UPI), a structural feature of bifurcation diagrams that plays a crucial role in the emergence of chaos. The identification of rare attractors with extremely narrow stability regions further underscores the necessity of the complete bifurcation approach, as these attractors are difficult to detect using conventional methods. The existence of these rare attractors demonstrates the complex and sensitive dependence of dynamical systems on parameter variations.

Moreover, the results obtained using numerical continuation techniques emphasize the importance of parameter continuation for capturing both stable and unstable solutions. The approach facilitates the identification of bifurcation points, where qualitative changes in stability occur, leading to the birth of new periodic regimes. This capability is critical for engineering applications, including the prediction of technical failures, vibration control, and the development of nonlinear mechanical systems.

IV. Conclusions

This study employs the method of complete bifurcation groups to systematically analyze the complex dynamics of nonlinear systems. A bilinear oscillator serves as the primary model for investigation. The research utilizes the SPRING software, developed at Riga Technical University under the guidance of Professor Mikhail Zakrzhevsky, to construct comprehensive bifurcation diagrams. This approach enables the identification of dynamic regimes, including rare attractors, that are often undetectable using traditional analysis methods. The methodology facilitates a deeper understanding of the mechanisms leading to complex behaviors in nonlinear dynamical systems.

This research represents the method of complete bifurcation analysis as a powerful tool for investigating the dynamics of nonlinear systems. The method allows for the systematic exploration of stable and unstable periodic solutions, revealing complex bifurcation structures such as period-doubling cascades, chaotic attractors, and rare attractors. The findings confirm that Unstable Periodic Infinitium (UPI) plays a crucial role in the emergence of chaotic behavior and highlight the importance of capturing rare attractors, which can significantly influence system stability.

The proposed methodology is not only theoretical but also has practical implications in various engineering domains. It enables more accurate simulation of nonlinear oscillatory systems, assists in predicting critical transitions leading to instability, and provides valuable insights for the design and optimization of engineering structures. Future research can extend this method to explore higher-dimensional dynamical systems, further enhancing our understanding of complex nonlinear phenomena.

The presented study highlights the effectiveness of the method of complete bifurcation groups in predicting the behavior of nonlinear dynamic systems. Constructing complete bifurcation diagrams that include both stable and unstable periodic solutions provides a deeper understanding of the system's dynamics, extending beyond traditional analyses.

The method of complete bifurcation groups enables the identification of fundamental mechanisms behind attractor formation, transitions to chaos, and the existence of rare attractors, thereby deepening our theoretical understanding of dynamic systems. Analyzing interactions between bifurcations across various periodic regimes enhances our comprehension of universal patterns in the dynamics of nonlinear systems. Furthermore, the consistent detection of attractors with extremely narrow stability regions highlights the complex and sensitive dependence of dynamic systems on parameter variations, which is crucial for chaos theory.

Practically, this method aids in predicting technical failures; understanding bifurcation mechanisms and chaotic behavior allows for anticipating potential failures in engineering systems, thereby increasing their reliability. Studying dynamic transitions also contributes to developing effective vibration control methods in mechanical systems, which is vital for ensuring stability and safety. Lastly, a comprehensive understanding of nonlinear dynamic behaviors facilitates the design of more efficient and robust mechanisms in various engineering applications.

In summary, the research underscores the importance of the method of complete bifurcation groups as both a theoretical tool for gaining profound insights into the dynamics of complex systems and a practical instrument for developing and optimizing engineering solutions.

V. ACKNOWLEDGMENTS

The authors express their sincere gratitude to Professor Mikhail Zakrzhevsky for fostering a creative and inspiring research environment. His guidance and support have been instrumental in the development of the method of complete bifurcation groups, enabling the systematic study and analysis of complex dynamics in nonlinear systems. Additionally, his visionary leadership made it possible to implement the ideas of this method in the software SPRING, further advancing the research in this field.

REFERENCES

[1] Y. Ueda, The Road to Chaos-II. Aerial Press. Inc. Santa Cruz, 2001.

[2] J.M.T. Thompson and H.B. Stewart, Nonlinear Dynamics and Chaos, 2nd Edition, Wiley, 2002.

[3] Vibrations in Engineering:Reference Book. Moscow: Machine Engineering, Oscillations of Nonlinear Mechanical Systems/Edited by I.I. Blehman, vol. 2, p.351, 1979. (in Russian).

[4] M. Lakshmanan and S. Rajasekar, Nonlinear Dynamics. Integrability, Chaos and Patterns. SpringerVerlag, Berlin, Heidelberg, 2003.

[5] M. Zakrzhevsky, Yu. Ivanov and V. Frolov, NLO: Universal Software for Global Analysis of Nonlinear Dynamics and Chaos. In Proceeding of the 2nd ENOC, Prague , vol. 2. pp.261-264, 1996.

[6] A.C.J. Luo and A.B. Lakeh, Period-m motions and bifurcation trees in a periodically forced, van der Pol–Duffing oscillator. International Journal of Dynamics and Control, vol. 2, pp. 474–493, Jan.2014.

[7] M. Zakrzhevsky, New concepts of nonlinear dynamics: complete bifurcation groups, protuberances, unstable periodic infinitiums and rare attractors. Journal of Vibroengineering, vol.10, Iss.4, pp.421-441, 2008.

[8] I. Schukin, M.Zakrzhevsky, Yu.Ivanov, V. Kugelevich, V.Malgin and V. Frolov, Application of software SPRING and method of complete bifurcation groups for the bifurcation analysis of nonlinear dynamical system. Journal of Vibroengineering, vol. 10, Issue 4, pp. 510-518, 2008.

[9] R. Smirnova, I. Schukin and M. Zakrzhevsky, Methodology "The Path to Chaotic and Rare Attractors in Dissipative Nonlinear Systems". In Catalogue of the 7th International Invention and Innovation Exhibition MINOX 2018. J.Dumpis ed. Riga, pp.51-52.,2018. ISBN 978-9984-885-33-9.

[10] R. Smirnova, M. Zakrzhevsky, V.Yevstignejev and I.Schukin, Paradoxes of Increasing Linear Damping in the Nonlinear Driven Oscillators. Journal of Vibroengineering, 2008, Vol.10, Issue 4, pp.529-537. , 2008. ISSN 1392-8716.

[11] R. Smirnova, M. Zakrzhevsky and I. Schukin, Global Analysis of the Nonlinear Duffing-van der Pol Type Equation by a Bifurcation Theory and Complete Bifurcation Groups Method. Vibroengineering Procedia, vol.16, Iss.3, pp.139.-143.lpp., 2014. ISSN 2345-0533.

[12] M. Zakrzhevskis, I. Schukins, R. Smirnova, V. Jevstigņejevs, V. Frolovs and E. Shilvans, Global Nonlinear Dynamics: New Novel Concepts and Their Realization Based on the Method of Complete Bifurcation Groups 16th US National Congress of Theoretical and Applied Mechanics (USNCTAM2010): Proceedings on CD, United States of America, State College, Pennsylvania, pp 1-2, 26.June-2. July 2010.

[13] A. Katok and B. Hasselblatt, Introduction to the modern theory of dynamical systems. Cambridge University Press, 1997.

[14] S. M. Zaslavsky and R. Z. Sagdeev, Introduction to nonlinear physics: from pendulum to turbulence and chaos. Moscow, Nauka, 1988. (in Russian)

[15] B. P. Demidovich, Lectures on the mathematical theory of stability. Moscow, Nauka, 1967. (in Russian)

[16] N. V. Butenin, Y. I. Nejmark and N. A. Fufajev, Introduction to the theory of nonlinear oscillations. Moscow, Nauka, 1967. (in Russian)

[17] A. P. Kuznetsov, S. P. Kuznetsov and I. R. Sataev, A variety of period-doubling universality classes in multi-parameter analysis of transition to chaos. Physyca D, vol. 109, pp. 91-112, 1997.

[18] H. S. Strogatz, Nonlinear dynamics and chaos: with to physics, biology, chemistry, and engineering. Westview Press, 1994.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 321-327

A Comparative Analysis of Native iOS Frameworks for Developing Graphics Scenes in Augmented Reality Applications

Mariya Shirokopetleva
Department of Software Engineering
Kharkiv National University of RE
Kharkiv, Ukraine,
marija.shirokopetleva@nure.ua

Olena Shevchenko
Department of Software Engineering
Kharkiv National University of RE
Kharkiv, Ukraine,
daria.koshkina@nure.ua

Daria Pervieieva
Department of Software Engineering
Kharkiv National University of RE
Kharkiv, Ukraine,
olena.shevchenko@nure.ua

Loreta Savulioniene
Faculty of Electronics and Informatics
Vilniaus Kolegija
Vilnius, Lithuania
l.savulioniene@viko.lt

Paulius Sakalys
Faculty of Electronics and Informatics
Vilniaus Kolegija
Vilnius, Lithuania
p.sakalys@eif.viko.lt

***Abstract*—While defining the technology stack for creating native AR apps for iOS, developers are faced with the need to choose between two popular Apple graphics frameworks: SceneKit and RealityKit. Most available studies are dedicated to the analysis of their internal architecture and most beneficial technical capabilities. Whereas this study focuses on the fundamental comparison of the frameworks using the multi-criteria decision analysis method. For this, the significant qualitative and quantitative comparison criteria are highlighted, as well as a series of experiments are conducted to compare frameworks in terms of scene rendering performance (FPS) and mobile device resource usage (CPU, GPU). Such a formal approach makes it possible to evaluate the effectiveness of frameworks and their suitability for different project types and development teams. This allows developers to make informed decisions during the design stage according to their needs. Confirming the potential of the proposed approach in practice, an example of its application to select the most appropriate framework for two different AR projects is presented. The specificity of applying this approach in the context of the current task was highlighted.**

Keywords*— *Augmented Reality, graphics scenes, iOS, multi-criteria decision analysis.

I. INTRODUCTION

Augmented reality (AR) technologies are becoming an integral part of everyday life, with applications spanning various fields. From mobile gaming to pre-project visualisation and interactive learning, AR enhances the user experience by integrating virtual elements into the real world [1], [2], [3]. According to ARTillary Intelligence [4] in 2024, the number of AR-ready Apple devices surpassed the number of similar devices from Google.

With interactive content becoming a norm, understanding AR frameworks is a crucial skill for software engineers mastering AR. However, integrating AR into iOS applications poses a challenge due to the variety of available frameworks, each with distinct advantages.

Choosing a technology stack when starting a new project is crucial for its development cost, set of features, further updates potential, future success in general and resulting profit. Developers can decide based on their experience and intuition or utilize any suitable formal method. Employing formal analysis can provide a defensible, evidence-based justification of the choice, ensuring that the decision is robust and balanced.

For Apple devices, there are three most commonly used native frameworks that could be utilized to implement high-performance AR applications: ARKit, SceneKit (SK), and RealityKit (RK).

The primary function of ARKit is environmental scanning and real-world integration [5], [6]: detect surfaces, track device position in space, and determine depth for placing virtual objects within the real

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8610
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

environment. ARKit can work with LiDAR scanners available on newer iOS devices, allowing the use of three-dimensional spatial data for real-time depth mapping [7]. There is no way to get access to all this functionality without ARKit for Apple devices. ARKit relies on SK, RK, or other graphics engines to render a graphical scene in an AR application [8].

SK is the oldest Apple implementation of rendering technologies. It was introduced in 2012 and was conceived for VR [9]. It is a flexible and powerful 3D rendering engine that enables developers to easily create 3D objects, apply materials, and set up lighting, cameras, animations, and physics simulations, as highlighted in [8], [10].

RK is a modern framework introduced by Apple in 2019 [11]. It enhances 3D object rendering realism in real-world, physics simulations, and spatial audio "out of the box", supports async loading and provides a networking layer to implement state synchronization, etc., as discussed in [10], [12].

If developers want to use only native tools to ensure productivity, they need to choose between SK and RK.

II. MATERIALS AND METHODS

A. Aim and tasks of the study

Despite numerous studies on SK, and RK, most focus is made on analysing their technical capabilities, performance, and integration. However, there are no clear recommendations on selecting the appropriate framework based on project requirements, particularly considering mobile device limitations, performance demands, and rendering specifics. This lack of guidance makes it challenging for developers working on AR applications, highlighting the need for this research.

The aim of this study is to investigate the impact of SK and RK frameworks on the performance and functionality of developed scenes in AR applications for iOS. The research objectives are:

a) Highlight the criteria that can influence the choice of a framework by the software architect, define types of criteria (qualitative or quantitative), measurement scales, ranges, and their possible aggregation groups; the grouping of some criteria is used to reduce their quantity in case it doesn't confuse experts during the criteria groups' weights adjustment.

b) Conduct an experiment to measure criteria values for every alternative (SK and RK frameworks in the current case).

c) Give an example of selected criteria usage to choose SK or RK for specific project and analyse the results.

B. Selecting a formal method for framework scoring

Among the suitable formal methods of alternative selection, there are, for example, neural networks [13], the classical method of multicriteria analysis (MCDA) [14], or its modification based on fuzzy logic [15]. On the one hand, neural networks require a large amount of historical data. This is unlikely to be available to an ordinary software development company. On the other hand, the use of fuzzy logic makes sense when there is partial uncertainty about the values of the selected criteria, or when several experts disagree in their assessments. For such a task as choosing one of two frameworks according to the needs of a particular project, in case all the parameters (criteria) can be measured in terms of certain numerical values and there are no major differences in the way they are interpreted by experts, a classic MCDA is faster and more transparent. This approach also helps to better analyse the pros and cons of the alternatives and to come up with confidence-aware decisions.

For this research classical additive MCDA has been chosen.

C. Criteria identification and definition

There are several aspects that should be considered while making a choice among different graphical frameworks for AR applications. They are performance, supported features (graphics, physics), integration level of AR operations, fine-tuning abilities, simplicity of use, and limitations. Fine-tuning (or customization) ability is the ability to implement such a feature that is not supported in the framework by default.

The values of all indicators are scaled to the selected universal interval scale [0-10], where 0 means not supported or absence of feature and 10 means the best possible level of support. For such parameters as, for example, "Necessity of Performance Tuning," the values are inverted to conform to a unified logic "the bigger - the better".

The performance of AR applications is measured using several key metrics [16]. They are listed in Table I. All the metric ranges in Table I are given non-normalized because it's easier for a person to perceive them in such a format.

The primary performance metric is Frames Per Second (FPS). A high FPS ensures a seamless user experience, whereas a low FPS can cause animation stuttering and degrade usability. For AR\VR applications, the optimal FPS is a stable 60 FPS. Measuring FPS helps assess how well frameworks handle scene rendering while maintaining high performance during animations [17].

CPU usage is critical for overall application performance. It is responsible for loading assets, managing and positioning 3D objects, transferring data to GPU, processing physical interactions and application logic, integrating data from sensors, etc.

Efficient CPU usage is necessary to maintain a balance between animation smoothness and minimal resource consumption [18].

The lower boundary for CPU Frequency is set to 1 GHz since that's the value for its 'idle' mode. The upper boundary for CPU Frequency is set to 3.2 GHz since for most iPhones (the device on which the experiment was performed) with an AX chip, the maximum frequency of 'large' cores can be approximately in the range of 2.3-3.2 GHz.

TABLE I. PERFORMANCE INDICATORS

Indicator	Range	Description
Average FPS, FPS	0-60	Frames Per Second, indicate the smoothness of the application performance
Occasional FPS Drops, FPS	0-60	FPS drops cause a poor user experience
Initial FPS Drops, FPS	0-60	Min observed FPS drops on pick loads
Max CPU Frequency, GHz	1-3.2	To what max frequency the processor was 'overclocked' at peak loads; this indirectly indicates how much the CPU has been utilized
Max GPU Usage, %	0-100	Shows how much GPU was utilized at pick loads

GPU utilization plays a key role in achieving high-quality graphics and real-time interaction in AR/VR applications. The GPU is specialized for rendering computations, making it responsible for displaying 3D objects, textures, shadows, reflections, and lighting. In AR applications, the GPU enables virtual objects to blend seamlessly with the real-world camera feed. High computational loads can cause FPS drops and a poor user experience, especially in complex scenes with many objects. To maintain 60 FPS or higher, GPU performance must be optimized to prevent frame rate delays, interface lag, and excessive battery consumption. Overloading the GPU can lead to overheating and rapid battery depletion, making balanced resource management essential for efficient AR application performance [19].

Ensuring framework adaptability allows developers to optimize resource usage while considering device limitations. Effective CPU and GPU management prevents excessive performance degradation and enhances the overall user experience [20].

All the indicators listed in Table I are estimated during the experiment that is described in section II.D as well as the values themselves.

The important functional graphics features are listed in Table II. In addition to the primary criteria, the analysis also considers additional graphics functional aspects [9], [10], [11] that might be crucial to the quality of AR application being developed. They are 3D file formats support (for assets), different animation types (action based, key frame, skeletal, morph target, inverse kinematics, animation blending, etc.), photorealistic quality of the scene (PBR, basic lighting and shadowing, environmental lighting, ray tracing), physical simulations support (collisions, gravity, forces, physical properties of the objects, etc.).

Since the target type of applications considered in this paper are AR-oriented applications, the level of AR operations integration into the frameworks being evaluated impacts crucially their development process and, thus, their comparison. For example, handling collision with real-world objects, occlusion (hiding partly or completely virtual objects behind real-world objects), and external real-world light consideration.

TABLE II. GRAPHICAL FEATURES INDICATORS

Indicator	SK	RK	Description
3D File Formats (GLTF, OBJ, FBX, USDZ, USD)	8	8	SK doesn't support the USD format; RK doesn't support the FBX format
Animations	8	7	Among all animations, SK doesn't support Real-Time AR-Driven animation only while RK doesn't support Inverse Kinematics and Animation State Machines at all or has limited support for Custom Animation Curves, etc.
Photorealism	7	8	For SK is possible and achieves good results with enough tweaking, but it requires more manual work. For RK automatic environmental lighting and reflection systems help deliver a realistic blend with the real world "out of the box".
Physical Simulations	7	6	SK supports common highly customizable physics interactions (rigid bodies, fields, constraints) but is not aimed at advanced fluid/soft-body out of the box. RK is streamlined for typical AR collisions and simple rigid body dynamics but has fewer advanced features or deep customization.
Average score	**7.5**	**7.25**	

According to this indicator, SK has got 6 points while RK has got 9 points. This is due to the fact that SK supports only basic AR Anchoring and Environmental Lighting out of the box. Other functionalities like Real-Time Plane Detection, Real-Time Occlusion, Physics-Based Real-World Interaction, Motion Capture Support, etc. are supported via manual setup with ARKit or not supported at all [10].

RK points are also not maximum because object recognition works based on pre-scanned 3D object models, it also relies heavily on ARKit's spatial awareness capabilities (e.g., tracking, plane detection, and occlusion) [11]. That's why this functionality in RK is significantly weaker than the same functionality in AI-powered frameworks, such as Vuforia and Unity [21]. Manual implementation of such AI-based algorithms is possible with the use of different object boundary segmentation algorithms, for example, those described in [22].

If the desired feature is not supported by default in the frameworks, it could be possible to implement it manually. Differences between SK and RK in the abilities of feature customization and performance tuning are listed in Table III.

TABLE III. FINE-TUNING INDICATORS

Indicator	SK	RK	Description
Performance Tuning	8	5	SK supports Level of Detail (LOD) management, profiling and reducing draw calls, and simplifying node hierarchies using Xcode Instruments; RK allows to structure "entity-component-system" (ECS) data efficiently
Custo-mization	9	5	SK supports custom shaders, PBR materials, lighting, and advanced postprocessing, e.g. [23], etc. RK supports *only* simple custom materials, reflections, and lighting adjustments
Average score	**8.5**	**5**	

The indicators collected in Table IV [24] are useful because in case other aspects are equal, a product that is easier to use is likely to be preferred.

TABLE IV. USAGE SIMPLICITY INDICATORS

Indicator	SK	RK	Description
Community, Docs, Samples	9	8	SK was introduced in 2012 and RK – in 2019. Both have detailed documentation and a lot of code samples.
Graphical Scene Editor	8	7	SK has an advanced scene editor in Xcode good for deep customization and control over every aspect of a 3D scene but lacks AR-elements integration out of the box; RK uses an external Reality Composer for quick prototyping of AR apps
Scene Organization approach	8	10	SK uses an old-style node-based hierarchy, good for 3D scenes; RK provides a modern and easy-to-start ECS approach, but fewer "classic" 3D scene graph control
Necessity of Performance Tuning	5	9	SK is capable to handle moderately complex scenes with advanced graphical effects but requires manual tuning for performance optimization RK provides a generally efficient graphical engine based on Metal API
Average score	**7.5**	**8.5**	

Limitations for rated frameworks are shown in Table V.

Platform compatibility influences the potential number of application clients, and Scene scalability affects the classes of AR applications, that could be developed with the corresponding framework.

D. Experiment

To measure the performance indicators of the SK and RK in terms of parameters listed in Table I the experiment was conducted. The ARPerfTester iOS application was developed. The application allows a user to create a three-dimensional scene, add and remove objects, perform animations and analyse system behaviour under varying loads.

TABLE V. LIMITATIONS INDICATORS

Indicator	SK	RK	Description
Compatibility	10	9	SK is available for all versions of iOS/macOS/visionOS; RK is available for iOS 13+/ macOS 10.15+/visionOS all versions
Scene Complexity Scalability	7	9	SK handles moderately complex scenes, but can struggle without fine performance optimizations; RK is generally efficient for complex scenes due to Metal utilization
Average score	8.5	9	

Several test scenarios are offered to evaluate the performance of SK, and RK frameworks. The main goal of the testing is to determine how these tools handle rendering a large number of objects, processing animations, user interactions, and utilizing the device's hardware resources.

Test scenario 1: evaluates performance with an increasing number of objects (up to 100, up to 10000 faces in total). The aim is to determine how object count affects rendering performance.

Test scenario 2: test the impact of animations on the performance. The goal is to determine how the framework processes the simultaneous animation of multiple objects. Using a scene with objects (up to 100, up to 10000 faces in total), a simultaneous rotation animation was executed.

Test scenario 3: stability after object removal. The goal is to check system performance as well as memory management efficiency and resource deallocation.

For the experiment, Xcode Instruments [20] were used as the primary tool for performance analysis and debugging of iOS applications. Instruments allow real-time monitoring of device resource usage, including CPU, GPU, FPS, memory, and power consumption, providing precise data on AR application performance.

Before running the tests, the following tools were configured in Xcode Instruments:

- Time Profiler – to analyse CPU load and identify peak processing moments during scene rendering.
- GPU Profiler – to monitor GPU usage while processing 3D objects and animations.
- Core Animation – to track frame rate (FPS) in real-time and assess the stability of the frameworks.

The experiment was conducted on a physical device (iPhone 8 Plus running iOS 16.7.10). During each test scenario, Xcode Instruments recorded all performance metrics, allowing for both real-time analysis and post-test review. The collected data was exported in .trace format,

enabling a detailed further analysis of the indicators. The results of the experiment are presented in Table VI below.

TABLE VI. SUMMARY OF THE PERFORMANCE RESULTS

Metric	SceneKit	RealityKit
Average FPS, FPS	58	54
Occasional FPS Drops, FPS	4	9
Initial FPS Drops, FPS	55	9
Max CPU Frequency, GHz	1.68	2.13
Max GPU Usage, %	18	53

Throughout most of the testing, SK indicates high performance. However, short-term drops were observed while adding a large number of objects. These drops occurred mainly in the initial step of changing stages when the system processed a large number of new objects or started to execute simultaneous animations.

RK exhibited more pronounced FPS fluctuations initially (when the stage was still empty) – frame rates dropped to 9 FPS, likely due to the high computational requirements for processing initial physics effects and rendering. Subsequently, FPS stabilized at 57-60 FPS, but periodic performance drops were still recorded. These drops were not as low as for SK, but RK was stabilizing longer than SK. This effect confirms higher system resource demands.

The GPU load in the SK remained relatively low. This suggests efficient computation optimization, where the load is evenly distributed among processes.

RK showed significantly higher GPU usage. The highest peak values were observed during active object interactions when complex lighting, physics effects, and animations were being rendered.

High CPU frequency on SK was observed during the addition of new objects and animation execution, but performance remained stable after object removal. RK indicates significantly higher computational requirements compared to SK. This is due to RK's extensive use of physics simulations and lighting rendering, which increases the overall processor load.

In order to utilize the obtained values for analysis using additive convolution [14], the parameters were normalized to the selected range [0-10] according to (1):

$$x_{norm} = \frac{x_i - x_{min}}{x_{max} - x_{min}} \times 10 \qquad (1)$$

The results of the calculations are presented in Table VII.

TABLE VII. NORMALIZED SUMMARY OF THE PERFORMANCE RESULTS

Metric	SceneKit	RealityKit
Average FPS, FPS	9.7	9
Occasional FPS Drops, FPS	0.67	1.5
Initial FPS Drops, FPS	9.17	1.5
Max CPU Frequency, GHz	3.09	5.14
Max GPU Usage, %	1.8	5.3
Average score	**4.89**	**4.49**

E. Application of MCDA to determine the feasibility of frameworks' usage for different applications

Let's describe two typical applications under development that can be used to assess the feasibility of frameworks' usage for their implementation.

Application1 is being developed by a small startup team. Application1 is a product catalogue of furniture and the utility for placing 3D models in space.

Application2 is being developed by a team with experience in 3D graphics or game development. Application2 is the Educational Physics Lab that allows students to place virtual setups (pendulums, mechanical models, etc.) into the real-world environment to investigate and experiment with precise physical interactions, adjusting physical characteristics of the setup components (e.g. motor torque, friction at joints, gear ratios, angular constraints, mass distribution, damping, joint strength, etc.).

Through the analysis of application functionality, weight values for each group of indicators have been proposed for each of the applications. The results of additive convolution [14] for Application1 for both frameworks are given in Table VIII, and for Application 2 are given in Table IX.

TABLE VIII. RESULTS FOR APPLICATION1

Criterion	Weight	SceneKit		RealityKit	
		c_i	$c_i * w_i$	c_i	$c_i * w_i$
Performance	0,25	4.89	1.22	4.49	1.12
Graphical Features	0,1	7.5	0.75	7.25	0.73
AR Integration	0,25	6	1.5	9	2.25
Fine-Tuning	0,1	8.5	0.85	5	0.5
Simplicity	0,2	7.5	1.5	8.5	1.7
Limitations	0,1	8.5	0.85	9	0.9
Total			6.67		**7.2**

TABLE IX. RESULTS FOR APPLICATION2

Criterion	Weight	SceneKit		RealityKit	
		c_i	$c_i * w_i$	c_i	$c_i * w_i$
Performance	0,25	4.89	1.22	4.49	1.12
Graphical Features	0,3	7.5	2.25	7.25	2.18
AR Integration	0,15	6	0.9	9	1.35
Fine-Tuning	0,2	8.5	1.7	5	1
Simplicity	0,05	7.5	0.38	8.5	0.43
Limitations	0,05	8.5	0.43	9	0.45
Total			**6.88**		6.53

The experiment demonstrates that RK is more suitable for Application1, whereas SK is preferable for Application2.

This is because for Application1 basic photorealism and support for various AR interactions, such as gestures to move and rotate objects, are fundamental, while Application2 is impossible without accurate modeling of complex physical interactions and careful performance tuning for complex graphical objects.

III. Results and Discussion

The obtained results demonstrate that the SK is more stable in maintaining frame rates and efficiently utilizes hardware resources, particularly the GPU, thus is suitable for projects where performance and energy optimization are critical. Conversely, with the same scene project in code RK provides more photorealistic rendering and complex physics interaction, but this comes at the cost of significantly higher CPU and GPU load, which leads to FPS instability and increased power consumption. This, in general, confirms the developers' observations obtained in [10], but Apple is constantly improving RK and Metal that is used in its background (instead of OpenGL, which is used by default in SK) and, in perspective, RK should outperform the SK.

According to the features and capabilities comparison, both frameworks cover the same set of them, but there are differences in specific features and how many of them are built-in versus needed manual work. In general, SK is more powerful, mature and flexible in graphical, physical and audio features, but it needs more manual work and professional knowledge to develop them. RK turns on, by default, simple variants of these features but is not able to implement extended versions of them at all. For example, specialized shader effects (non-realistic “Cel” or “toon”-rendering with discrete colour bands, sharp lightning transitions and outlined edges) are not possible in RK at all. They could be useful in educational AR applications, artistic visualization or interactive guides, where it is necessary to help users easily distinguish virtual AR content from real-world scenes.

The same situation is in physical simulations. Powered by Bullet [25], SK allows to set up advanced physical properties of graphical objects, as for Application2. Such interactions are very hard to implement in RK which lacks the granularity needed to provide educationally accurate, highly customizable demonstrations of complex mechanical principles.

On the other side, as the study showed, RK outperforms SK in AR features support. RK was built for AR, so it has AR conveniences that SK alone doesn’t (e.g. automatic gesture handling). A crucial weakness of SK is that under visionOS it runs only in 2D mode, lacking visionOS immersive integration at all.

As a more modern development tool, RK is simpler (though less customizable) than SK for less experienced developers. SK suites developers teams who are professionals in 3D graphics.

In general, RK emerges as the recommended choice for new AR-specific projects. Developers should also consider RK to prototype and future-proof their applications, especially in the context of Apple’s spatial computing initiatives, including visionOS. Nevertheless, SK continues to serve as a reliable general-purpose 3D graphics framework, particularly useful when AR capabilities are secondary, or there are some features that are much harder or not possible to implement in RK than in SK.

IV. Conclusions

This study conducted a comprehensive analysis of the performance and capabilities of the SK and RK frameworks in the context of developing AR applications for iOS. Key evaluation criteria were identified and assessed. A method of MCDA was offered to rigorously select a framework that better meets the requirements of a specific project. It is necessary to pay attention to the peculiarity of the MCDA application in the case when there are mandatory ("must-have") features, e.g. vertex-shaders control or custom graphical post-processing effects. Such mandatory criteria should be excluded from MCDA and checked first. The following MCDA should be made among the alternatives that have passed the mandatory criteria test.

Regarding the future perspective, it is necessary to focus on the research of AI-driven methods in AR, such as detailed spatial understanding, semantic scene segmentation, and mesh classification [26],[27], which could greatly enhance AR functionality for native iOS applications.

References

[1] M. K. Shaleh Md Asari, N. M. Suaib, M. H. Abd Razak, M. A. Ahmad, and N. M. Shaleh, "Empowering Skill-Based Learning with Augmented Reality and Virtual Reality: A Case Study," in 2024 IEEE International Symp. on Consumer Technology, Kuta, Bali, Indonesia, 2024, pp. 225-229, https://doi.org/10.1109/ISCT62336.2024.10791270.

[2] B. Ton, N. Tempert, and D. Plass, "Immersive visualisation of point cloud data of railway environments," in 2024 10th International Conf. on Virtual Reality, Bournemouth, United Kingdom, 2024, pp. 233-239, https://10.1109/ICVR62393.2024.10868576.

[3] A. Dhiya' Mardhiyyah, Vincent, K. L. Mario Gracius, F. Permana, and F. I. Maulana, "LonelyScape: Increasing Attractiveness of Escape Room Game Using Augmented Reality Technology," in 2023 International Conf. on Information Management and Technology, Malang, Indonesia, 2023, pp. 795-800, https://doi.org/10.1109/ICIMTech59029.2023.10277954

[4] MobiDev,”12 Augmented Reality Technology Trends of 2025: New Milestones in Immersive Innovations,” MobiDev, 2024. [Online]. Available: https://mobidev.biz/blog/augmented-reality-trends-future-ar-technologies. [Accessed: Nov. 17, 2024].

[5] Th. A. R. Sure, “Motion Tracking in iOS Applications Using Augmented Reality,” Journal of Android and iOS Applications and Testing,vol. 8, no. 3, pp.1-5, Oct. 2023.

[6] L. Nissen et al., “Towards Preventing Gaps in Health Care Systems Through Smartphone Use: Analysis of ARKit for Accurate Measurement of Facial Distances in Different Angles,” Sensors, vol. 23, no. 9, 4486, May 2023, https://doi.org/10.3390/s23094486.

[7] Apple, “Apple Developer Documentation ARKit,” 2024. [Online]. Available: https://developer.apple.com/documentation/arkit. [Accessed: Nov. 21, 2024].

[8] J. Nhan, “Building Your First ARKit App with SceneKit,” in Mastering ARKit, Berkeley, CA: Apress, 2022, pp. 14-27.

[9] Apple, “Apple Developer Documentation. SceneKit,” 2024. [Online]. Available: https://developer.apple.com/documentation/scenekit. [Accessed: Nov. 27, 2024].

[10] “RealityKit vs SceneKit vs Metal – High-Quality Rendering,” Mar. 7, 2024. [Online]. Available: https://stackoverflow.com/questions/60505755/realitykit-vs-scenekit-vs-metal-high-quality-rendering. [Accessed: Jan. 17, 2025].

[11] Apple, “Apple Developer Documentation. RealityKit,” 2024. [Online]. Available: https://developer.apple.com/documentation/realitykit. [Accessed: Dec. 1, 2024].

[12] S. Sasmoko, F. L. Gaol, and T. Oktavia, “Augmented Reality SDK Overview for General Application Use,” International Journal of Advanced Computer Science and Applications, vol. 14, no. 11, pp. 54-60, 2023, http://doi.org/10.14569/IJACSA.2023.0141106.

[13] S. Wang, B. Mo, and J. Zhao “Deep neural networks for choice analysis: Architecture design with alternative-specific utility functions,” Transportation Research Part C: Emerging Technologies, vol. 112, pp. 234-251, Mar. 2020, https://doi.org/10.1016/j.trc.2020.01.012.

[14] A. Ishizaka and P. Nemery, Multi-Criteria Decision Analysis: Methods and Software. Hoboken, NY: Wiley, 2013, https://doi.org/10.1002/9781118644898.

[15] L. Maretto, M. Faccio, and D. Battini, “A Multi-Criteria Decision-Making Model Based on Fuzzy Logic and AHP for the Selection of Digital Technologies,” IFAC-PapersOnLine, vol. 55, no. 2, pp. 319-324, 2022, https://doi.org/10.1016/j.ifacol.2022.04.213.

[16] P. Nowacki and M. S. Woda “Capabilities of ARCore and ARKit Platforms for AR/VR Applications,” Engineering in Dependability of Computer Systems and Networks, vol. 987, pp. 358–370, 2020.

[17] A.M. Boutsi, C. Ioannidis, and S. Verykokou "Multi-Resolution 3D Rendering for High-Performance Web AR," Sensors, vol. 23, no. 15, 6885, Aug. 2023, https://doi.org/10.3390/s23156885.

[18] M. Hort, M. Kechagia, F. Sarro, and M. Harman "A Survey of Performance Optimization for Mobile Applications," IEEE Transactions on Software Engineering, vol. 48, no. 8, pp. 2879–2904, Aug. 2022, https://doi.org/10.1109/TSE.2021.3071193.

[19] F. Nusrat, F. Hassan, H. Zhong, and X. Wang. "How Developers Optimize Virtual Reality Applications: A Study of Optimization Commits in Open Source Unity Projects," in ICSE '21: Proceedings of the 43rd International Conf. on Software Engineering, pp. 473–485, Nov. 2021, https://doi.org/10.1109/ICSE43902.2021.000.

[20] “Getting Started with Instruments. WWDC Notes,” 2019. [Online]. Available: https://wwdcnotes.com/documentation/wwdcnotes/wwdc19-411-getting-started-with-instruments. [Accessed: Oct. 17, 2024].

[21] “Vuforia Instruct Is Now Vuforia Expert Capture,” May 2023. [Online]. Available: https://www.ptc.com/en/products/vuforia/vuforia-instruct. [Accessed: Jan. 17, 2025]

[22] K. Smelyakov, S. Smelyakov., and A. Chupryna, “Chapter 1. Adaptive Edge Detection Models and Algorithms,” in Advances in Spatio-Temporal Segmentation of Visual Data.Studies in Computational Intelligence, vol. 876: Springer, Cham, 2020, pp.1-51, https://doi.org/10.1007/978-3-030-35480-0_1.

[23] K. Smelyakov, M. Hvozdiev, A. Chupryna, D. Sandrkin, and V. Martovytskyi, “Comparative EfficiencyAnalysis of Gradational Correction Models of Highly Lighted Image,” in 2019 IEEE International Scientific-Practical Conf. Problems of Infocommunications, Science and Technology, Kyiv, Ukraine, 2019, pp. 703-708, https://doi.org/10.1109/PICST47496.2019.9061356.

[24] I. Gruzdo, I. Kyrychenko, G. Tereshchenko, N. Shanidze, “Metrics Applicable for Evaluating Software at the Design Stage,” in COLINS-2021: 5th International Conference on Computational Linguistics and Intelligent Systems, vol. I (2870): Main Conference, Lviv, Ukraine, 2021, pp.916-936. [Online]. Available: https://ceur-ws.org/Vol-2870. [Accessed: Nov. 21, 2024].

[25] C. Dickinson, Learning Game Physics With Bullet Physics and OpenGL, Packt Pub Ltd, 2013.

[26] R. Yenni and A. P V, "Semantic Segmentation and Spatial Relationship Modeling in Hyperspectral Imagery Using Deep Learning and Graph-Based Representations," in 2024 14th Workshop on Hyperspectral Imaging and Signal Processing: Evolution in Remote Sensing, Helsinki, Finland, 2024, pp. 1-4, https://doi.org/10.1109/WHISPERS65427.2024.10876420.

[27] N. Ali, A. Z. Ijaz, R. H. Ali, Z. Ul Abideen and A. Bais, "Scene Parsing Using Fully Convolutional Network for Semantic Segmentation," in 2023 IEEE Canadian Conf. on Electrical and Computer Engineering, Regina, SK, Canada, 2023, pp. 180-185, https://doi.org/10.1109/CCECE58730.2023.10288934.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 329-336

Application of Turbo Codes in Unmanned Aerial Systems

Georgi Stanchev
"Georgi Benkovski" Bulgarian Air Force Academy
Dolna Mitropolia, Bulgaria
gstanchev@af-acad.bg

Vanya Katsarska
"Georgi Benkovski" Bulgarian Air Force Academy
Dolna Mitropolia, Bulgaria
vkatsarska@af-acad.bg

Abstract* — *In the modern world, unmanned aerial systems play an extremely important role in the economy, research, environmental protection, and military operations. Unmanned aerial vehicles, as elements of these systems, operate and perform their tasks by transmitting data and commands over communication radio channels that often face harsh conditions and limitations on frequency-time and energy resources. At the same time, the demand for higher quality and accuracy of the information obtained and the commands issued are constantly increasing. The purpose of this research work is to examine and evaluate the potential of using turbo codes for error correction, especially packet codes, in the communication radio channels of unmanned aerial systems. Different types of turbo encoder designs are reviewed, along with their advantages and disadvantages, to assess their applicability for these channels. The importance of interleaving is discussed, and a structure and algorithm for the operation of an interleaver is proposed as an essential element of the turbo encoder design. Finally, conclusions and recommendations are made for directions for further research and the application of turbo codes in unmanned aerial systems.

Keywords*— *communication channel, interleaver, turbo encoder design, unmanned aerial system.

I. Introduction

Unmanned aerial systems (***UAS***) are currently employed across a wide range of applications, including aerial photography and mapping, target engagement, search and rescue operations, delivery services, environmental and infrastructure monitoring, surveillance and policing, and much more.

Communication technologies used as a means of control and data transfer between main ***UAS*** elements – unmanned aerial vehicles (***UAV***s), also commonly known as drones and the command center (***CC***) – play an essential role in the effective and safe operation of these systems.

The most commonly used types of communication technologies between elements of UAS are autonomous radio channels; Wi-Fi (IEEE 802.11 family) networks; mobile cellular networks (3G, 4G, 5G) and satellite communication networks. These communication technologies, serving as a medium between UAS elements, possess distinct advantages and disadvantages. They determine the main technical parameters of the electronic equipment of ***UAS***s such as the frequency range, the transmitter power and the data transfer rate. In the majority of cases, the purposes, encoding methods and techniques of the control and command signals and data are strongly affected by this medium, as well.

In the ***UAS***s, especially those using satellite communication networks, control commands and data are transmitted over radio channels that are susceptible to noise and interference, which can lead to errors in the transmitted information.

Thus, error correction coding in communication channels is required to increase the reliability of transmission of control commands and data transfer. An encryption to protect information and control over the ***UAS***s from unauthorized access is necessary, as well.

Technological complexity, along with challenges in ensuring reliable and sustainable operation, is observed in ***UAV***s using satellite communication networks, as illustrated in Fig. 1.

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8575
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

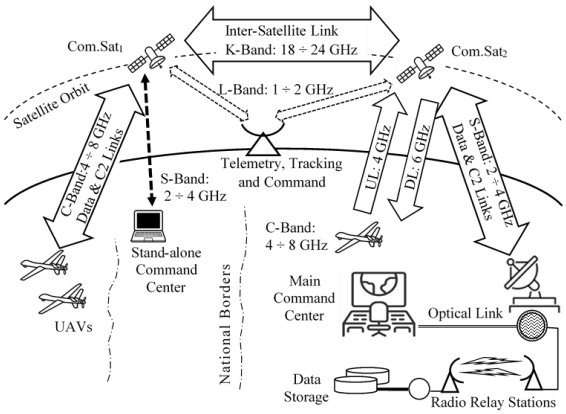


Fig. 1. UAS deployed via satellite communication network.

II. MATERIALS AND METHODS

A combination of quantitative and qualitative analysis methods, stochastic methods from Probability Theory, mathematical modelling and computer simulation were used to explore the conditions in the radio channels of ***UAS*** and assess the applicability of various turbo codes for error correction in these channels.

Satellite communications provide global coverage and are suitable for missions where UAVs operate in remote or hard-to-reach areas – forests, deserts or mountains.

Satellite communications are less susceptible to industrial interference compared to other communication methods, because of frequency range used (1 ÷ 40 GHz). However, in these cases, the signal-to-noise ratio (***SNR***) suffers greatly due to the large and varied attenuations in the communication channels. The frequency dependence of molecular absorption, along with absorption peaks caused by oxygen and water vapor in the Earth's atmosphere necessitates allocating higher frequency transmission range to the equipment with more energy resources and the frequency range around 22.5 GHz for inter-satellite links.

One of the most characteristic features of lines involving a communication satellite (***CS***) is their great physical length. For low Earth orbit (***LEO***) constellations of communication satellites, it ranges from 400 to about 2,000 *km*, but for highly elliptical orbits (***HEO***), it can reach up to 42,000 *km*. This is also the order of the line length when the communications are carried out via a communication satellite located in geostationary orbit (***GEO***), when visible at low elevation angles. The propagation attenuation reflects this significant physical length without taking into account additional factors affecting attenuation. These include such as molecular absorption, absorption by hydrometeors, refraction and inaccurate pointing of antennas, mismatch between the polarizations of the receiving and transmitting antennas, etc. This attenuation can be estimated by (1):

$$L_0 = 21.984 + 20(lgD - lg\lambda), dB \qquad (1)$$

where $\boldsymbol{D}$ is the distance between the transmitter and receiver in the communication line, and $\boldsymbol{\lambda}$ is the wavelength.

The molecular absorption (2) in the atmosphere is:

$$L_a = \frac{[L_{O2}(h_{O2} - h_s) + L_{H2O}(h_{H2O} - h_s)]}{sin\theta}, dB \qquad (2)$$

where $\boldsymbol{L_{O2}}$ and $\boldsymbol{L_{H2O}}$ are the specific absorption coefficients from oxygen and water dissolved in the air, respectively in *dB/m*; $\boldsymbol{h_{O2}}$ and $\boldsymbol{h_{H2O}}$ are equivalent atmospheric heights for oxygen and water dissolved in the air, respectively in *m*; $\boldsymbol{h_S}$ is the altitude of the ground station or ***UAV***, communicating with satellite, and $\boldsymbol{\theta}$ is the elevation angle of the communication satellite above the horizon.

Other factors leading to signal attenuation in the long satellite communication links include absorption by hydrometeors, dust and smoke in the lower layers of the atmosphere, as well as obstruction by tall vegetation, and others. The accurate assessment of these additional losses ($\boldsymbol{L_d}$) is a complex problem of a stochastic nature, in the solution of which the climate model of Crane [1] is often used.

The total signal power losses $\boldsymbol{L_\Sigma}$ are defined as (3):

$$L_\Sigma = L_0 + L_a + L_d, dB \qquad (3)$$

The total attenuation in a satellite communication line is significant and difficult to predict accurately, so some redundancy in terms of signal power is required. In addition, it should be taken into account that highly directional antennas are not used on board ***UAV***s to ensure their maneuverability. This results in an even worse ***SNR*** compared to the lines between a communications satellite and a fixed earth station. At the same time, it is pointless to take into account the losses from tropospheric and ionospheric refraction of radio waves, which are different in cause but the same in result as the losses coming from inaccurate pointing of antennas towards each other in the radio channels between receiver and transmitter if at least one of whose antennas is non-directional.

Other characteristic features of satellite communication channels are significant values and fluctuations in the Doppler shift $\boldsymbol{F_D}$ and signal spectrum broadening, especially at ***CS*** on ***LEO***. There are detailed studies of the distance ***D*** between the ***CC*** or UAV and the ***CS***, as a function of the altitude $\boldsymbol{H_S}$ and the inclination ***i*** of the orbit of the ***CS***, the latitude ***B*** of the UAV, and the time ***t***, i.e. $\boldsymbol{D\ (H_S,\ i,\ B,\ t)}$ and as a consequence of its change – the Doppler shift of the signals $\boldsymbol{F_D(H_S,\ i,\ B,\ t)}$. The large Doppler shift of the frequency spectrum of the signals means that the receiver bandwidth must be expanded to capture them. Expanding the frequency band of the receiver beyond the width of the frequency spectrum of the signals means a deterioration of the ***SNR***. Therefore, the lower attenuation of signals in ***LEO***-based systems compared to those using ***GEO*** is to some extent compromised by the high noise level after the receiver input and the associated low ***SNR***.

The Doppler shift in the system is given by the radial velocity $V_R(t)$ between the transmitter and the receiver through the expression:

$$F_D = -F_0 V_R(t)[V_R(t) + c]^{-1}, Hz \qquad (4)$$

where $c = 2{,}998.10^8$ *m/s* is speed of light.

The change in the distance $D(H_S, i, B, t)$ between ***CC*** or ***UAV*** and ***CS*** determines the radial velocity V_R between them :

$$V_R(H, i, B, t) = \frac{\partial D(H, i, B, t)}{\partial t}, m/s \qquad (5)$$

and the solution of the task of determining the Doppler shift F_D is reduced to deriving an expression for the instantaneous distance between ***CC*** or ***UAV*** and ***CS***.

Although the variation is complex and the amplitudes are large, the Doppler shift is accurately predictable, e.g. Doppler Shift in Globalstar satellite communication system – Table 1 [2], especially if the latitude of the ***CC*** or ***UAV***, the 22 *km* difference between the equatorial and polar radii of the Earth, and the ephemeris data of communication satellites are taken into account. Thus, it becomes easily achievable to compensate for the Doppler shift of the signals and the damage to the reliability of the data, if the ***UAV*** is equipped with a receiver for one of the global positioning systems and a change in the heterodyne frequency is applied in the superheterodyne receiver circuit to neutralize this shift and stabilize the intermediate frequency.

TABLE 1. DOPPLER SHIFT IN GLOBALSTAR SATCOM SYSTEM.

H_S=1414 *km* (LEO), i=52° ; f_0=2,5 *GHz* (Down Link XIII ch.)			
Maximum elevation, θ_{max}	Time of visibility, *s*	Relative Doppler shift	Absolute Doppler shift, *kHz*
1. Latitude of the CC or UAV ***B***=42° N			
30°	± 433	± 1.51·10 $^{-5}$	± 37,75
60°	± 511	± 1.79·10 $^{-5}$	± 44,75
90°	± 526	± 1.83·10 $^{-5}$	± 45,75
2. Latitude of the CC or UAV ***B***=0° (equatorial position)			
30°	-438 ÷ 440	-1,48 ÷ 1,50·10 $^{-5}$	- 37,0 ÷ 37,5
60°	-512 ÷ 514	-1,78 ÷ 1,79·10 $^{-5}$	- 44,5 ÷ 44,75
90°	± 525	± 1,83·10 $^{-5}$	± 45,75

In addition to the large and highly variable attenuations and Doppler shifts, the control and data transfer between ***CC*** and ***UAV***s in ***UASs*** using communication satellites is characterized by significant latency due to the large distances that signals must overcome in such systems. This means that control commands to the ***UAV***s and data from them arrive at their destinations with a noticeable time delay. ***UAV***s are extremely fast and highly maneuverable flying vehicles due to the absence of a human factor on board. If, during the performance of a complex task, a ***UAV*** needs to change abruptly its flight mode, and the command for this is not recognized correctly, then approaches requiring retransmission of commands or automatic repeat query (***ARQ***) are not very suitable because of this latency.

The aforementioned characteristics of satellite communication networks and their role as a medium in ***UAS*** are a prerequisite for special attention to the reliability and error protection of the transmitted information (data and commands) in these systems. To increase the reliability of transmitted control commands and data transfer in unmanned aerial systems, the implementation of channel coding with error correction codes is absolutely required [3]. The choice of ***Forward Error Correction*** (***FEC***) code depends on both the specific requirements of the communication system and the characteristics of the communication channel [4], [5].

III. RESULTS AND DISCUSSION

*A. Error Correction Codes in **UAS** – General Overview*

Several types of error correction codes are suitable for use in communications in ***UAS***s, including the following:

• Low Density Parity Check (***LDPC***) codes that are a special case of block linear codes with parity check. What is special about them is that the check matrices contain a small number of significant elements (sparse matrices), which achieves relative simplicity of the encoding process on the one hand, and provides a relatively high net data rate on the other, while maintaining their high error correction capabilities.

• Reed-Solomon codes are non-binary cyclic codes and represent a special case of Bose–Chaudhuri–Hocquenghem (***BCH***) codes, widely used in digital communications. The elements of the code vector are not individual binary symbols, but entire groups of them, the most common being those that work with bytes (octets). Reed-Solomon codes are optimal in terms of packet length and possible errors to correct – when using ***2n*** check symbols, no less than ***n*** errors can be corrected. Reed-Solomon codes are particularly well-suited for communication channels prone to packet errors, making them highly effective for communication systems implemented in ***UAS***, where such type of errors frequently occur.

• Convolutional codes are a type of non-separable, continuous (recurrent) codes, which, in combination with a subsequent interleaving process, are one of the most effective and commonly used measures of combatting packet errors resulting from fading. Even better results in channels with strong interference are obtained if a convolutional code with a subsequent interleaving procedure is used as the inner error protection coding, and a Reed-Solomon code as the outer one. Of course, in this case too, the increased reliability of data transfer comes at the expense of the net data rate.

• Turbo codes are a relatively young class of ***FEC*** codes and are the first practically usable codes that bring the actual channel capacity extremely close to the maximum channel capacity (Shannon limit). Due to their

undoubtedly valuable characteristics, turbo codes have established themselves as usable in 3G (UMTS) and 4G (LTE, IEEE 802.16 – WiMAX) mobile cellular communications, as well as in satellite communications and communications with objects in deep space.

Turbo code types and their capabilities, as well as their application in ***UAS***s are the subject of further consideration in this work.

B. Turbo Codes – Advantages and Drawbacks.

Turbo codes, while a class of ***FEC*** codes, differ significantly from traditional ***FEC*** codes (e.g. Reed-Solomon, convolutional codes) in the way they achieve error correction. The key advantages of turbo codes compared to traditional ***FEC*** codes are, as follows [6], [7]:

• Superior error correction performance – turbo codes are very useful with their ability to approach the theoretical Shannon limit, and this near-Shannon-limit performance provides highly efficient error correction even at low ***SNR***.

• Enhanced decoding accuracy – turbo codes use an iterative decoding process based on soft-decision inputs, which provides higher error correction accuracy. Traditional ***FEC*** codes (e.g. Reed-Solomon) often rely on hard-decision decoding, which can be less effective in correcting errors.

• Robustness in noisy environments – turbo codes perform exceptionally well in environments with high noise, interference, or fading, while traditional ***FEC*** codes tend to degrade faster in such environments. This feature makes turbo codes ideal for ***UAV*** operations in challenging conditions.

• Efficiency at low ***SNR*** – turbo codes are optimized for environments with low ***SNR***, enabling reliable communication with reduced power or over long distances (e.g. satellite communication line). Traditional ***FEC*** codes typically require higher power or higher ***SNR*** for similar error correction performance.

• Adaptability for different applications – scalable code rates are applicable in turbo coding processes, i.e. they can be configured for different rates and block lengths. This adaptability makes turbo codes highly versatile for different data types, including telemetry, command, and video transmission. Although some of the traditional ***FEC*** codes can be adaptive, they often lack the full flexibility or efficiency of turbo codes in ***UAS*** applications.

• Reduced bandwidth requirements – turbo codes allow communication systems to achieve reliable data transmission at lower ***SNR***, which can be translated to reduced bandwidth usage. Traditional ***FEC*** codes often require more bandwidth to achieve comparable reliability.

• Handling burst errors – turbo codes are highly effective at correcting burst errors, which are common in ***UAS*** communications due to interference, multipath fading, or obstacles. Some traditional ***FEC*** codes fail with burst errors but are better suited for correction of randomly distributed single errors.

• Energy efficiency – by reducing retransmissions through effective error correction, turbo codes can save energy. These power savings are an important factor for ***UAV***s, which have limited on-board power. Traditional ***FEC*** codes may require higher transmission power or multiple retransmissions, consuming more energy.

Turbo codes have some drawbacks compared to traditional ***FEC*** codes:

• Computational complexity – the iterative decoding requires more processing power, which is bad for systems with limited computational resources.

• Memory requirements – turbo decoders require more memory to store intermediate decoding states.

• The intensive decoding process consumes more energy, which can be critical in ***UAV***s where power is a precious resource. Increased power usage for decoding reduces the available energy for other systems, like motors, sensors, and communication hardware and impose a battery life impact.

• Latency for iterative decoding – in some applications turbo codes exhibit higher latency compared to traditional ***FEC*** codes with simpler decoding processes. Critical applications and processes in ***UAS*** requiring minimal latency are ***C2*** links, collision avoidance, live video streaming, etc. Moreover, the number of iterations depends on the error level, leading to variable and unpredictable latency.

• Sensitivity to interleaver design – turbo codes rely heavily on interleaving to fight burst errors. Poor interleaver design can lead to suboptimal performance, making the system more sensitive to specific error patterns. Applying a more complex interleaver design in order to optimize it for specific use cases adds complexity to the system design.

• Lack of universal suitability – turbo codes are not optimal for short blocks. Their performance advantage is most apparent with long block sizes. ***UAS*** transmitting short control messages may benefit more from simpler ***FEC*** codes. In some cases, e.g. extremely high data rates or low latency requirements other codes like ***LDPC*** outperform turbo codes.

C. Turbo Codes – Main Types and Features.

The main idea that led to the achievement of the unique characteristics of turbo codes is in the joint work of at least two encoders on different variants of the same block of data. The classic scheme of a turbo encoder implementing this idea is shown in Fig. 2 [8].

Based on this classic turbo encoder design, several basic types have been developed and used. They differ in the type of specific encoders embedded in the basic circuit, additional devices such as interleaving blocks and memory blocks, as well as the way in which these essential elements are connected in the overall turbo encoder circuit.

Although convolutional encoders are most often used as embedded encoders in designs, and their connection structure is mostly parallel, there are also more specific solutions created in search of characteristics suitable for different conditions. These particularities in the design naturally lead to different properties of the resulting turbo codes, such as capabilities for combating different types of errors, applicability to different types of data and different conditions in the communication channel, latency, capabilities for adapting to different speeds and volumes of the processed data blocks, computational complexity, power consumption, etc.

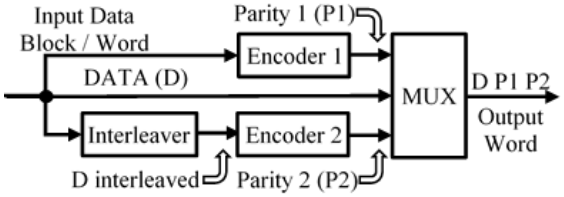


Fig. 2. Classic design of turbo encoder

The design of the decoders in the receiving devices is intrinsically linked to that of the encoders in transmitting devices, with variations in decision-making methods for received code words. For instance, the Viterbi decoding algorithm can be employed using either a hard decision (based on Hamming distance) or a soft decision (based on Euclidean distance).

A soft-in soft-out (***SISO***) design is a typical one for turbo decoding and for serial concatenated decoders, in common. The SISO decoder is based on the assumption of an independent input sequence and a memoryless channel.

The types of turbo codes, their most characteristic properties, and their possible applicability in ***UAS***s are described below:

• Parallel-concatenated convolutional (***PCC***) encoder – The most widely used turbo encoder design consists of two or more recursive systematic convolutional (***RSC***) encoders connected in parallel, with their inputs interleaved. RSC encoders differ from non-recursive ones due to the presence of feedback in their shift-register design, making them infinite impulse response filters [9]. An example of ***RSC*** encoder with constraint length ***K*** of 4, and feedback from outputs of second and third stage of the shift-register (D-Trigers), realized by Boolean ***XOR*** function units is shown in Fig. 3.

A structure of ***PCC*** turbo encoder, consisting of three ***RSC*** encoders and two interleavers is shown as an example in Fig. 4.

A block of ***N*** data bits is applied to the input of the ***PCC*** turbo encoder above. The data block goes to the first ***RSC*** encoder directly, but to the inputs of the other two encoders through two interleavers. The interleavers have the same size of ***N*** bits, but different maps of interleaving, so in the inputs of the three encoders are entering three different permuted variants of the data block – ***ND***, ***NDI1*** and ***NDI2***.

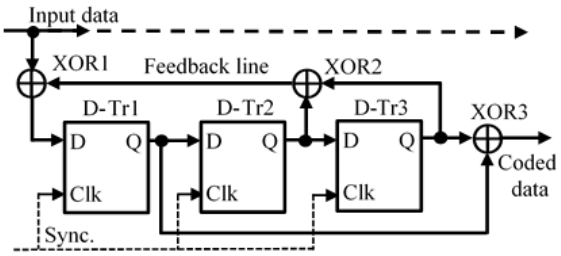


Fig. 3. An example of RSC encoder.

Because all of the embedded encoders are systematic ones, they generate at their outputs ***N*** parity bits – ***NP1***, ***NP2*** and ***NP3***. Multiplexing them and adding the raw input data block to the output digital stream, at the output of this turbo encoder exists a coded data block with volume of ***4N*** bits, i.e. the rate of the encoder above is ***R***=1/4. They can be utilized in a serial or parallel manner for different modulation schemes. This type of turbo encoding has high coding gain and is appropriate to ***UAS***s where reliability and low latency are strongly required, e.g. satellite communication lines of ***UAS***s.

• Serial concatenated convolutional (***SCC***) encoder – it uses convolutional encoders in a serial configuration, so the data stream at the output of one of the decoders is input data stream to the next one. This type of codes are very suitable for iterative decoding, which is the essential point when transferring data using turbo codes. The typical ***SCC*** encoder includes outer convolutional coder, which processes input from a data source, an inner convolutional encoder that transmits its output data stream to a noisy channel, and an interleaver that connects the two encoders, as illustrated in Fig. 5.

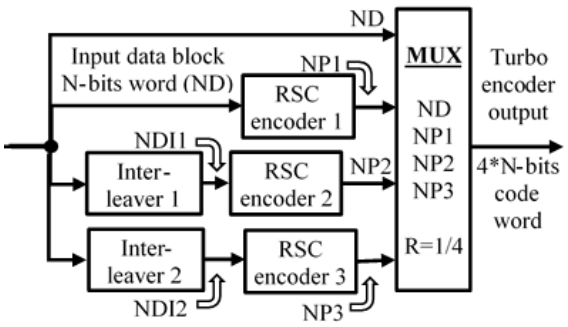


Fig. 4. An example of turbo encoder with PCC design.

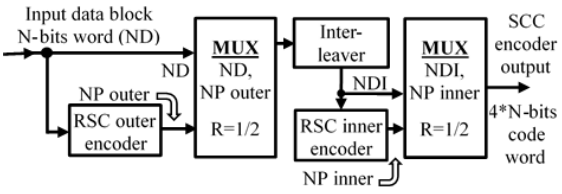


Fig. 5. An example of turbo encoder with SCC design.

A very important feature of ***SCC*** encoders is the inclusion of an ***RSC*** encoder as an inner encoder, which ensures their superior coding gain. Codes of this type have better characteristics compared to ***PCC*** codes around so-called ***error floor*** – the area of the diagram of the bit error probability (***BER***) as a function of the ***SNR***, after which the trend of decreasing ***BER*** with increasing ***SNR*** decreases significantly. In such cases, the use of other types of ***FEC*** codes (e.g. Reed-Solomon or ***LDPC***) is more appropriate than the use of turbo codes, precisely because of the ***error floor*** phenomenon.

• Hybrid concatenated convolutional (***HCC***) encoder, which combines both serial and parallel connections between its built-in RSC encoders, and the relevant interleavers in the structure, is shown in Fig. 6.

The combination of the two main types of connection between the built-in ***RSC*** encoders allows the turbo encoder with the ***HCC*** design to achieve the very good performance (high coding gain) of ***PCC*** encoders at low ***SNR*** and, as inherited from the ***SCC***, a low error floor at high ***SNR***. In addition, the complex ***HCC*** design creates wider possibilities for adapting the encoder to different coding rates, by puncturing (taking away part of the check bits according to a certain pattern) at several points in the connection scheme. The superior performance of turbo codes with ***HCC*** design over a wide range of ***SNR***, as well as the ability to adapt to work with different data types makes them extremely suitable for use in ***UAS***. This is because during the execution of a mission, the distance between the ***CC*** and the ***UAV***, and thus the ***SNR***, varies widely. These changes are even more drastic if a satellite communication system, whose satellites are located on ***LEO***, is used as the medium between the ***UAS*** elements. In addition, limitations in energy resources and the mass of the payload on board a ***UAV*** require that the same elements be used in the widest possible range of purposes and conditions.

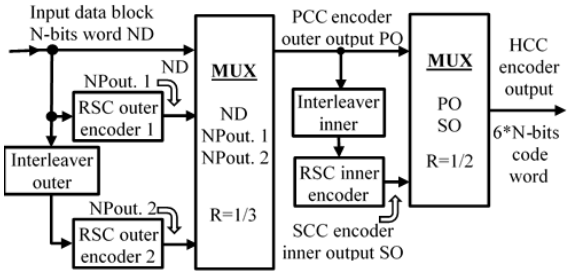


Fig. 6. An example of turbo encoder with HCC design.

Turbo codes with ***HCC*** design, with their ability to adapt to different data types, coding rates and data rates, as well as to work well under different conditions in communication channels, meet these requirements to a high degree.

• There are several other types of turbo codes that will be mentioned briefly only for the sake of completeness. This is because they either are tailored to specific types of communication systems or are used in conditions very different from those in ***UAS*** communication channels and equipment.

Block turbo codes – in the design of these encoders, unlike the aforementioned types of turbo encoders, the typical embedded ***RSC*** encoders are replaced by block ones (e.g. LDPC, Reed-Solomon or other BCH). Due to the simplified decoding compared to that of convolutional codes, as well as the robust error correction for large blocks of data, these turbo codes are used in data storage devices or high-speed optical communications.

Turbo product codes: two or more different block codes are applied in the encoding process on multidimensional data structure – each code in different dimension of the data structure. This code design is so-called "product of codes". Turbo product codes have very good performance on data blocks with long lengths and with soft-decision decoding. This is why they are implemented widely in deep space communications and optical communications.

UMTS/LTE turbo codes – Optimized and standardized code design for 3G/4G mobile communications needs. They consist of two 8-state ***RSC*** encoders and a quadratic permutation polynomial interleaver for optimal interleaving. The optimization of the encoding process for such communication systems allows for high data throughput and very low latency in them. The implementation of these turbo codes in ***UAS*** is the default when 3G/4G cellular communication systems are used as the medium between the ***UAS*** main elements – ***UAV***s and ***CC***.

D. Interleaver – design and features.

The interleaver performs the important task of spacing the pulses that share the information from one input pulse for the convolutional encoder at a sufficient distance (as a time interval) from each other. This ensures effective control of burst errors, which are a common occurrence in channels with pronounced fading from multipath propagation, from shadowing by local objects and landscape features, mobility of the environment, from working with ***UAV***s beyond the line of sight – all conditions typical of communication channels in ***UAS***. The design of the interleaver determines the memory required to perform the interleaving, largely the performance, latency, and power consumption of the turbo encoder as a whole.

A possible variant of performance and design of an interleaver working together with a convolutional encoder with code rate ***R***=1/3 are proposed below.

The encoder is adapted to a set of standard data rates and a frame (data block) duration of 20 ms – in the given example the data rate is 28.8 kbps. A similar design was used in the Globalstar satellite communications system [10], operating on a modified version of the Interim Standard 95 (IS-95) CDMA-based radio interface.

The digital data stream obtained after the ***RSC*** encoder output is divided into frames with a standard duration of 20 ms and with a volume of 576 bits, i.e. 192 triplets of bits, which are input and processed in the interleaving block.

The pulses from the frame are recorded sequentially in a memory with a capacity of 576 bits, represented as a square matrix with dimensions of 24x24, as it is shown in Fig. 7. Time duration of the frame is 20 ms, and is formed by time duration of 24 rows (24*833.33 μs = 20000 μs).

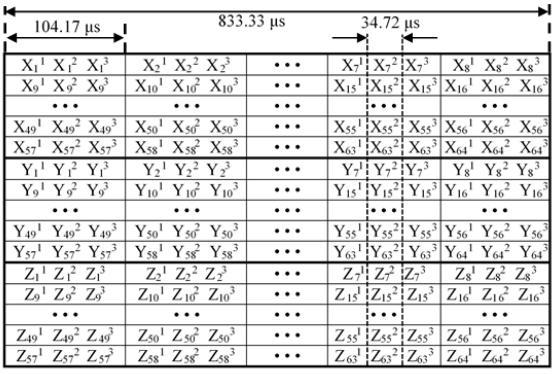


Fig. 7. Records of the RSC output in 576-bits interleaver memory.

The shifting of individual sub-blocks of recorded information occurs according to a certain scheme, in which the bits belonging to a certain triplet (with the same lower indices) are shifted into conditional groups ***X***, ***Y*** and ***Z***, the goal being to separate the bits belonging to a certain triplet of bits (these ones with superscripts 1, 2 and 3).

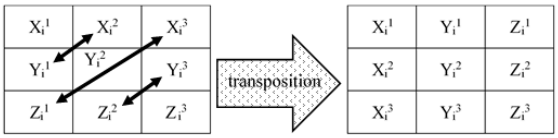


Fig. 8. Recorded bits transposition between groups X, Y and Z.

After the shifting, the bits from the sub-blocks and conditional groups are scattered across the memory matrix as shown in Fig. 9.

This algorithm ensures the dispersion of the triplets of bits involved in the transmission of the same information cyclically at 833.33 μs and 9582.72 μs, which is an average of 5280 μs, or in other words, neighboring bits and the information contained in them, initially vulnerable to packet errors, are separated by an average distance of 150 bits.

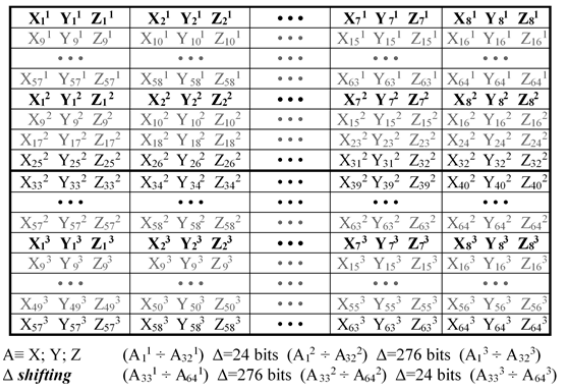


Fig. 9. Recorded bits transposition between groups ***X***, ***Y*** and ***Z***.

The interleaver memory is read in sub-frames, 16 in number, each with duration of 1250 μs and according to the scheme shown in Fig. 10.

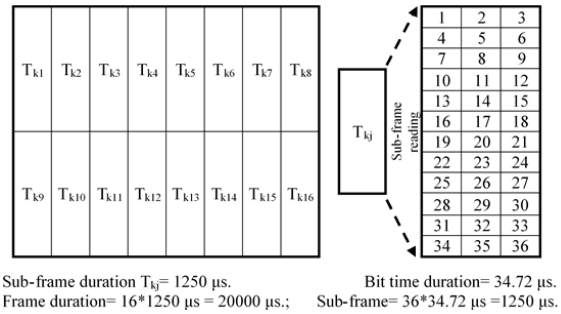


Fig. 10. Reading of theb frame by sub-frames and aidividual bits.

Of course, the processes of writing, reordering and reading are presented as time-separated above, just to illustrate the algorithm and the result of interleaving. In practice, they happen this way and in this order only through a suitably set table for addressing the write and read cells from the memory block.

The time intervals are only representative of the specified standard data rate of 28.8 kbps and can be scaled to any other rate. Thus, the proposed interleaving block design is suitable for combating both medium and fast fading, with these classifications being aligned with the speed of the turbo encoder processes and the rate of the data being processed.

IV. CONCLUSIONS

The conditions in the communication radio channels for data transfer and control commands in ***UAS*** are extremely difficult, especially in systems using artificial Earth communication satellites for their transmission. On the one hand, they are as a result of very low ***SNR*** due to the presence of noise and interference with high spectral density and low power level of the useful signal because of limitations in energy resources, especially on board the ***UAS***, and high values of channel losses. On the other hand, the ways of propagation of signals in the channels - multipath propagation and mutual motion between transmitters and receivers of the system further worsen the conditions for reception and correct evaluation of the signals.

Therefore, a few key points need to be considered:

• The conditions in communication radio channels for data transfer and control commands in UAS create a high likelihood of multiple errors in digital data streams, with packet errors being more typical. This requires the use of correction codes that have good performance close to the theoretical capacity of the channel. Such characteristics are possessed by turbo codes – with some differences in the details for their different type of design and complexity.

• The conditions in ***UAS*** radio communication channels vary widely, especially with respect to signal-to-noise ratio. Turbo codes, while superior to other ***FEC*** codes when operating near the Shannon limit, at high signal-to-noise ratios fall behind traditional high-power error correction codes. In this respect, hybrid turbo codes retain their superiority over the widest range of ***SNR***, compared to turbo codes with parallel or serial design. Overcoming this problem can be achieved either by using two different types of ***FEC*** codes – e.g. a hybrid turbo code for low ***SNR*** and some block code from the ***BCH*** family for high ***SNR***, or by using one hybrid turbo code and power control of the transmitted signals by a reverse channel, which would lead to much better energy efficiency of the communication equipment on board ***UAV***s.

• Different types of digital data in ***UAS*** communication channels have different sensitivity to errors occurring during their transmission. Command and control (***C2***) signals, even at the lowest data rate, should be maximally protected from errors and at the same time this should be done through encoders and decoders that introduce minimal additional latency. The nature of other data types allows for a higher level of single-error rates and even significant additional associated latency due to the sensors onboard UAVs, such are, e.g. video streams captured by UAV cameras in the infrared light range. This requires careful selection and possible switching of turbo encoders to ensure the necessary and sufficient noise immunity of the different data types.

• The other main building blocks in the design of turbo encoders, besides the built-in RSC encoders, which largely determine the characteristics of the generated turbo code, are the interleavers. The aim of these is to obtain an efficient spreading of the bits belonging to one information group, without this leading to significant added latency and the use of large computational resources and memory volumes.

Carefully constructed, flexible algorithms for the operation of the interleavers can satisfy these requirements.

• Of the turbo codes studied, those derived from turbo encoder hybrid design appear to be most suitable for use in the complex conditions of UAV communication channels. The hybrid design offers a wide variety of multi-level connections and the flexibility to incorporate various built-in encoders: either RSC encoders with different code rates and constraint lengths or replacing some of the built-in RSC encoders with other types of powerful error correction encoders. To fully exploit the potential of hybrid turbo encoders, i.e. to combine the advantages and mutually eliminate the drawbacks of the inbuilt interleavers and encoders of different types, much more theoretical, simulation and practical research is required.

ACKNOWLEDGMENTS

This work was supported by the NSP SD program, which has received funding from the Ministry of Education and Science of the Republic of Bulgaria under the grant agreement no. Д01-74/19.05.2022.

REFERENCES

[1] R. K. Crane, A Two-Component Rain Model for the Prediction of Attenuation and Dihversity Improvement. New Hampshire Hanover: Dartmout College, 1982.

[2] G. Stanchev, Satellite Communications (in Bulgarian), Veliko Tarnovo: National Military University “Vasil Levski”, 2006, pp. 38-39, ISBN-10:954-713-078-1, ISBN-13:978-954-713-078-4

[3] T. S. Rappaport, Wireless Communications: Principles and Practice, Prentice Hall; Subsequent edition, 2002, pp 339-356

[4] S. Lin and D. J. Costello Jr., Error Control Coding, London: Pearson, 2nd edition, 2004, pp. 257-315.

[5] B. Sklar, Digital Communications: Fundamentals and Applications. (Скляр, Б., Цифровая связь – теоретические основы и практическое применение. Второе издание, исправленное. М., “Вильямс”, 2004.) pp. 332-452.

[6] K. Sripimanwat, Turbo Code Applications (a journey from a paper to realization), New York: Springer, 2005.

[7] B. Vucetic and J. Yuan, Turbo Codes: Principles and Applications, New York: Springer Science+Business Media LLC, 2000, pp. 73-80. ISBN 978-1-4613-7013-0

[8] C. Berrou and A. Glavieux, Near Optimum Error Correcting Coding and Decoding: Turbo-Codes, IEEE Trans. on Communications, vol.44,No.10, October 1996, pp. 1261-1271

[9] J. G. Proakis and M. Salehi, Communication System Engineering, 2nd edition, PHI Learning Private Limited, New Delhi, 2011, pp. 591-601, 640-646

[10] N. I. Smirnov, N. A. Ivanchuk and S. F. Gorgadze, Advantages of low-orbit satellite information transmission systems with synchronous code division multiplexing such as Globalstar. (in Russian), Moscow: Electrosvyaz Magazine, No 2(3), 1997, pp. 20-24, ISSN:0013-5771

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 337-344

Image Recognition in the Traffic Sign System - Semiotic and Linguistic Aspects

Dilyana Stoicheva
Sofia University "St. Kliment Ohridski",
Sofia, Bulgaria
stoicheva.dilyana@abv.bg

***Abstract*- The traffic sign system is a complex structure composed of images and verbal text. This research aims to focus on the nature of the road sign as an image, its recognition by road users, the relationship between verbal text and image in road sign design, how much they interact and how text contributes to the basic functions of the sign - to direct and regulate traffic and the behaviour of road users. The theory of sign, a subject of study in semiotic science, is examined. The sign as an image influences, informs, regulates the behaviour of road users - these are its main functions. The system of road signs is composed on the basis of a common code of symbols and images, which is modified in different linguistic and cultural environments. The text component complements and supports the functions of the image. Its structure and pattern in different languages are also investigated in order to check the necessity or redundancy of the verbal text in the composition of the road sign as a whole. By using an interdisciplinary approach between semiotics and linguistics, the research could be extended towards improving the design of road signs in order to improve communication on the road through the road sign system, an element of traffic.**

***Keywords*— semiotics, linguistics, road safety, road signs, code, image**

I. Introduction

The object of the research is the system of road signs. Usually the problems are considered in the research field of road engineers, planners, builders, traffic control and transport authorities. Road signs as an element of infrastructure are part of our surroundings. But they are also a communication system that could be studied by specialists in the fields of cognitive psychology, linguistics, even cultural anthropology.

The subject of this research is the relationship between images and verbal text in road signs and how they interact as a whole.

The aim of the study is to broaden the field of analysis from highly specialized scholars who seem to have monopolized the topic of the perception of road signs as only regulating traffic rules. The research would be more thorough if it were complemented with methods from other scientific fields and an interdisciplinary approach to the study of this topic - how road signs affect road users - was created. Road signs are a complex of image (symbol) and referenced verbal text. In their unity, they perform the functions of directing, guiding and indicating the correct directions and courses of action for road users. Their correct perception contributes to the fulfilment of their functions.

I will try to analyse to what extent the text or the image prevails over the picture (symbol), how they interact, whether there is a need to increase the volume of the verbal text, comparing the type of construction in the text between English and other languages.

The research methodology compiles various methods from the scientific field of semiotics, linguistics (general linguistics, cognitive linguistics, sociolinguistics), engineering design of road signs. It is part of a larger scientific work on the subject. By conducting a content analysis of traffic regulations and enforcement manuals, regulations of different countries, it compares different approaches in their amendment and enforcement. Certain examples are selected to summarize the conclusions drawn due to the limited length of the text. The corpus of the present study covers such road signs which have correspondences in the Bulgarian language and which lack verbal text but are present in other languages. The studied material contains road signs from the systems of Bulgaria, Poland, USA, Russia, Japan in order to find the differences in trends. The common ground between all is the international conventions designed to unify the rules and create a common and universal code of communication. Given the cultural and social differences around the world, as well as a number of geographical, ethno-social, economic and other factors, there are also particularities,

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8574
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

which are illustrated by examples, with comparisons being made with Bulgarian regulations. The material under study is considered as an object of semiotic science, since by its nature it is a sign system.

The research procedures applied are comparative analysis of the content of road signs between different languages, content analysis of traffic regulations and manuals, empirical observations: analysis of real road signs and their effects on the behaviour of road users, photographic material, attitude survey of 56 respondents with an online questionnaire in Bulgarian.

Road signs have been known to mankind since ancient times. In the Roman Empire, stone tablets and other signs indicated distances and directions. In the Middle Ages, the materials used to make signs changed [1], and with the advent of industrialization, the increasing use of the automobile and the increase in traffic flow and international traffic in the early 20th century, there was a need to develop uniform rules and norms for all countries of the world in order to regulate traffic and guide drivers.

The first international discussions and forums held to discuss and establish common rules for road traffic in Paris in 1909 and 1926, and in Geneva, led to the adoption of the Geneva Convention of 1931 for the unification and standardisation of traffic signals and the Vienna Convention on Road Signs and Signals of 1968.

II. MATERIALS AND METHODS

Use tables and figures to adjust column length. On the last page adjust the length of columns so that they are equal. Use hyphenation only if it is necessary. Use Spell check. The Roman numerals used to number the sections are optional. If you do use them, do not number Acknowledgment and References, and arrange subheadings with letters.

The general characteristic of the traffic sign system is given by the definition in the Bulgarian legislation. According to Ordinance No. RD-02-21-1 of 23.11.2023 on road signalization with road signs (the Ordinance) "a road sign is a planar representation of a certain shape, dimensions, colours and symbols" [2]. Road signs and other means of signalling shall comply with the requirements of BDS 1517:2006 "Road traffic signs. Dimensions and letters".

If we apply the semiotic approach and the theory of Charles Pearce [3] and Charles Morris about the sign (index, image, icon, symbol), then we could say that road signs fit into the general definition of what a sign is: a material structure that denotes a certain object of reality, "something that stands in for something else different" from our surroundings [4]. For example, the road sign, whose material expression is the A18 'Pedestrian crossing', conveys the idea that crossing is permitted at the precise location. There is a process of communication between road signs and road users in which it is important to analyse how road signs are interpreted by different social groups of people (drivers, pedestrians, cyclists). Road signs are a means of communication between road users and the road infrastructure and are part of the road-human-car system.

Using Ch. Pearce [5] for a "triadic relation" [6] of the elements in the sign system, based on the "sign triangle" [7] of the German mathematician Gottlob Frege [8] and later extended by Ch. Morris [9], we obtain the following configuration for the traffic sign system:

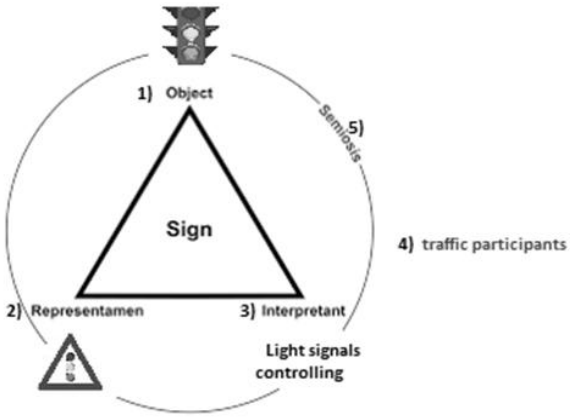


Fig. 1. Semiotic system of traffic signs: 1) Object of reality which the sign replaces; 2) Representamen – a form representing the sign; 3) Interpretant – mental image or thought arising in the mind of the individual interpreter; 4) Interpreter: the person/subject involved in the perception of the message [10] all road users; 5) Semiosis/sign situation: the process of sign functioning [11]

The relation between the signified object of reality and the sign itself by which it is signified is studied by the semiotic division semantics, the relation between the sign and the other signs in the system as combinations is of interest to syntactics, and the relation of signs to interpreters is studied by pragmatics as a division of semiotics. In this sense, it is important to analyse "the behaviour of signs in the actual processes of communication" [12], to what extent an image has a clear relationship with the object of reality, how a particular sign functions in consonance or disharmony with other signs, whether a sign with textual content and an image often contradict or complement each other, and how the sign influences and whether it is recognized by recipients.

In the study of the linguistic elements in the structure of the road sign, an analysis is applied at the lexical, morphological, syntactic and semantic levels. The source of the researched material are examples from Bulgarian reality in comparison with their analogues or lack of such from other languages. The present study is far from exhaustive due to the extensive corpus to be studied, but it is a guideline and a reason for further elaboration of the issues. A linguistic analysis could also contribute to a deeper investigation of the structures, word combinations, and sentence nature of the selected phrases. They function together in a complex system and therefore have features of intertextuality, as they are subordinated to a common form of existence - the regulation of traffic.

III. RESULTS AND DISCUSSION

A. Semiotic analysis: classical theory of sign

Road signs are a complex system that is inherently secondary, artificially created, consisting of verbal text (lexemes) and iconic text (containing information about the specific object. For example, the A18 'Pedestrian crossing' road sign contains a pictogram, but in combination with the triangular shape in red border signals and warns (one of the functions of road signs).



Fig. 2. Road sign A18 Pedestrian crossing [13]

As stated in the Ordinance, Art. 1, "group A danger warning signs shall have the form of an equilateral triangle with a horizontal base and a vertically superimposed apex, a red border stripe, a white background and symbols in black". Pursuant to Article 23, para. 1 of the same Regulation, "danger warning signs shall be placed before the dangerous section at a distance of 50 to 100 m - in populated areas". All this information is contained in the road sign marked A18 'Pedestrian crossing ', which in turn is the name of the sign itself. Non-linguistic signs have no nominative function, they do not name an object, but they themselves bear a name, which in turn gives them a special status and distinguishes them from other signs in semiotic systems.

Initially, in defining road signs in international conventions, the principle of arbitrariness in determining their form and type is fundamental [14]. The visualisation and symbolism of signs could be found in colours as well as shapes and sizes. However, in the choice of colours of traffic lights, the three colours (red, yellow and green) are not directly related to the act of driving. But from a cultural point of view, we have given them special importance so that they take up positions as the main traffic lights.

The colour red symbolizes the situation that is associated with the occurrence of risk, danger, endangerment, symbolizes physical injury and blood, is associated with emergency or urgent care (the colours of ambulances and hospitals); yellow implies focusing attention, showing a reaction or taking some action (stopping or continuing traffic), preparing to perform an action; the colour green is presumably associated with nature, relaxation, tranquillity [15], it means a permissive mode of performing an action - crossing the roadway. The choice of the colours of light signals is motivated, conventional, not arbitrary. It depends on a number of factors that play a role in the reading of the code by the interpreter, which in our case are the road users. The perception and interpretation of the traffic sign, in particular the traffic light, by the interpreter himself depends on his age, education, inner conviction in following the conventionally accepted code (whether to follow the rules imposed in the regulations). Accordingly, in the event of non-compliance, i.e. in the event of non-compliance with the message code, he will incur his own penalty (e.g. a penalty follows if the light turns red).

The semiotic system of road signs contains the following characteristic according to the closed-open paradigm: on the one hand, it is a closed system because it presupposes the functions of signs to signal and indicate specifically and only the traffic on the road. But it is also open in that it is subject to change, to the addition of new signs, to the deletion of others due to obsolescence, etc. This shows its flexibility, its relevance to meet contemporary challenges and its ability to be transformed and updated according to need and public attitudes.

Road signs are: artificial, secondary, linguistic (signs with text) or non-linguistic (images, symbols, indices), audio (some systems in cars, traffic light beep, car horn), tactile (pedestrian and blind signal sensors), visual - according to their mode of perception; conventional, motivated - according to their mode of occurrence. Road signs according to their object relation according to the classification of prof. Mosko Moskov [16] could be defined as: icon (image of the signposted object, but has similarity and resemblance to it); index (the object signposted by the sign has an impact on the sign itself), symbol (expresses in general terms the idea conceptually and motivated according to accepted customs and beliefs), signal (pre-agreed sign).

In order to be recognised and clearly understood, traffic signs should be subject to a certain code known in advance to the recipients. "A code is any system of symbols (signs) which, by prior agreement, is determined to convey information and to transmit it from the transmitter to the receiver" [17]. "A sign is a relation, a relationship between a transmitter and a receiver against the background of reality" [18]. It is necessary that the codes of the sender of the message match the codes of the receiver of the message in order for the message to be successfully read and received [19]. Since road signs exist as a means of communication between people and are a product of human society, they are highly social in nature, but they only fulfil their functions as signs with a certain meaning in a communication environment by a prearranged agreement [20]. Road signs are complex constructions consisting of different types of elements, each of which carries information and aims to convey that information in a clear and explicit manner.

B. Linguistic analysis of the textual content

Linguistic analysis is applied in examining the linguistic constructs, verbal expressions and phrases contained in the structure of road signs, to what extent they help or hinder the correct perception at the sensory level of the image.

The verbal text is in its own way also a sign - a language. The ancient philosopher Augustine united the theory of sign and the theory of language, defining signs as a genus and the linguistic sign as their kind [21]. In the field of linguistics, the linguistic sign became the main object of study for the French scholar Ferdinand de Saussure, "the

founder of modern theoretical linguistics" [22]. He developed the idea of signifier and signified (the word and the object of reality it represents). "As the most complex and universal sign system, natural (verbal) language is a part of semiotics", due to the fact that "as a system of signs, it possesses all the qualities of signification sui generis. Language is the most important, fundamental means of communication in human society" [23] and is present at every level and dimension of human existence. The linguistic signs are the basic building unit in the structure of the language, these are: morpheme, word, phrase, sentence, text [24]. In road signs, word, phrase and sentence are present depending on the length of the phrase. In some countries additional signs or signs containing verbal text are used.

In the absence or presence of a text element to clarify the main image in the traffic sign, confusion or ambiguity of the sign information could occur. Empirical observations show that in the Bulgarian traffic sign system the content of text material is much more limited than images and symbols. From the point of view of designers and traffic engineers this is acceptable, since during traffic, especially when driving a vehicle, any additional activity (looking at a sign or long text) would lead to distraction and distraction, which would cause a risk of an accident. There are also cases of designing and making road signs where the message is not clear and explicit. Example:



Fig. 3. Road sign A42 Reduced visibility ahead [25]

When a blitz survey was conducted on the meaning of a particular road sign with road users in an informal setting during a training session, the responses were "Traffic jam", "Obstruction on the road" and "Poor visibility". Allowing for different interpretations of the sign suggests that its depiction is not sufficiently clear and explicit, hence it does not fulfil its communicative and appealing (regulative) function. If there were a brief explanation of the content of the sign, then the possibility of its misinterpretation would certainly be ruled out.

At the morphological and syntactic level, English-speaking countries have word combinations and syntactic structures that could constitute independent sentences, even verbless ones. Example: "Not a through street", "Left lane ends", "Centre Lane Closed Ahead", "No Traffic Signs", etc., from the group of warning signs (W - warning, from English), unlike in Bulgarian-out of all 43 warning signs from group "A", none contains verbal text.



Fig. 4. Road sign W8-14 Fallen Rocks (US)



Fig. 5. Road sign A17 Risk of collapse or presence of fallen stones

Again in the USA, signs containing the additional verbal expression " No turn on red", in combination with a red dot symbol, and "Yield to pedestrian ahead" are common.

For comparison with the Bulgarian system, again there is a difference in the representation of the character with symbol and text. [26], [27].

Comparing the English and Russian traffic sign systems, V. H. Shashkova distinguishes two tendencies: in English "verb phrases, including predicate binomials, predominate, and in Russian - noun phrases" [28]. What peculiarities of the language is this due to? Predicate constructions contain much more action, the actor is concretized - each participant in the movement, the interpreters, which achieves greater involvement in the process of moving and driving and personal involvement by personalizing the actor.

In the use of syntactic structures, it is also necessary to refine the length of the phrase so as not to distract drivers.

At the semantic level, the meaning of the signified is conveyed through an iconic image, including a pictogram or a visually recreated image of the object from reality. In semasiological terms, this is reminiscent of ancient alphabets, some of the first known in history, which consisted of a series of symbols and representations of animals, plants, people, geographical objects, etc., for the purpose of communication and information delivery, a fundamental function of language as a sign system. In this sense, given the sequence of symbols and images in the road sign system, we could conclude that we are dealing with a language of communication whose code is the specific images in road signs. Unlike in English, where only images are present to convey information, in English the verbal phrase purposely carries an additional clarification to the main message and overlaps semantically with the image.



Fig. 6. (a) and (b) Road sign A13 Artificial bumps on the traffic lane [29], [30]



Fig. 7. (a) and (b) Road sign R4-7b Keep Right Diagonal Arrow Sign (US) [31]



Fig. 8. (a) and (b) Road sign Distance over which road humps extend (UK) [32]

In English-speaking countries, the tendency is to supplement the image with a textual explanation to facilitate and guide road users. The sign is actualized, it is in the process of use, its material aspect is sensually perceived by the addressee. It can be seen that both cases of sign use in Bulgarian reality apply only the graphic representation. At the same time, the semantic sign is limited because its content lacks the information about the section to which the sign applies, which is additionally necessary to assimilate as a code and accessible knowledge (in Art. 23, para. 1 of the Ordinance - for settlements outside the boundaries of settlements, motorways, expressways and urban expressways). The sign thus remains simplified to its graphic representation and is likely to mislead or confuse road users, especially foreign visitors.

The vocabulary used as content in the overall image of the sign is logically related to the sphere of transport: road, traffic, directions - left right, forward, street, exit, zone, pedestrian, attention, danger, limit, speed. The lexemes used could be categorised according to their function - to indicate an object of reality (a type of obstacle or impediment), direction of traffic or restrictions, elements of the road infrastructure and environment, weather phenomena, etc.



Fig. 9. Road sign R2-1 Speed Limit (US) [33]

The speed limit is clearly and unambiguously imposed by the specific phrase, whereas symbols could not give the same information definitively without prior knowledge. Such texts clearly state the rules, helping primarily to comply with local regulations. For comparison with Bulgarian:



Fig. 10. Road sign Ж19 Recommended speed (Bulgaria) [34]

Only the blue colour indicates the recommended but not mandatory character of the sign, which should be known in advance in relation to the Bulgarian legislation.

It is interesting to consider another application of the same sign 'Ж19'. A mathematical model is used to design the traffic light regime [35] so that the so-called "green wave" is respected, but in addition to the green signal, the 'Ж19' recommended speed sign should also be respected, which in this case is 50 km/h. Under these two conditions the interpreter (driver) could use the green wave' for faster and optimised movement. The two signs (light signal and speed advisory sign) are independent signs, but in the specific communication environment they form a heterogeneous - "super-sign", "formed by pre-existing simpler signs" [36] and their compliance as a whole result in a "green wave". In this sense, the "green" light signal is mandatory and conventional with respect to its appearance, but also function (always on green is allowed to pass). And the 'Ж19' sign is conventional in its introduction but arbitrary (arbitrary) in its function (it is up to the driver to decide whether to obey it as it is advisory).



Fig. 11. Road sign 1012-34 Grüne Welle bei km/h (Germany)

At the same time, the German legislation [37] explicitly states in a verbal expression under which conditions the "green wave" is observed. The verbal combination of the noun "Welle" and the adjective "grüne" is a noun phrase, a verbless clause followed by a circumstantial explanation of modality. As a syntactic construction it fulfils nominative, appellative, cognitive and representative functions - it names the idea of a green wave, indicates and regulates the behaviour of drivers, provides information about the correct functioning and application of the signified and as an expression presents the idea, the concept of observing certain conditions in order to "green wave" the road.

Differences in the interpretation of road signs could be observed in different countries around the world, which could lead to difficulties in sign recognition:

• according to the level of knowledge and/or proficiency in the language:



Fig. 12. Designation that indicates that vehicles and streetcars must slow down



Fig. 13. Closed to pedestrians and small and remote-controllable mobiles (Japan) [38]



Fig. 14. Road sign D-52 strefa ruchu – „Traffic zone“



Fig. 15. Road sign T-13 plate indicating a road stretch that has ruts as deformations of road surface (Poland) [39]

• according to cultural and linguistic specificities and differences



Fig. 16. (a) and (b) Road sign STOP in Japan and standard international sign [40], [41]



Fig. 17. (a) and (b) Road sign Snow chains sign in Bulgaria and Russian Federation [42]

In the Ordinance on Traffic Signals and Traffic Equipment on the Roads in Slovenia [43], Article 4 regulates the use of language in traffic signals - the inscriptions on traffic signals are in Slovenian throughout the country. In bilingual areas, in addition to signs in Slovenian, there are also signs in another language, so that the sign is first in Slovenian and then in the foreign language. Inscriptions on vertical road signs on motorways, expressways and main roads may be in languages other than Slovenian. Inscriptions on tourist signs may also be in foreign languages.

The particular cases in different countries contribute to the more extensive application of verbal structures in road sign construction. From the point of view of pragmatics, there is a wide application of verbal elements according to the peculiarities of the linguistic, social and cultural anthropological environment of communicators.

Verbal signs could facilitate communication and further enrich the structure of road images, taking into account the peculiarities of the particular linguistic environment as well as specifics in the cultural-social differentiation of societies. The tendency to use more verbal text in some countries, as opposed to the absence of it in others, could suggest the level of perception and correct application of the rules regulated by road signs.

By combining different types of elements - graphic, iconic, verbal - it enriches the information field and creates clarity and greater explicitness in conveying the message and complements the recognition of the images in them. However, it should also be limited so as not to cause distraction for drivers, who should receive and process data and information in the shortest possible time without disturbing their concentration and creating conditions for risk. There should be precise guidelines on how much verbal text a sign can contain or the better and more appropriate option is a main sign with an image and an additional one with explanatory text. It is also important in what language the text is written. In a multi-language environment, one could select the most recognizable one so that the given code can be read by a larger number of interpreters. In countries where there is a single spoken language, it will only be familiar to locals. In this case, for the different language communities, the graphic material is more appropriate, the image carries information. But it needs to be designed and presented in a clear form, colour and composition.

"The question of the sign and its nature is common to many sciences. Any attempt to solve it from the point of view of only one science is at least one-sided, if not risky" [44]. In any case, the issue deserves attention and deeper analysis, especially in the Bulgarian reality, where the statistics on traffic accidents and road casualties and traumatism are alarming. We as a society are obliged to analyse thoroughly and apply ever wider ranges in the approach of researching the problem of road safety in order to make the elements of it work better.

IV. CONCLUSIONS

After a review of the content of traffic rules and enforcement manuals in languages such as Bulgarian, Romanian, German, it is noticeable that there is a tendency for a much smaller number of road signs to contain verbal text. At the same time, in the English-speaking world and countries such as the USA, Australia, UK, signs containing verbal text or elements with text account for more than half. This could be due to cultural anthropological, social, economic, ethno-linguistic or psychological factors. We are in an era of a rapidly evolving society, both technologically and evolutionarily. All of this calls for global uniform international legal norms to standardize and unify perceptions as far as this is applicable.

Given the different levels of awareness and experience, it is necessary to pay attention to the elements that make up the road sign in its material entirety - in addition to shape and colours, consideration should also be given to whether the image is sufficiently clear and gives clear and unambiguous information. There is a need to reinforce the concept of conformity to frame the applicability of signs and their uniformity. There is a need to study more thoroughly and carefully the differences in the perceptions of different social groups according to their competences, education, age, experience through surveys and questionnaires. Evaluating the effectiveness of signs in different social and cultural contexts could lead to new opportunities for improving the system and improving the design of the signs themselves.

A wider range of methods and approaches could be used, not only in road construction, design, but also in psychology and other seemingly distant scientific fields, such as cognitive linguistics, semiotics. Opportunities are also opening up for conducting technological research with sensors on how drivers react on a physical level when perceiving elements of road infrastructure. In this way, their reaction in the presence of more text than images, only

text or only images could be detected. This would contribute to a better design of road signs to increase their quality and improve their functions.

Nowadays, when traffic is becoming more and more intense, our quest to ensure better road safety calls for different perspectives, syncretic methods that involve an interdisciplinary approach, in order to get out of the field of narrow specialists and provide a broader range of scientific knowledge that can enrich and improve the current achievements.

In conclusion, a recommendation should be made regarding our country's efforts to build consensus in enforcing legal norms with a view to implementing the Road Traffic Act and implementing the signs and their auxiliary symbols.

ACKNOWLEDGMENTS

The author would like to thank to the organizers of the 16th International Scientific Practical Conference “Environment. Technology. Resources” for the opportunity to publish the results of the research. He present work is part of a wider scientific research for PhD thesis defence.

REFERENCES

[1] "Istoriyata na patnite znatsi". [Online]. Available: https://automedia.investor.bg/a/2-novini/40428-istoriyata-na-patnite-znatsi [Accessed October 10, 2024].

[2] Naredba № RD-02-21-1 ot 23.11.2023 g. za signalizatsia na patishtata s patni znatsi, Ministerstvo na regionalnoto razvitie i blagoustroystvoto.[Online].Available: https://www.mrrb.bg/bg/naredba-rd-02-21-1-ot-23-11-2023-g-za-signalizaciya-na-putistata-s-putni-znaci/. [Accessed January 31, 2025].

[3] Ch. Peirce, " Izbrani sachinenia ". Sofia : Iztok-Zapad, 2022.

[4] Jean-Marie Klinkenberg, "Kurs po obshta semiotika". Sofia : Sonm, 2019, p. 29.

[5] D. Dobrev, E. Dobreva, "Teoriyata za znaka v lingvistikata i literaturnata nauka". Sofia : Nauka i izkustvo, 1988, p. 63-64.

[6] D. Dobrev, E. Dobreva, "Spravochnik na semiotichnite termini". Shumen: Glauks, 1992, p. 150.

[7] T. Berov, "Rechnik po semiotika". Varna : Knigoizdatelstvo Zograf, 2008, p. 155-205, p. 508.

[8] Y. Stepanov, "Semiotika". Sofia : Nar. prosveta, 1979, p.79-85.

[9] R. Milenkova – Kien, "Uvod v semiotikata“. Sofia: Sanra, 1999, p. 19.

[10] T. Berov, "Rechnik po semiotika". Varna : Knigoizdatelstvo Zograf, 2008, p. 272.

[11] St. Dimitrova, "Lingvistichna pragmatika". Sofia: Veles, 2009, p.5.

[12] St. Dimitrova, "Lingvistichna pragmatika". Sofia: Veles, 2009, p.5.

[13] Naredba № RD-02-21-1 ot 23.11.2023 g. za signalizatsia na patishtata s patni znatsi, Ministerstvo na regionalnoto razvitie i blagoustroystvoto. [Online]. Available: https://www.mrrb.bg/bg/naredba-rd-02-21-1-ot-23-11-2023-g-za-signalizaciya-na-putistata-s-putni-znaci/. [Accessed January 31, 2025].

[14] M.Moskov, "Ezik i ezikoznanie : Ch. 1". Sofia: Ciela, 2000, p. 80.

[15] M. Almaleh, "Tsvyat i slovo". Sofia: Prof.Marin Drinov, 2001.

[16] М.Москов, "Език и езикознание : Ч. 1". София: Ciela, 2000, стр. 86-88.

[17] R. Milenkova – Kien, "Uvod v semiotikata“. Sofia: Sanra, 1999, p. 71.

[18] Iv. Lekov, "Ezikat kato znakova sistema". "Ezik i literatura: spisanie za obshtodostapno razglezhdane na ezika, literaturata i narodnia bit". Sofia : D-vo na na filolozite-slavisti v Bulgaria, XVII – 1962, 2, p. 51-54.

[19] G. Dacheva, "Semiostilistika". Sofia : IK Semarsh, 2001.

[20] Zh. Molhova, "Za znakovia harakter na ezika". "Ezik i literatura: spisanie za obshtodostapno razglezhdane na ezika, literaturata i narodnia bit". Sofia : D-vo na na filolozite-slavisti v Bulgaria, XVII – 1962, 1, p. 68.

[21] Em. Pavlov, "Semiotika i kultura". Blagoevgrad : Univ. izd. Neofit Rilski, 2005, p.43.

[22] Zh. Boyadzhiev, "Portreti na imeniti ezikovedi : Iz istoriyata na svetovnata lingvistika". Sofia : Karina M, 1997, p. 57.

[23] Zh. Molhova, "Za znakovia harakter na ezika". "Ezik i literatura: spisanie za obshtodostapno razglezhdane na ezika, literaturata i narodnia bit". Sofia : D-vo na na filolozite-slavisti v Bulgaria, XVII – 1962, 1, p. 69.

[24] M.Moskov, "Ezik i ezikoznanie : Ch. 1". Sofia: Ciela, 2000, p. 108.

[25] Naredba № RD-02-21-1 ot 23.11.2023 g. za signalizatsia na patishtata s patni znatsi, Ministerstvo na regionalnoto razvitie i blagoustroystvoto. [Online]. Available: https://www.mrrb.bg/bg/naredba-rd-02-21-1-ot-23-11-2023-g-za-signalizaciya-na-putistata-s-putni-znaci/. [Accessed January 31, 2025].

[26] Manuel on Uniform Traffic Control Device. [Online]. Available: https://mutcd.fhwa.dot.gov/kno_11th_Edition.htm. [Accessed February 6, 2025].

[27] Naredba № RD-02-21-1 ot 23.11.2023 g. za signalizatsia na patishtata s patni znatsi, Ministerstvo na regionalnoto razvitie i blagoustroystvoto. [Online]. Available: https://www.mrrb.bg/bg/naredba-rd-02-21-1-ot-23-11-2023-g-za-signalizaciya-na-putistata-s-putni-znaci/. [Accessed January 31, 2025].

[28] В. Н. Шашкова, "Знаки дорожного движения как знаковая система особого рода". Журнал "Современный ученый“, eISSN: 2541-8459, Номер: 3, 2021, стр.252-256. [Online]. Available: https://elibrary.ru/item.asp?id=45755898. [Accessed December 12, 2024].

[29] Naredba № RD-02-21-1 ot 23.11.2023 g. za signalizatsia na patishtata s patni znatsi, Ministerstvo na regionalnoto razvitie i blagoustroystvoto. [Online]. Available: https://www.mrrb.bg/bg/naredba-rd-02-21-1-ot-23-11-2023-g-za-signalizaciya-na-putistata-s-putni-znaci/. [Accessed January 31, 2025].

[30] "Bez saglasuvane Obshtina Tran montirala gumeni izkustveni neravnosti v selo Glavanovtsi", Zapadno.com. [Online]. Available: https://zapadno.com/2021/08/26/%D0%B1%D0%B5%D0%B7-%D1%81%D1%8A%D0%B3%D0%BB%D0%B0%D1%81%D1%83%D0%B2%D0%B0%D0%BD%D0%B5-%D0%BE%D0%B1%D1%89%D0%B8%D0%BD%D0%B0-%D1%82%D1%80%D1%8A%D0%BD-%D0%BC%D0%BE%D0%BD%D1%82%D0%B8%D1%80%D0%B0%D0%BB/. [Accessed January 27, 2025].

[31] Manuel on Uniform Traffic Control Device. [Online]. Available: https://mutcd.fhwa.dot.gov/kno_11th_Edition.htm. [Accessed February 6, 2025].

[32] Traffic signs , GOV.UK. [Online]. Available: https://www.gov.uk/guidance/the-highway-code/traffic-signs. [Accessed February 6, 2025].

[33] Manuel on Uniform Traffic Control Device. [Online]. Available: https://mutcd.fhwa.dot.gov/kno_11th_Edition.htm. [Accessed February 6, 2025].

[34] Naredba № RD-02-21-1 ot 23.11.2023 g. za signalizatsia na patishtata s patni znatsi, Ministerstvo na regionalnoto razvitie i blagoustroystvoto. [Online]. Available:

https://www.mrrb.bg/bg/naredba-rd-02-21-1-ot-23-11-2023-g-za-signalizaciya-na-putistata-s-putni-znaci/. [Accessed January 31, 2025].

[35] M. Diallo, "Razrabotvane na determiniran matematicheski model za avtomobilno dvizhenie prez krastovishte, regulirano sas svetofar". Godishnik na Tehnicheskia Universitet – Sofia, ISSN 1311-0829, 48, 2, 1995, стр. 385-390.

[36] D. Dobrev, E. Dobreva, "Spravochnik na semiotichnite termini". Shumen: Glauks, 1992, p. 144.

[37] Verkehrszeichen online. [Online]. Available: https://www.verkehrszeichen-online.org/verkehrsschilder_in_deutschland_stvo.pdf. [Accessed February 5, 2025].

[38] Traffic Bureau. National Police Agency, Japan. [Online]. Available: https://www.npa.go.jp/english/bureau/traffic/index.html. [Accessed February 1, 2025].

[39] Znaki i sygnały drogowe. Ministerstwo Infrastruktury, Poland. [Online]. Available: https://www.gov.pl/web/infrastruktura/znaki-i-sygnaly-drogowe. [Accessed February 1, 2025].

[40] Traffic Bureau. National Police Agency, Japan. [Online]. Available: https://www.npa.go.jp/english/bureau/traffic/index.html. [Accessed February 1, 2025].

[41] Naredba № RD-02-21-1 ot 23.11.2023 g. za signalizatsia na patishtata s patni znatsi, Ministerstvo na regionalnoto razvitie i blagoustroystvoto. [Online]. Available: https://www.mrrb.bg/bg/naredba-rd-02-21-1-ot-23-11-2023-g-za-signalizaciya-na-putistata-s-putni-znaci/. [Accessed January 31, 2025].

[42] Правила дорожного движения РФ 2024, Приложение 1. Дорожные знаки. [Online]. Available: https://stpddrf.ru/prilozheniye-1. [Accessed February 3, 2025].

[43] Pravilnik o prometni signalizaciji in prometni opremi na cestah, Pravno-informacijski sistem Republike Slovenije. [Online]. Available: https://pisrs.si/pregledPredpisa?id=PRAV11505. [Accessed February 1, 2025].

[44] Iv. Lekov, "Ezikat kato znakova sistema". "Ezik i literatura : spisanie za obshtodostapno razglezhdane na ezika, literaturata i narodnia bit". Sofia : D-vo na na filolozite-slavisti v Bulgaria, XVII – 1962, 2, p. 51.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 345-351

Application of a Large Language Model for Air Pollution Analysis by Using a RAG System

Svetlomir Stankov
Faculty of Mathematics and Informatics
Sofia University "St. Kliment Ohridski"
Sofia, Bulgaria
sv_stankov@abv.bg

Desislava Velinova
Development of C4I Systems
Bulgarian Defence Institute "Prof. Tsvetan Lazarov"
Sofia, Bulgaria
velinova.desislava@gmail.com

***Abstract*—The paper examines the application of an LLM (Large Language Model) for analysing text information about air pollution using a RAG (Retrieval-Augmented Generation) system. It describes what RAG systems are and how they help increase the credibility of the text generated by LLM models (reducing their hallucinations) using information retrieval from reliable sources. An approach for the development of a RAG system suitable for answering queries on imported text documents by the user is presented. The realisation of this approach is the development of a RAG chatbot using the Python language, answering queries (questions) towards a database of uploaded text documents by the user. Some results from experiments on a selected database of scientific publications related to air pollution are presented.**

***Keywords*—Air pollution, Artificial Intelligence, LLM, RAG System**

I. Introduction

The area of Artificial Intelligence (AI) was developed enormously in recent years, and one of its most significant novelties was the introduction of Large Language Models (LLMs), which revolutionised text generation models with the ability to process and generate natural human-like texts. These models were made accessible to the general public both on the web and locally, on personal computers, and they gained massive popularity. They are being used for a variety of applications, such as chatbots and assistants.

Large Language Models (LLMs) are advanced machine learning algorithms that are designed to understand and generate human-like text (Fig. 1).

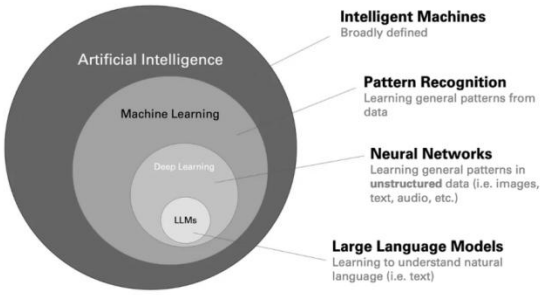


Fig. 1. Essence of Artificial Intelligence in layers [1].

These models are trained on massive datasets of text, which enables them to learn patterns, grammar, and vocabulary. As a result, LLMs can perform a wide range of tasks, including language translation, text summarization, question answering, and even creative writing. Some of the most well-known LLMs include GPT, BERT, Gemini, T5, DeepSeek, which have been developed by organizations such as OpenAI, Google, Microsoft, Hangzhou AI.

Their ability to understand and generate human-like text has made them valuable tools in fields such as customer service, content creation, and language translation. For instance, LLMs are used to power chatbots that can engage in natural conversations with customers, provide information, and even assist with problem-solving.

One of the distinctive and key strengths of LLMs is their ability to respond to unpredictable queries. Unlike other computer programs and models, which perform specific commands from a finite set of them or anticipate specific user inputs, LLMs can operate with natural human language and respond to unstructured commands, which revolutionized the artificial intelligence field [2].

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8603
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the CreativeCommonsAttribution 4.0 InternationalLicense.

A. The problem with LLMs – hallucinations

While LLMs are great at generating good-looking, human-like text, they can sometimes suffer from a phenomenon known as "hallucinations". Hallucinations occur when an LLM generates incorrect or nonsensical information that is not based on any factual evidence. This undermines LLMs' reliability and causes doubts about the accuracy of the information they provide. Mitigating these hallucinations is therefore a critical issue to be addressed both by the developers of the models and the creators of programs that use these LLMs.

There are different types of hallucinations, which include factual inaccuracies, nonsensical responses and contradictions. The first type (also known as fact-conflicting hallucinations) represents LLMs' tendency to sometimes generate incorrect or misleading information that is not based on any real facts. For instance, a user may ask for information about a non-existent person and the LLM may generate a story about him that, although well written, does not correspond to reality. The nonsensical responses (input-conflicting hallucinations) refer to the fact that LLMs at times respond with irrelevant information to a query, mainly due to not understanding the context correctly. There are also cases when LLMs may generate contradicting statements in a prolonged conversation or even in the same response in some instances (context-conflicting hallucinations). Studies have found a notable presence of self-contradictory responses in LLMs. For example, the contradiction rate of ChatGPT has been estimated to be 14.3% [4], [5], [6].

Hallucinations can happen for several reasons, including the model's training data containing inaccuracies and false information, the model's inability to fully understand the context of a given task, or the model's tendency to overgeneralize or make assumptions. The massive datasets used by companies that develop LLMs to train the models contribute to the problem with hallucinations because they consist of a variety of different resources on many different topics, and the verification of the factuality and unbiasedness of the information is challenging.

All in all, it could be said that LLMs are designed and trained in a way to identify patterns in texts and predict well the next word in a sequence, and the emphasis is on generating good-looking and plausible-sounding text. This makes the LLMs so good at generating human-like text but hinders the factuality and truthfulness of the information they provide, especially in cases where they lack sufficient information about a topic. More information can be found in [6].

B. Retrieval-Augmented Generation (RAG)

One of the most comprehensive solutions to improve the problem with hallucinations in LLMs for specific use cases and applications is the Retrieval-Augmented Generation (RAG) framework. There has been a lot of research on this methodology in recent years, and it has proved to be very effective at mitigating hallucinations in generative models by combining information retrieval techniques with the creativity of LLMs.

The main idea of RAG is to use pre-trained models to retrieve relevant documents from large databases and then use a generative model (LLM) to create answers based on the extracted information.

This approach is particularly useful in cases where the generative model does not have access to specific data, but can obtain it by retrieving it from suitable sources. RAG allows models to use information from various sources, thereby improving the accuracy and quality of the generated answers.

RAG consists of several key stages:

- Preprocessing and indexing: At the beginning, the documents in the database are preprocessed, and longer documents are broken into several smaller chunks so that it helps the retrieval process but also so that the relevant chunks fit the context size of the chosen LLM. The document chunks are then embedded by a chosen embedding model (it turns the chunk into a vector of high dimensions and is trained to capture the semantic meaning of a text), which makes them eligible for semantic search (they are compared to the embedding of the user query).
- Retrieval: A pre-trained embedding model (may be combined with a keyword-based algorithm) is used to retrieve relevant documents or passages from a database that are related to the user's question. In order to achieve this, the user query must be processed and embedded and then added to the search models to find the most relevant chunks of text (which are also preprocessed and embedded in the initial stage). This is a crucial stage that has a great impact on the performance of a RAG system.
- Augmentation: The top-ranked chunks (passages of text) retrieved by the retrieval stage are added to the prompt. The prompt at the end consists of instructions to the LLM (to read and gather information from the context when answering the query), the relevant context passages, and the user query for which an answer is expected.
- Generation: A generative model (LLM) is used to create an answer to the user's question on the basis of the context provided [7], [8], [10].

RAG is particularly effective in the context of tasks such as question answering, document summarization, and content creation based on information from multiple sources. This approach allows models to be more informative and accurate while still retaining their ability to generate creative and contextually relevant answers.

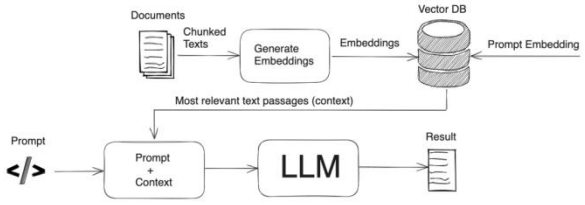


Fig. 2.Basic RAG pipeline [9]

II. MATERIAL AND METHODS

A. Approach for the realisation of RAG in a system which answers user queries in English and Bulgarian

As RAG systems are still in the beginning of their development and such systems with user interfaces for general use are not known to exist for Bulgarian language, an approach for developing such is proposed. Existing such systems (like the NVIDIA RAG Chatbot) mainly use LLMs that are intended to work in English language and do not perform efficiently enough for the Bulgarian language, as the information is translated between the languages, and this hinders the accuracy of the answers.

For this reason, the proposed approach is based on the utilization of the recently developed and introduced LLM for Bulgarian language, BgGPT-Gemma-2, developed by INSAIT [11], [12], which was built on top of Google's Gemma 2 family of models with various additional improvements, including continuous pre-training on around 100 billion tokens in Bulgarian and a novel instruction-fine tuning.

The essence of the proposed approach here is to provide the user with the ability to upload his own documents and use RAG on them so that valuable knowledge and insights in the documents texts are gained by asking queries to a chatbot while the hallucinations in the LLM are reduced.

The proposed approach utilizes several techniques at different parts of the system workflow.

The first part of the RAG process is the preprocessing of each document and splitting the longer documents into chunks. For this part of the process, it is suggested to use sentence-based chunking for general text documents and use cases, as it captures the context of the full sentences and not just a part of them because it represents a natural and logical division of the text. It is proposed the chunking size to be 20 sentences with an overlap of 2 sentences between the chunks to maintain the connection between sequential chunks. Smaller documents (less than the chosen chunking size) should not be split. The formed chunks are then embedded into high-dimensional vectors used for performing semantic search in the retrieval process. It is proposed to use the embedding model BGE-M3 by BAAI, as it is multilingual and is able to process inputs of different granularities – from short sentences to long documents up to 8192 tokens [17]. That functionality is essential for RAG systems, as user queries are generally short but have to be compared to large documents to find the most relevant ones. The embeddings are proposed to be stored in a vector database like FAISS to improve the semantic search speed, which is essential for systems with large document databases. In order to improve the retrieval of relevant chunks, the performing of a keyword search along with the semantic (vector) search is proposed. For the keyword search, the BM25 algorithm is proposed, which is implemented in the bm25s package in Python as well as in other packages like rank-bm25. For the keyword search to be more efficient, a lemmatisation of the chunks is needed. The package simplemma in Python can be used, as it also offers lemmatisation in multiple languages and also has a language detector useful for RAG systems that are intended to work with multiple languages.

In order to combine the results from the keyword and the semantic (vector) search, a ranking algorithm is needed. The reciprocal rank fusion (RRF) algorithm is proposed to be used, as it is a simple and fast algorithm that shows remarkable results, better than even its more complex competitors [18].

RAG Fusion uses the LLM to generate similar queries to the original one by making small modifications so that a wider view of the topic is obtained for improving the retrieval of relevant chunks to the user query. These similar queries, along with the original one, are then given to the retrieval process to find relevant contexts for each of the generated queries (plus the original user query). The results are combined by the RRF algorithm.

The HyDE retrieval method is a zero-shot learning technique; the LLM is used to provide an answer without relevant context, as when RAG is not used. This answer (a hypothetical document) is then embedded by the embedding model, and vector search as well as keyword search is executed, finding relevant chunks to the generated answer. Even if some details provided in the generated answer are inaccurate, the method tends to capture relevant patterns which improve the retrieval process [15]. Moreover, the generated answer has a lot more words and sentences than a single-line user query, for example, and can capture deeper semantic

relationships between the words, which helps the search process, as the chunks also contain a lot of information and are longer in length.

The generated subqueries method uses the LLM to detect whether the query is a complex query and if the user has turned on the generated sub-queries option, another function breaks the user query into several self-sufficient simple queries. These are used to improve the retrieval process, as sometimes the query may ask for information about different topics which may hinder the retrieval process. Moreover, it improves the generation of the answers for complex queries, as the sub-queries are numbered and given to the LLM, which ensures that every distinct question in the query is answered and is not ignored. The retrieved relevant text chunks for each subquery are combined with the RRF algorithm to get the final top relevant chunks.

The most important aspect of the RAG systems is the retrieval process. It needs to find relevant context to a query from the database of text documents. For this purpose, along with the keyword search and the semantic search, the use of several different advanced techniques that utilize the LLM is proposed – RAG Fusion, HyDE approach, generated sub-queries, LLM filtering of the retrieved contexts and modification of the original user query based on the chat conversation if the query is not classified as a standalone one (it is connected with a previous interaction with the chatbot).

In order to improve the retrieval process for specific documents and use cases, one or more of the abovementioned methods may be used. It is suggested to use both HyDE and RAG Fusion methods, as they generally bring the best retrieval results when used together. When used together, the results from these methods are ranked by the RRF algorithm to obtain the final relevant context chunks, which are then given to the LLM (or filtered by the LLM before that if this option is chosen). Furthermore, a reranking model could be used to rerank the top 20 context chunks by the RRF algorithm ranking, based on their relevancy to the user query. The top reranked context chunks are then provided to the LLM (or additionally filtered by the LLM before that if this option is chosen).

For the last part of the RAG pipeline, the generation phase where an LLM is used to generate the answer, the most important point is the prompt engineering or the instructions given to the LLM in the prompt. Here it is suggested to set a clear instruction to the LLM that it needs to use factual information from the provided context by the retrieval process to answer the query and to not be reluctant to say that it cannot answer the question if it does not have enough information on the matter.

III. Results and discussion

A. Application of the developed RAG system in ecology - for extracting information from air pollution documents.

Based on the approach proposed above, a RAG system was developed, using the Python programming language, with the application of the BgGPT-Gemma-2 LLM. The quantized GGUF models are used with llama.cpp for Python so that the LLM can be loaded on the GPU (using the CUDA toolkit of NVIDIA) of normal personal computers with limited available VRAM. The system was tested on the version "BgGPT-Gemma-2-9B-IT-v1.0.Q6_K.gguf" but has the ability to download other quantized versions of the LLM based on the VRAM available on the user's personal computer. The generative model can work with both English and Bulgarian languages.

The developed RAG system works for the Bulgarian and English languages and also has a user interface. The system gives users the opportunity to get more reliable information from the LLM and the ability to see the resources used by the LLM for answering their query.

An important feature of the developed system is that it gives users the ability to import their own text documents and files in various formats (PDF, TXT, DOC, DOCX and JSON) and ask queries about them. The system is designed to be used locally, on a personal computer, so the files will not be uploaded on any servers. The feature provides the user with the opportunity to take advantage of the LLM's strengths in text generation on his own text files in a more reliable way.

In the case when the user has not imported any files, the system has a default database of thousands of Bulgarian articles from Bulgarian Wikipedia [13] and focus news website [14]. They are used in order to help mitigate the LLM hallucinations and give relevant resources accompanying the answer to the query. It is an optional database that can be used or not based on the user preference.

B. Testing of the developed RAG system for air pollution documents, experimentations and results

The developed RAG system can be used in various areas, as it is made to work with any text documents. The system was tested for extracting information from around 40 research papers on the topic of air pollution in English. They were imported into the system as a database for the RAG. The documents are PDF files containing various research papers in the field of air pollution. The files were processed normally following the RAG pipeline described in this paper. In order to assess the presented system, around 70 queries were asked on topics that are mainly discussed in the chosen articles.

In order to evaluate the system, the REMi evaluation model was chosen, classified by the developers as the first open-source RAG evaluation model [3]. The model is based on the RAG Triad evaluation approach, which is based on three metrics to evaluate RAG systems:

- answer relevance: assesses how relevant the generated answer is to the query
- context relevance: assesses the relevance of the retrieved context to the query
- groundedness: assesses the degree to which the generated answer is grounded in the provided retrieved context (how much the answer supports the information in the context)

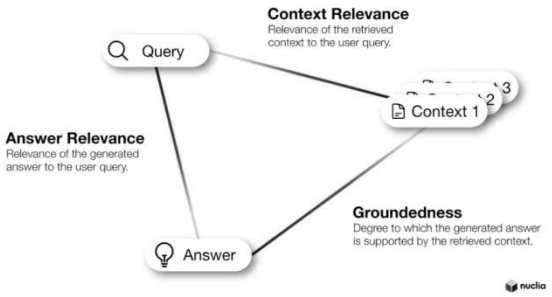


Fig. 3. Diagram illustrating the RAG Triad evaluation metrics [16].

The model REMi used to evaluate the RAG system is a relatively small (around 15 GB) and efficient LLM adapted on top of Mistral AI's Mistral 7B v0.3 Instruct. It was fine-tuned specifically for evaluation with the RAG Triad metrics. The REMi model gives scores from 0 to 5 on each of the metrics while also providing an additional reasoning for the answer relevance score. It is provided by the nuclia-eval package in Python. All the model needs to do the evaluation is the query, the retrieved relevant contexts and the generated answer from the system. The model provides an opportunity to assess how the RAG system works without having ground truths and golden datasets and makes it easier to detect early potential problems.

The model gives one score for the answer relevance, while for the context relevance and the groundedness, it gives scores for each retrieved context for the query in the form of a list. For the metrics to be observed with a single value each, an aggregation is needed along the context pieces for a single query and then across the multiple queries. The proposed aggregation by the developers of the evaluation model is to get the maximum score for each of the contexts retrieved for the query and then average along all queries [3]. This method is also used to evaluate the implemented RAG system.

As was already mentioned, around 70 queries were asked to the RAG system in order to evaluate its performance on the dataset of around 40 air pollution research papers. In this section we will take a look at some of these experiments and the obtained results.

C. Analysis of the results

As a whole, the results obtained from the evaluation model are pretty positive – from around 70 queries asked, one answer was given a 0 score for answer relevance to the query, 2 answers were given a 3 score, 23 were given a 4 score and the rest 43 answers were given the maximum relevancy score. The average score for answer relevance across all queries is, therefore, 4.5 or 90%.

For the context relevance metric, the average score across the queries for the top 3 chunks retrieved is 3.95 or 79%, which is very high considering this result is obtained for all 3 top chunks used for these experiments. The aggregation proposed by the creators of the evaluation model REMi [3] uses just the maximum relevance score of the retrieved contexts for a query, and then an average across all queries is performed. Using this approach, the average context relevance score across the queries is 4.81 or 96%, which shows that for almost every query asked in the experimentation process, a chunk with the highest context relevance score is retrieved. This is a very positive assessment of the retrieval process in the RAG system.

Speaking of which, the most effective approach is found to be using both HyDE and RAG Fusion methods, which may hinder slightly the speed of the answer generation but improves the retrieval process and the overall results. When both HyDE and RAG Fusion are used, the average results using the maximum score for a query regarding the context relevance and groundedness scores are the following: answer relevance of 4.6 (92%), context relevance of 4.97 (99%) and groundedness of 4.4 (88%). It can be seen that combining both techniques improve the scores and is better than the general results at all 3 metrics. If we calculate the average score across all 3 top retrieved chunks for a query and just the one with the best score, the context relevance average is 4.26 (85%) and the groundedness is 2.4 (48%). This means that in most cases all 3 of the retrieved chunks have very high relevance scores to the query, confirming the theory that using both HyDE and RAG Fusion improves the overall RAG process.

Otherwise, the groundedness general average score is 3.89 (78%). If we take a look across all scores for the top 3 chunks retrieved, the score is 2.08 (42%), which is not a problem because it is across all top 3 chunks retrieved for a query, and it is hard and impractical in many cases for the LLM to use all 3 retrieved chunks for the generation of the answer (provided all 3 are actually relevant to the query and can be used for the answer). This shows that the system tends to use mainly 1 and sometimes 2 of the retrieved chunks to answer a query. These results also show that a better retrieval process (when using both HyDE and RAG Fusion) also improves the groundedness of the answers in the contexts.

These results are a promising assessment of the developed RAG system based on the proposed approach in the paper, which shows that the pipeline implemented in the system can be very effective in generating factual answers when a dataset of quality documents is provided. These results, however, are based very much on the queries asked, as they have to be relevant to the documents provided; otherwise, the scores on the metrics will drop. Therefore, providing relevant documents to the topic of interest is essential for the user to improve his experience with such RAG systems. The dataset used for these

experimentations was with documents in English, but the system can perform equally well also with Bulgarian documents, which was the initial and primary objective of this system. This was confirmed by the experiments that were conducted with Bulgarian research papers on the topic of air pollution, as the results from them were very similar to the results obtained from the experiments with the English research papers.

Further experiments were conducted to compare the different techniques for the context retrieval process using repetition of the asked queries as well as new queries for each technique (around 45 queries were asked for each technique) in order to obtain more factual results. Bear in mind, however, that although there were a number of cases where the same query was asked for all possible combinations of techniques, there were also unique queries for some of the techniques. It was not the same set of queries asked for all combinations of the used techniques.

The obtained results from these experiments confirmed once again that using both RAG Fusion and HyDE provides the best overall results. The results from combining the two techniques showed around 2% less average answer relevance than the other techniques (around 90% for combining both RAG Fusion and HyDE, while the techniques alone show results around 92%, and the usage of none of these techniques also shows 92%); but significant improvement in the retrieval phase – the max context relevance average was 99% (while using only RAG Fusion was 97%, only HyDE was 95% and using none of the techniques was around 93%); the max groundedness scores average was around 90% (while using only RAG Fusion was 67%, only HyDE was 82% and using none of the techniques was also 82%). If we take a look at the context relevance average scores (not taking just the score for the most relevant context for a query but the average of the scores for the 3 retrieved contexts), combining both techniques showed a result of 84% (while only RAG Fusion was 78%, only HyDE was 81% and using none of the techniques was 75%). The groundedness average score for combining the two techniques was 47% (while using only RAG Fusion was 33%, only HyDE was 43% and using none of the techniques was around 42.5%).

If we compare HyDE and RAG Fusion based on the obtained results from these experimentations, then we can see that in answer relevance they provide pretty much the same results; in max context relevance average, RAG Fusion has a 2% advantage, while in context relevance average, HyDE has a 3% advantage. In the max groundedness average, HyDE provides significantly better results with around a 15% advantage over RAG Fusion, while in the groundedness average, it has an advantage of 10%. Based on the significant difference of over 10% in the groundedness scores, HyDE has an advantage over RAG Fusion, according to the conducted experiments. In the other two metrics, however, the two techniques are pretty similar.

IV. Conclusions

In the presented paper, an approach for creating a RAG system that enables the user to import his own documents to ask queries on them is proposed. A realization of the suggested approach is also presented in the form of a RAG system that uses the new BgGPT model suitable for the Bulgarian and English languages. The developed system was tested on a set of research papers in the field of ecology and, more specifically, air pollution. The results showed that the system gives factually based answers and mitigates the LLM hallucinations.

RAG systems developed on the basis of the proposed approach can be implemented in various different fields and can be used to improve the searching of information in big textual documents and serve as a useful and powerful tool to gain knowledge and information on various topics.

Acknowledgements

This work was supported by the NSP "Security and defence" program, which has received funding from the Ministry of Education and Science of the Republic of Bulgaria under the grant agreement no. Д01-74/19.05.2022.

References

[1] A.Vina, "From Code to Conversation: How Does an LLM Work?",November 2024.[Online]. Available: https://www.ultralytics.com/de/blog/from-code-to-conversation-how-does-an-llm-work [Accessed: Jan. 30, 2025].

[2] Cloudflare, "What is a large language model (LLM)?". [Online]. Available: https://www.cloudflare.com/learning/ai/what-is-large-language-model/ [Accessed: Jan. 30, 2025].

[3] C. Onielfa, "Introducing REMi, the first ever open-source RAG evaluation model", August 2024. [Online]. Available: https://nuclia.com/developers/remi-open-source-rag-evaluation-model [Accessed: Jan. 30, 2025].

[4] Nexla, "LLM Hallucination-Types, Causes, and Solution".[Online]. Available: https://nexla.com/ai-infrastructure/llm-hallucination/ [Accessed: Jan. 30, 2025].

[5] N. Muendler, J. He, S.Jenko, M. Vechev, "Self-Contradictory Hallucinations of LLMs: Evaluation, Detection and Mitigation", March 2024.[Online]. Available: https://arxiv.org/pdf/2305.15852 [Accessed: Feb. 07, 2025].

[6] A. Choudhury, "Best Strategies to minimize Hallucinations in LLMs: A Comprehensive Guide", November 2023. [Online]. Available: https://www.turing.com/resources/minimize-llm-hallucinations-strategy [Accessed: Feb. 07, 2025].

[7] H. Chawre, "What Is Retrieval-Augmented Generation (RAG) in LLMs?".[Online]. Available: https://www.turing.com/resources/understanding-retrieval-augmented-generation-rag [Accessed: Feb. 07, 2025].

[8] Wikipedia, "Retrieval-augmented generation".[Online]. Available: https://en.wikipedia.org/wiki/Retrieval-augmented_generation [Accessed: Feb. 07, 2025].

[9] K. Safjan, "Understanding Retrieval-Augmented Generation (RAG) empowering LLMs".[Online]. Available: https://safjan.com/understanding-retrieval-augmented-generation-rag-empowering-llms/ [Accessed: Feb. 07, 2025].

[10] P. Menon, "How RAG Works: A Detailed Explanation of its Components and Steps", January 2024.[Online]. Available: https://www.linkedin.com/pulse/how-rag-works-detailed-

explanation-its-components-steps-pradeep-menon-ws7sc [Accessed: Feb. 07, 2025].

[11] BgGPT-Gemma-2, [Online]. Available: https://huggingface.co/collections/INSAIT-Institute/bggpt-gemma-2-673b972fe9902749ac90f6fe [Accessed: Feb. 07, 2025].

[12] INSAIT, "INSAIT releases new AI models, setting a standart for open national language models", November 2024.[Online]. Available: https://insait.ai/insait-releases-new-ai-models-setting-a-standard-for-open-national-language-models/ [Accessed: Feb. 15, 2025].

[13] Dataset Card for Wikipedia, [Online]. Available: https://huggingface.co/datasets/legacy-datasets/wikipedia [Accessed: Feb. 07, 2025].

[14] FOCUS News, [Online]. Available: https://www.focus-news.net/[Accessed: Feb. 15, 2025].

[15] H. Sajid, "Improving Information Retrievala nd RAG with Hypothetical Document Embeddings (HyDE)", July 2024.[Online]. Available: https://zilliz.com/learn/improve-rag- and-information-retrieval-with-hyde-hypothetical-document-embeddings [Accessed: Feb. 15, 2025].

[16] Z. Rackauckas, "RAG-Fusion: A new take on Retrieval-Augmented Generation", February 2024.[Online]. Available: https://arxiv.org/pdf/2402.03367 [Accessed: Feb. 20, 2025].

[17] BGE-M3, [Online]. Available: https://huggingface.co/BAAI/bge-m3 [Accessed: Feb.15, 2025].

[18] G. Cormack, C. Clarke, S. Buettcher, Reciprocal Rank Fusion outperforms Condorcet and individual Rank Learning Methods.[Online]. Available: https://plg.uwaterloo.ca/~gvcormac/cormacksigir09-rrf.pdf [Accessed: Feb. 20, 2025].

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 353-358

Mathematical Methods for Evaluation of Webometric Indicators of Information Library Centers

Diyora Talipova
Library information system department Tashkent University of Information Technologies
Tashkent, Uzbekistan
d.talipova88@gmail.com

***Abstract*. Nowadays, new technologies are being used in every aspect of our lives. In particular, public libraries are focusing on attracting readers and introducing new services through the use of various new technologies. Therefore, providing information to users through public library websites, studying data on the duration of website use, the number of visits, determining the purposes of users' visits, and evaluating their visits are among the pressing issues of today. The purpose of this research is to analyze the websites of public libraries operating in the library sector, and to improve the efficiency of the system to provide quick and quality remote services to users. The article proposes a system for determining webometric indicators of public library websites, coefficients for evaluating the system, comprehensive mathematical methods for multi-criteria evaluation of websites. As part of the study, a method and mathematical solutions for expert evaluation of websites using the rating method are proposed. In particular, the proposed methods for multi-criteria evaluation of library websites were tested by special experts on the example of 14 websites belonging to the same category. Based on the studied criteria, webometric indicators were summarized, and based on the analysis conducted, the data were processed and the evaluation coefficient of the system for determining webometric indicators of library websites was calculated. Having obtained these results, it is possible to rank library websites. The essence of this method is that using this method, we can not only evaluate a website in a traditional way, but also obtain the following useful results: a complete evaluation of websites, an evaluation of websites according to certain criteria, and a comparison of website ratings. In general, evaluating public library websites is necessary not only to determine the popularity of libraries, but also to make sound management decisions, as well as to identify the needs and interests of readers.**

***Keywords*— information library centers, assessment, webometrics, website, expert evaluation.**

I. INTRODUCTION

As the world develops, technical capabilities and Internet websites are becoming more and more numerous. In an era of digital technologies, the library sector has become a center for managing knowledge resources in the intellectual practice of the population, and determining webometric indicators for delivering information to users through library websites and evaluating their visits is one of the urgent issues of today [1]. The development of libraries centers in our society is determined by the globalization of activities, increasing the importance of technology and intellectualization. Websites are considered the vital network of libraries and are mainly used as a virtual image of the library and a virtual network reflecting the information and services provided by the library [2]. Currently, there are more and more different websites around the world, and scientists are developing various scientific works and programs to analyze them brackets [3], [4].

The website of public libraries is considered their lifeline, and websites are mainly used as a virtual image of the library and an advertising platform for the information and services provided by the library. According to the analysis, analytical tools for effectively evaluating the activities of library websites on the web are becoming increasingly popular today. In particular, webometrics is a tool for measuring websites, web pages, phrases on web pages, website visits, hyperlinks, web search engine results and web aspects [5]. Webometric tools and their current state include four main areas of webometric research [6]: web page content analysis [7]; web link structure analysis [8]; website usage analysis (including users' search and

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8577
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

browsing behavior) [9]; web technology analysis (search engine performance) [10].

The main issue in determining the webometric indicators of a library website is to obtain all the criteria at the same time and to maintain them in a perfect system. In addition, some studies have different purposes or uses, and there are no strict webometric indicators for evaluating all websites. Each of them has solved the problem using a certain method. Therefore, nowadays it is necessary to develop a perfect system for studying and evaluating both subjective and objective criteria in a wide range of ways when determining the webometric indicators of library websites.

II. MATERIALS AND METHODS

The purpose of this research is to analyze the websites of public libraries operating in the library sector, and to improve the efficiency of the system to provide quick and quality remote services to users. Evaluation criteria of public library websites were developed as a result of generalization of webometric indicators, based on the performed analysis and preliminary data processing. The criteria were initially processed by experts and the evaluation coefficient of the system for determining webometric indicators of library websites was calculated. These evaluation criteria and the values of the criteria are shown in Table 1.

TABLE 1. CRITERIA FOR ASSESSMENT OF WEBOMETRIC INDICATORS OF LIBRARIES AND THEIR VALUE

№	Criteria for assessment		
	Evaluation criterion	***Criteria indicators***	***The value of the criteria***
M1	Completenes of library website content	Availability of information about library management	1
		Availability of library structural divisions	1
		Library history availability	1
		Description of library tasks and functions	1
		Library address and Trust phone existence	1
		Total:	5
M2	Reliability of using the library website	Availability of information security policy of Library website	1
		Controlling user access to the information system	1
		Protecting users' personal accounts	1
		Protecting library data	1
		Protecting library records	1
		Total:	5
M3	Accessibility of library website content	Availability of ramps and other devices for people with disabilities	1
		Opening and using the user's personal account	1
		Ease of page navigation	1
		Availability of a site map	1
		Total:	4
M4	Availability of a search engine for all information posted on the website	Availability of search engine	1
		Search for new literature	1
		Search for periodicals	1
		Search for articles	1
		Search for general text information	1
		Total:	5
M5	Availability of information about regulatory documents	Decisions related to the library sector	1
		Laws related to the library sector	1
		Regulations related to the library sector	1
		Standards related to the library sector	1
		Service for downloading all documents	1
		Total:	5
M6	Library news coverage	The completeness of library news coverage	2
		Library News Posting more than 8 news in per month	2
		Covering the content of news with pictures	1
		Total:	5
M7	Availability of language support	Website text maintained in Uzbek	2
		Website text maintained in Russian	1
		Website text maintained in English	1
		Total:	4
M8	Online book delivery	Search for online books by keyword	1
		Download full text	1
		Save books to your personal account	1
		View popular books	1
		Availability of books in audio and video format	1
		Total:	5
M9	Completenes s of information about regional libraries	Information about the activities of regional libraries	1
		Information about regional libraries managers	1
		Contact addresses of regional libraries	1
		Web addresses of regional libraries	1
		Total:	4
M10	Information about events and book exhibitions held by the library	Information about library events	1
		Information about library book fairs	1
		Information about library event announcements	1
		Information about famous Uzbek writers	1
		Information about world writers	1
		Total:	5
M11	Web site design suitability for the library	Website design appropriate to library life	1
		Website logo appropriate to library	1
		Page navigation appearance	1
		Information about partner organizations with logos and links	1
		Website design updated to reflect national holidays	1
		Total:	5
M12	User inquiries to the library website (interactive inquiries)	"Ask the Librarian" virtual information service	1
		Online consultation	1
		Electronic delivery of documents	1
		Extension of the book return deadline	1
		Online information for users	1
		Total:	5

When analyzing the popularity of public library websites, it is important to pay attention to statistics obtained using various sources. One of the most useful methods for evaluating and monitoring overall results

based on webometric indicators is expert evaluation method.

Expert evaluation method **-** determined by website experts by checking the availability of pages on social networks and electronic library services, ensuring information security, as well as the availability of relevant information and its accessibility on websites **.**

III. RESULTS AND DISCUSSION

Nowadays, it is important to evaluate library websites in order to improve their performance and continuous development. However, all the reviewed methods are only one-criteria, so we have combined various suitable multi-criteria methods and with the participation of several experts who are library specialists, we will consider methods for multi-criteria evaluation of websites. The proposed expert evaluation method for multi-criteria evaluation of library websites includes four stages.

The first stage is to calculate the importance coefficient of each of the library website indicators using the expert rating method [6].

The second stage is evaluation of the library website for each criterion by a separate expert using an expert method.

In the third stage, the average value of each website is calculated separately for each criteria, taking into account the assumptions of all methods.

In the fourth stage, the values of the selected library websites are calculated according to all criteria.

A. Stage 1. Rating method.

Using the rating method, experts-*t* determine the importance coefficient of each of the *n* criteria for evaluating the library website.

TABLE 2. THE FIRST EXPERT'S EVALUATION OF EACH WEBSITE ACCORDING TO VARIOUS CRITERIA

Criteria *(k-criterion)*	**Website assessments** *(v-websites)*													
	v1	*v2*	*v3*	*v4*	*v5*	*v6*	*v7*	*v8*	*v9*	*v10*	*v11*	*v12*	*v13*	*v14*
k1	5	2	4	3	5	4	2	1	4	3	2	1	4	3
k2	2	5	4	4	2	1	4	3	2	1	5	2	2	1
k3	4	2	4	4	3	2	1	4	2	4	2	2	2	4
k4	2	1	2	5	1	4	3	2	1	5	2	2	1	5
k5	2	4	2	1	4	3	2	1	1	5	2	5	1	5
k6	4	3	2	1	1	4	3	2	1	1	5	2	1	1
k7	4	2	1	4	3	2	1	1	4	3	2	1	4	3
k8	4	2	1	4	3	2	1	5	4	2	1	4	4	2
k9	2	4	2	1	4	3	2	1	4	4	2	1	4	4
k10	3	2	1	4	2	1	4	3	2	1	2	2	2	1
k11	2	5	4	2	1	4	3	2	1	5	2	2	1	5
k12	1	4	3	2	1	5	2	4	2	1	4	3	2	1

TABLE 3. THE SECOND EXPERT'S EVALUATION OF EACH WEBSITE ACCORDING TO VARIOUS CRITERIA

Criteria *(k-criterion)*	**Website assessments** *(v-websites)*													
	v1	*v2*	*v3*	*v4*	*v5*	*v6*	*v7*	*v8*	*v9*	*v10*	*v11*	*v12*	*v13*	*v14*
k1	4	2	1	4	3	2	1	1	4	3	2	1	2	1
k2	1	4	3	2	1	5	2	3	2	1	5	2	5	2
k3	2	1	4	2	4	2	2	4	2	4	2	2	2	2
k4	4	3	2	1	5	2	2	2	1	5	2	2	2	2
k5	3	2	1	1	5	2	4	1	1	5	2	5	2	4
k6	4	3	2	1	1	5	2	2	1	1	5	2	5	2
k7	2	1	1	4	3	2	1	1	4	3	2	1	2	1
k8	2	1	4	4	2	1	4	5	4	2	1	4	1	4
k9	3	2	1	4	4	2	1	1	4	4	2	1	2	1
k10	1	4	3	2	1	2	2	3	2	1	2	2	2	2
k11	4	3	2	1	5	2	2	2	1	5	2	2	2	2
k12	5	2	4	2	1	4	3	4	2	1	4	3	4	3

TABLE 4. THE THIRD EXPERT'S EVALUATION OF EACH WEBSITE ACCORDING TO VARIOUS CRITERIA

Criteria *(k-criterion)*	**Website assessments** *(v-websites)*													
	v1	*v2*	*v3*	*v4*	*v5*	*v6*	*v7*	*v8*	*v9*	*v10*	*v11*	*v12*	*v13*	*v14*
k1	3	5	4	2	1	4	4	2	1	4	3	2	3	2
k2	4	2	1	4	3	2	1	4	3	2	1	5	4	2
k3	4	3	2	1	4	2	2	1	4	2	4	2	2	1
k4	5	1	4	3	2	1	4	3	2	1	5	2	1	1
k5	1	4	3	2	1	1	3	2	1	1	5	2	2	1
k6	1	1	4	3	2	1	4	3	2	1	1	5	1	4
k7	4	3	2	1	1	4	2	1	1	4	3	2	4	4
k8	4	3	2	1	5	4	2	1	4	4	2	1	1	4
k9	1	4	3	2	1	4	3	2	1	4	4	2	3	2
k10	4	2	1	4	3	2	1	4	3	2	1	2	2	1
k11	2	1	4	3	2	1	4	3	2	1	5	2	4	2
k12	2	1	4	2	4	2	4	2	4	2	1	4	4	4

The proposed methods for multi-criteria evaluation of library websites were tested on a sample of 14 websites belonging to the same category. All the criteria are randomly selected by 3 experts based on Table 1. The scores given by ***l***-experts to 14 ***v***-websites for each ***k***-criterion are shown in Table 2:

There are *n* criteria for *t* expert evaluation of library websites, each of them gives a score for each criterion in the range from 1 to *n.*

First, $\|a_{lk}\|$ is table of the ratings assigned to *t* experts on ***n*** criteria, where a_{lk}– is the rating given to *k*-criterion ***l*** **-** expert, $l = \overline{1,3}, k = \overline{1,12}$.

In the next step, we consider the sum of the ratings given by all *t* experts for each of the *n* criteria [11]:

$$a_k = \sum_{l=1}^{t} a_{lk} \qquad (1)$$

from this, $k = 12$.

Using the given formula, we calculate the total score of 14 websites by 3 experts on 12 criteria:

TABLE 5. (A). EXPERTS' EVALUATION OF 14 WEBSITES ACCORDING TO 12 CRITERIA BY USING (1) FORMULA

V-websites	**Web site assessment by criteria *(k-criterion)***					
	k1	***k2***	***k3***	***k4***	***k5***	***k6***
V1	a *I1* =12	a *I2* =7	a *I13* =10	a *I4* =11	a *I5* =6	a *I6* =9
V2	a *I1* = 9	a *I2* = 11	a *I13* = 6	a *I4* = 5	a *I5* = 10	a *I6* = 7
V3	a *I1* = 9	a *I2* = 8	a *I13* =10	a *I4* = 8	a *I5* =6	a *I6* = 8
V4	a *I1* = 9	a *I2* = 10	a *I13* = 7	a *I4* = 9	a *I5* = 4	a *I6* = 5
V5	a *I1* = 9	a *I2* = 6	a *I13* = 1 1	a *I4* = 8	a *I5* = 10	a *I6* = 4
V6	a *I1* =1 0	a *I2* = 8	a *I13* = 6	a *I4* = 7	a *I5* =6	a *I6* = 10
V7	a *I1* = 7	a *I2* =7	a *I13* = 5	a *I4* = 9	a *I5* = 9	a *I6* =9
V8	a *I1* = 4	a *I2* = 10	a *I13* = 9	a *I4* = 7	a *I5* = 4	a *I6* = 7
V9	a *I1* = 9	a *I2* =7	a *I13* = 8	a *I4* = 4	a *I5* = 3	a *I6* = 4
V10	a *I1* =1 0	a *I2* = 4	a *I13* =10	a *I4* =11	a *I5* = 11	a *I6* = 3
V11	a *I1* = 7	a *I2* = 11	a *I13* = 8	a *I4* = 9	a *I5* = 9	a *I6* = 11
V12	a *I1* = 4	a *I2* = 9	a *I13* = 6	a *I4* = 6	a *I5* = 12	a *I6* =9
V13	a *I1* = 9	a *I2* = 11	a *I13* = 6	a *I4* = 4	a *I5* = 5	a *I6* = 7
V14	a *I1* = 6	a *I2* = 5	a *I13* = 7	a *I4* = 8	a *I5* = 10	a *I6* = 7

TABLE 5. (B).

V-websites	**Web site assessment by criteria *(k-criterion)***					
	k7	***k8***	***k9***	***k10***	***k11***	***k12***
V1	a *I7* =10	a *I8* =10	a *I9* =6	a *I10* =8	a *I11* =8	a *I12* =8
V2	a *I7* = 6	a *I8* = 6	a *I9* = 10	a *I10* =8	a *I11* = 9	a *I12* = 7
V3	a *I7* = 4	a *I8* = 7	a *I9* =6	a *I10* = 5	a *I11* = 10	a *I12* = 11
V4	a *I7* = 9	a *I8* = 9	a *I9* = 7	a *I10* = 10	a *I11* = 6	a *I12* = 6
V5	a *I7* = 7	a *I8* =10	a *I9* = 9	a *I10* = 6	a *I11* =8	a *I12* = 6
V6	a *I7* = 8	a *I8* = 7	a *I9* = 9	a *I10* = 5	a *I11* = 7	a *I12* = 11
V7	a *I7* = 4	a *I8* = 7	a *I9* =6	a *I10* = 7	a *I11* = 9	a *I12* = 9
V8	a *I7* = 3	a *I8* = 11	a *I9* = 4	a *I10* = 10	a *I11* = 7	a *I12* = 10
V9	a *I7* = 9	a *I8* =1 2	a *I9* = 9	a *I10* = 7	a *I11* = 4	a *I12* =8
V10	a *I7* =10	a *I8* = 8	a *I9* = 12	a *I10* = 4	a *I11* = 11	a *I12* = 4
V11	a *I7* = 7	a *I8* = 4	a *I9* = 8	a *I10* = 5	a *I11* = 9	a *I12* = 9
V12	a *I7* = 4	a *I8* = 9	a *I9* = 4	a *I10* = 6	a *I11* = 6	a *I12* = 10
V13	a *I7* =10	a *I8* = 6	a *I9* = 9	a *I10* = 6	a *I11* = 7	a *I12* = 10
V14	a *I7* = 8	a *I8* =10	a *I9* = 7	a *I10* = 4	a *I11* = 9	a *I12* =8

B. Stage 2. Expert method.

The library website is evaluated by experts for each criterion separately. We determine the ***k-*** criterion of the ***p*** -experts for each website. First, for each ***r*** of ***v*** -websites, we find the sum of their ratings. As a result, we find the sum of the criteria based on the evaluation order given to each website by the experts[7]:

$$C_r^{pk} = \sum_{l=1}^{3} a_{rl}^{pk} \qquad (2)$$

Here $r = 14,\ p = \overline{1,3}, k = \overline{1,12}$

TABLE 6. EXPERTS' EVALUATION OF WEBSITES BY (2) FORMULA

№ Web sites	**Experts' assessment**		
	First expert evaluation 14 websites on 12 criteria	**Second expert evaluation 14 websites on 12 criteria**	**Third expert evaluation 14 websites on 12 criteria**
1	C_1^{1k}=35	C_1^{2k}=35	C_1^{3k}=35
2	C_2^{1k}=35	C_2^{2k}=28	C_2^{3k}=30
3	C_{31}^{1k}=36	C_{31}^{2k}=28	C_{31}^{3k}=34
4	C_4^{1k}=30	C_4^{2k}=28	C_4^{3k}=28
5	C_5^{1k}=35	C_5^{2k}=35	C_5^{3k}=29
6	C_6^{1k}=30	C_6^{2k}=31	C_6^{3k}=28
7	C_7^{1k}=35	C_7^{2k}=26	C_7^{3k}=34
8	C_8^{1k}=28	C_8^{2k}=29	C_8^{3k}=28
9	C_9^{1k}=29	C_9^{2k}=28	C_9^{3k}=28
10	C_{10}^{1k}=28	C_{10}^{2k}=35	C_{10}^{3k}=28
11	C_{11}^{1k}=31	C_{11}^{2k}=31	C_{11}^{3k}=3 5
12	C_{12}^{1k}=27	C_{12}^{2k}=27	C_{12}^{3k}= 31
13	C_{13}^{1k}=28	C_{13}^{2k}= 31	C_{13}^{3k}= 31
14	C_{14}^{1k}=35	C_{14}^{2k}= 26	C_{14}^{3k}= 28

Based on the studied criteria, the webometric indicators were summarized, and based on the conducted analyses, the data was pre-processed and the evaluation coefficient of the system for determining the webometric indicators of library websites was calculated. These evaluation criteria and their values are reflected in Table 6.

C. Stage 3. Calculating the sum of criteria.

The average value of each identified website is calculated separately for each criterion, taking into account the estimates of s experts. Then, for all ***v***-websites, a sum of alternative ratings for the criteria is formed [11]:

$$C^{pk} = \sum_{r=1}^{14} C_r^{pk} \qquad (3)$$

Here $p = \overline{1,3}, k = \overline{1,12}$

$$C^{1k}=C_1^{1k}+C_2^{1k}+\ldots C_{14}^{1k}=442$$
$$C^{2k}=C_1^{2k}+C_2^{2k}+\ldots C_{14}^{2k}=418$$
$$C^{3k}=C_1^{3k}+C_2^{3k}+\ldots C_{14}^{3k}=427$$

Then, we find the ***k*** - criterion score of ***v*** website for each ***r,*** based on the ***p***-expert score:

$$V_r^{pk} = \frac{C_r^{pl}}{C^{pk}} \quad (4)$$

Here $r = \overline{1,14},\ p = \overline{1,3}, k = 12$

TABLE 7. V_r^{pk} - EVALUATION OF EXPERTS ON GENERAL WEBSITES BY CRITERIA

№ Web sites	General assessment of experts		
	The first expert's evaluation of each website according to formula (4)	*The second expert's evaluation of each website according to formula (4)*	*The third expert's evaluation of each website according to formula (4)*
1	V_1^{1k}= 0.079	V_1^{2k}= 0.0837	V_1^{3k}= 0.0820
2	V_2^{1k}= 0.081	V_2^{2k}= 0.0670	V_2^{3k}= 0.0703
3	V_3^{1k}= 0.068	V_3^{2k}= 0.0670	V_3^{3k}= 0.0796
4	V_4^{1k}= 0.079	V_4^{2k}= 0.0670	V_4^{3k}= 0.0656
5	V_5^{1k}= 0.068	V_5^{2k}= 0.0837	V_5^{3k}= 0.0679
6	V_6^{1k}= 0.079	V_6^{2k}= 0.0742	V_6^{3k}= 0.0656
7	V_7^{1k}= 0.063	V_7^{2k}= 0.0622	V_7^{3k}= 0.0796
8	V_8^{1k}= 0.066	V_8^{2k}= 0.0694	V_8^{3k}= 0.0656
9	V_9^{1k}= 0.063	V_9^{2k}= 0.0670	V_9^{3k}= 0.0656
10	V_{10}^{1k}= 0.079	V_{20}^{2k}= 0.0837	V_{10}^{3k}= 0.0656
11	V_{11}^{1k}= 0.070	V_{11}^{2k}= 0.0742	V_{13}^{3k}= 0.0820
12	V_{12}^{1k}= 0.061	V_{12}^{2k}= 0.0646	V_{12}^{3k}= 0.0726
13	V_{13}^{1k}= 0.063	V_{13}^{2k}= 0.0742	V_{13}^{3k}= 0.0726
14	V_{14}^{1k}= 0.079	V_{14}^{2k}= 0.0622	V_{14}^{3k}= 0.0656

It should be noted that the main source of information in the formation of expert assessments are websites. In addition, the most competent specialists should be selected to conduct the examination. Specialist-experts and an objective method, for which many factors are taken into account: work experience in this field, research activities, previous work experience in the decision-making process, etc.

C. Stage 4. Overall assessment.

The values of the selected websites are calculated for all criteria. As mentioned above, each of the ***n*** criteria has its own importance coefficient (5). Thus, the evaluation of each website, taking into account the importance coefficient of each of the ***n*** criteria, is calculated as follows:

$$E_r = \sum_{t=1}^{3} v_r^{tk} \quad (5)$$

Then, the websites included in the selection can be sorted by values of E_r, $r = \overline{1,14}$.

The evaluation of each of the three websites, taking into account the evaluation on each of the three criteria, is found according to (5):

$$E_1 = V_1^{1k} + V_1^{2k} + V_1^{3k} = \mathbf{0.2449}$$
$$E_2 = V_2^{1k} + V_2^{2k} + V_2^{3k} = 0.2187$$
$$E_3 = V_3^{1k} + V_3^{2k} + V_3^{3k} = 0.2145$$
$$E_4 = V_4^{1k} + V_4^{2k} + V_4^{3k} = 0.2117$$
$$E_5 = V_5^{1k} + V_5^{2k} + V_5^{3k} = 0.2195$$
$$E_6 = V_6^{1k} + V_6^{2k} + V_6^{3k} = 0.2189$$
$$E_7 = V_7^{1k} + V_7^{2k} + V_7^{3k} = 0.2052$$
$$E_8 = V_8^{1k} + V_8^{2k} + V_8^{3k} = 0.2006$$
$$E_9 = V_9^{1k} + V_9^{2k} + V_9^{3k} = \mathbf{0.1959}$$
$$E_{10} = V_{10}^{1k} + V_{10}^{2k} + V_{10}^{3k} = 0.2285$$
$$E_{11} = V_{11}^{1k} + V_{11}^{2k} + V_{11}^{3k} = 0.2263$$
$$E_{12} = V_{12}^{1k} + V_{12}^{2k} + V_{12}^{3k} = 0.1983$$
$$E_{13} = V_{13}^{1k} + V_{13}^{2k} + V_{13}^{3k} = 0.2101$$
$$E_{14} = V_{14}^{1k} + V_{14}^{2k} + V_{14}^{3k} = 0.2070$$

III. CONCLUSIONS

Moreover, the highest value E_r, corresponds to the first level, etc. So, in the example shown, the first website was rated the highest, and the ninth website was rated the lowest .

In conclusion, an expert method for multi-criteria evaluation of websites was proposed, which solves the following tasks: a complete evaluation of websites, expert evaluation of websites according to certain criteria, a model library plays an important role in ranking websites. Libraries need to effectively manage their web resources and enhance their remote services from the library. Depending on the specific characteristics of the types of users, libraries should offer remote services that take into account the improvement of technologies, the availability of search features. For this, and the use of information resources, as well as the attraction of users who are not yet library readers. Therefore, library websites require constant evaluation to determine their quality level and new areas of activity. Having obtained these results, it is possible to rank library websites. Effective use of modern information technologies, ensuring the availability of information resources and their high-quality use ensure the success of any library.

REFERENCES

[1] I.Barba, R.Cassidy, E. De Leon and B. J. Williams, Web analytics reveal user behavior: TTU libraries experience with Google Analytics. Journal of Web Librarianship, 2013, 7 (4), pp. 389-400.

[2] R.Serrano-Vicente, R.Melero and E.Abadal, Evaluation of Spanish institutional repositories based on criteria related to technology, procedures, content, marketing and personnel. Data Technologies and Applications. 2018. Vol. 55, N3. pp. 384–404. DOI: 10.1108/DTA-10-5017-0074.

[3] I.Davydova, O.Marina, A.Solianyk and Y.Syerov, Social Networks in Developing the Internet Strategy for Libraries in

Ukraine. In: CEUR Workshop Proceedings. Vol 5395: Proceedings of the 1st International Workshop on Control, Optimisation and Analytical Processing of Social Networks, COAPSN-2019, Lviv, pp. 155–133 (2019).

[4] A.V.Mikhailova, Analysis of library web pages of cultural institutions as a tool to implement the external direction of integrating information-educational resources. Вестник културий и искусств, 2017, 3, pp. 49-59. (In Russ.).

[5] G.Muruganandham, Webometrics research methods adopted in library and information science: an overview. (2019) Library Philosophy and Practice (e-journal). 2869.

[6] D. Talipova , B. Ganiyeva , S. Normatov and M.Rakhmatullaev, "A method for determining and evaluating webometric indicators of public libraries ", Environment, Technology, Resources, 2024, 2, pp. 281 – 285, Jun.

[7] S.Novljan and M.Zumer, "Web pages of Slovenian public libraries: evaluation and guidelines", Journal of Documentation, Vol. 60 No. 1, pp. 62-76.

[8] L.B Shevchenko. Content analysis website library scientific uchrejdeniy GPNTB SO RAN// UDK 02:004 https://doi.org/10.33186/1027-3689-2022-1-71-90 .

[9] P.V. Skorodumov and A.Y. Kholodev, Analysis of the website popularity of a scientific institution using various systems to collect statistical data. 2016, 1, pp. 1-10. (In Russian).

[10] R.Jean and T.Zainab, The impact story of retracted articles: altmetric it! // 5th International symposium on emerging trends and technologies in libraries and information services. Noida, 2018. pp. 402–406. DOI:10.1109/ETTLIS.2018.8485245.

[11] M.R.Alguliyev, G.Ch.Nabibayova and S.R.Abdullayeva, Evaluation of Websites by Many Criteria Using the Algorithm for Pairwise Comparison Alternatives. IJ Intelligent Systems and Applications, 2020, 6, pp. 64-74 DOI: 10.5815/ijisa.5050.06.05

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 359-366

Decision Making Decision Making Based on Fuzzy Preference Relations

Oleg Uzhga-Rebrov
Rezekne Academy of RTU
Rezekne, Latvia
rebrovs@tvnet.lv

***Abstract* – Many fuzzy versions of common multi-criteria decision making (MCDM) methods have been proposed to date. Among these methods, a special place is occupied by the method based on fuzzy preference relations (FPR). This method is fuzzy in nature and has no crisp analogue. The essence of the method is to evaluate preferences on pairs of alternatives. The source for evaluation is subjective judgments of expert specialists based on their knowledge and experience. The purpose of this article is to present in detail and clearly the theoretical foundations of this specific method in the context of multi-criteria decision making under conditions of highly uncertain initial information. Based on the initial assignments of the experts, using relevant computational procedures, the resulting preference scores for each of the alternatives are determined. These resulting scores are the basis for selecting the optimal alternative or ranking the alternatives by preference. The article presents two alternative versions of this method. The article presents three illustrative examples, whose purpose is to demonstrate the relevant computational procedures.**

Keywords – aggregation of fuzzy preference relations, expert assessment of fuzzy preference relation, fuzzy preference relation (FPR), fuzzy strict preference relation, fuzzy nondominance relation.

I. Introduction

In general, the selection of optimal decision in multi-criteria decision making (MCDM) problems can be performed based on two general principles:

1. Based on comparisons of criterion values for all alternatives.

2. Based on paired comparisons of alternatives by preference for each criterion, without using the criterion values.

As examples of methods of the first group, the PROMETHEE, ELECTRE, TOPSIS methods should be mentioned. The "classic" example of a method of the second group is the AHP method.

There are many extensions of the AHP method to a fuzzy environment. In all of these extensions, the preference scores are expressed in the form of some fuzzy numbers.

This paper uses a different approach to pairwise comparison of alternatives by preference. This approach is based on the direct construction and use of fuzzy preference relations (FPR) in MCDM problems. Unlike fuzzy versions of AHP, this approach uses the values of the membership function of the pairwise evaluation results to the relevant FPR to map the results of fuzzy preference evaluation on pairs of alternatives. Although these values are discrete, their semantics reflects the uncertainties in the experts' assignments.

II. Matherials and Methods

As a working version, this article uses a conditional group problem of multi-criteria decision making by some criterion, including four alternatives. Two experts perform relevant assessments. A detailed description of the fuzzy preference relations used in the article is based on data presented in relevant literature sources.

A. Introduction to Fuzzy Relations

The concept of relations between elements of one set or between elements of different sets is a fundamental mathematical concept that is widely used in various scientific and practical fields.

In mathematics, a relation denotes some kind of connection between two objects in a set of such objects, which may or may not be supported [1]. Formally, a relation R on a set X can be considered as a set of ordered pairs (x_i, x_j) - members of R [2].

The relation R in these definitions is a binary relation. There are more complex n-ary relations, but this article considers only binary relations. A binary relation can also be defined on two sets X, Y of objects, subjects, etc. Then

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8570
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

we are talking about ordered pairs of objects (x_i, y_j), $x_i \in X$, $y_j \in Y$.

The concept of fuzzy relations was first proposed in [3]. A detailed historical overview of the development and practical applications of fuzzy relations is given in [4]. The concept of a fuzzy relation is an extension of the standard concept of a relation. Fuzzy relations include uncertainties regarding the degree of effectiveness of these relations.

Definition 1 [5]. Fuzzy relation R is a mapping from Cartesian space $X \times Y$ to interval [0. 1], where the strength of mapping is expressed by the membership function of the relation

$$R \subseteq X, Y \text{ and } \mu_R = X, Y \to [0.1] \quad (1)$$

Let X and Y be two relevant sets. A fuzzy relation R between X and Y (or from X to Y) is a fuzzy set of the form

$$R = \{(x, y), \mu_R(x, y) / x \in X, y \in Y\} \quad (2)$$

If X=Y, R is a fuzzy relation on X. If X and Y are finite sets, $X = \{x_1, ..., x_m\}$, $Y = [y_1, ..., y_n]$, then the fuzzy relation can be represented in the form of a matrix (table)

$$R = \left[\mu_R(x_i, y_j)\right]_{m \times n},\ i = 1, ..., m,\ j = 1, ..., n.$$

The value $\mu_R(x_i, y_j)$ is the value of the membership function, reflecting the strength of the relationship between the values of $x_i \in X$ and $y_j \in Y$. This value is written at the intersection of the i-th row and the j-th column of the matrix R.

Let two fuzzy relations R and S be defined on the Cartesian product of sets $X \times Y$. Let us define the most common operations on these relations.

1. Union $(R \cup S)$:

$$\mu_{R \cup S} = \max\left[\mu_R(x, y), \mu_S(x, y)\right] \quad (3)$$

2. Intersection $(R \cap S)$:

$$\mu_{R \cap S} = \min\left[\mu_R(x, y), \mu_S(x, y)\right] \quad (4)$$

3. Complement $(\bar{R})$:

$$\mu_{\bar{R}}(x, y) = 1 - \mu_R(x, y) \quad (5)$$

4. Containment $(R \subset S)$:

It can be stated that a fuzzy relation R is contained in a fuzzy relation S if and only if

$$R \subset S \equiv \mu_R(x, y) \le \mu_S(x, y), \forall x, y \text{ (6, a)}$$

By analogy, we can state that a fuzzy relation S is contained in a fuzzy relation R if and only if

$$S \subset R \equiv \mu_S(x, y) \le \mu_R(x, y), \forall x, y \text{ (6, b)}$$

Let us present some important properties of fuzzy relations on the set X.

1. Reflexivity:

$$(x_i, x_i) \in R,\ \forall x_i \in X \quad (7)$$

2. Symmetry:

$$(x_i, x_j) \in R \to (x_j, x_i) \in R,\ \forall x_i, x_j \in X \quad (8)$$

3. Transitivity:

$$(x_i, x_j) \in R, \text{ and } (x_j, x_k) \in R \to (x_i, x_k) \in R,$$
$$\forall x_i, x_j, x_k \in X \quad (9)$$

B. Using FPR in MCDM Problems

In this article, we use a special type of fuzzy relations – fuzzy preference relations (FPR) – to evaluate alternatives and select the optimal alternative in the MCDM problem. The idea of such an approach was first proposed by L. Zadeh in his work [6].

Fig. 1 shows the graph of the membership function FPR P.

The horizontal axis shows the gradations of the strength of preference on a pair of alternatives (a_i, a_j). These gradations can be expressed by the following linguistic terms:

0 - a_j absolutely preferred to a_i;

1 - a_j very strongly preferred to a_i;

2 - a_j strongly preferred to a_i;

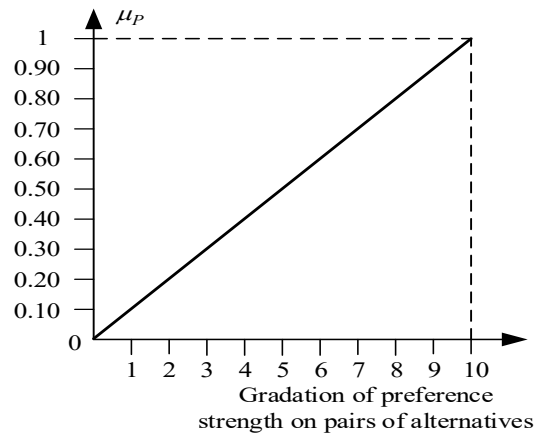


Fig. 1. Graph of the membership function μ_P FPR P.

3 - a_j moderately preferred to a_i;

4 - a_j slightly preferred to a_i;

5 - indifference between a_j and a_i;

6 - a_i slightly preferred to a_j;

7 - a_i moderately preferred to a_j;

8 - a_i strongly preferred to a_j;

9 - a_i very strongly preferred to a_j;

10 - a_i absolutely preferred to a_j.

The vertical axis shows the membership function's values corresponding to the subjective assignments of the expert's preference strength on pairs of alternatives. Using his knowledge and experience, the expert subjectively evaluates the preference strength on the relevant pair of alternatives. Using the membership function graph μ_P in Fig. 1, the value $\mu_P(a_i, a_j)$ can be determined. The set of values $\mu_P(a_i, a_j)$, $\forall a_i, a_j \in A$, form the initial data set in the MCDM problem.

The gradations 1–10 of the strength of preference in Fig. 1 are only guidelines for the expert to express his subjective judgments. In practice, he can assign any decimal number in the interval [0, 10] and determine the corresponding value of the membership function $\mu_P(a_i, a_j)$ in the interval [0, 1].

In general, FPR P can be either multiplicative $(p_{ij} * p_{ij} = 1)$ or additive $(p_{ij} + p_{ji} = 1)$. In this paper, we consider the additive FPR variant.

The main requirement for any set of results of pairwise comparisons of alternatives by preference is the consistency (compatibility) of these results. If an expert prefers alternative a_i to alternative a_j and he/she prefers alternative a_j to alternative a_k it is quite obvious that he should prefer alternative a_i to alternative a_k. In other words, the results of pairwise comparisons of alternatives should always be transitive.

Various types of transitivity on FPR are presented in [7]:

- weak transitivity:

$$p_{ij} \geq 0{,}5,\ \ p_{jk} \geq 0{,}5 \rightarrow p_{ik} \geq 0.5, \forall i, j, k \quad (10)$$

- max-min transitivity:

$$p_{ik} \geq \min(p_{ij}, p_{jk}), \forall i, j, k \quad (11)$$

- max- max transitivity:

$$p_{ik} \geq \max(p_{ij}, p_{jk}), \forall i, j, k \quad (12)$$

- restricted max-min transitivity:

$$p_{ij} \geq 0{,}5,\ p_{jk} \geq 0{,}5 \rightarrow p_{ik} \geq \min(p_{ij}, p_{jk}), \forall i, j, k \quad (13)$$

- restricted max-max transitivity:

$$p_{ij} \geq 0{,}5,\ p_{jk} \geq 0{,}5 \rightarrow p_{ik} \geq \max(p_{ij}, p_{jk}), \forall i, j, k \quad (14)$$

- multiplicative transitivity:

$$(p_{ji} / p_{ij}) * (p_{kj} / p_{jk}) = p_{ki} / p_{ik} \forall i, j, k \quad (15)$$

- additive transitivity:

$$(p_{ij} - 0{,}5) + (p_{jk} - 0.5) = (p_{ik} - 0.5), \forall i, j, k \quad (16)$$

Equivalently, the additive transitivity property can be represented in the form [8].

$$p_{ij} + p_{jk} + p_{ik} = \frac{3}{2}, \forall i, j, k \quad (17)$$

A detailed analysis of the above types of transitivity on FPR can be found in [9].

This paper uses a version of FPR with additive transitivity. In this version, a formal check of the compatibility of the results of pairwise comparisons can be performed according to the condition [9].

$$p_{i(i+1)} + p_{(i+1)(i+2)} + \ldots + p_{(j-1)j} + p_{ji} = \frac{j-1+1}{2}, \forall i < j. \quad (18)$$

Testing under condition (18) can only confirm or disprove the compatibility of the relevant FPR. This naturally raises the question: is it possible in principle to construct an initial FPR that is compatible under condition (18). The following algorithm for solving this problem is proposed in [8].

Algorithm to construct a consistent reciprocal preference relation P' on $A = \{a_1, \ldots, a_n, n \geq 2\}$ from n-1 preference values $\{p_{12}, p_{23}, \ldots, p_{(n-1)n}\}$ presents the following steps:

1. $B = \left\{ p_{ij}, i < j \wedge p_{ij} \notin \left\{ p_{12}, p_{23}, \ldots, p_{(n-1)n} \right\} \right\}$,

$$p_{ij} = \frac{j-i+1}{2} - p_{i(i+1)} - p_{(i+1)(i+2)} - \ldots - p_{(j-1)j}.$$

2. $a = \left| \left\{ \min B \cup \left\{ p_{12}, p_{23}, \ldots, p_{(n-1)n} \right\} \right\} \right|$.

3. $P = \left\{ p_{12}, p_{23}, \ldots, p_{(n-1)n} \right\} \cup B \cup$
$\cup \left\{ 1 - p_{12}, 1 - p_{23}, \ldots, 1 - p_{(n-1)n} \right\} \cup \neg B.$

We will present the operation of this algorithm in an illustrative example later in this section.

In [9], an algorithm for constructing the multiplicative consistent fuzzy preference relation from an inconsistent fuzzy preference relation is proposed. This algorithm is not considered in this paper.

Let a group of experts perform pairwise comparisons of mutual preferences of alternatives. As a result, we have a set of individual FPRs. The problem of aggregating these individual FPRs into a generalized FPR, which we will call collective FPR, arises. Various methods have been proposed to solve this problem [10], [11], [12]. In this paper, we use the method presented in [12].

Let there be a group of m experts who performed pairwise comparisons of preferences of n alternatives. The results of their evaluations are reflected in the form of FPR $P_k = \left[p_{ij}^k \right]$, $p_{ij}^k + p_{ji}^k = 1$, $p_{ii}^k = 0.5$, i, j =1,..., n, k = 1,..., m. To aggregate individual FPR Pk into a collective FPR P^c, in [12] it is proposed to use the simple additive weighting (SAW) method.

$$P^c = \sum_{k=1}^{m} w_k P_k \tag{19}$$

where $P^c = \left[p_{ij}^c \right]_{n \times n}$; w_k - weight of the k-th individual FPR.

To determine the weight vector $W = \left[w_1, w_2, ..., w_m \right]^T$, the following computational procedures must be performed.

The values of the differences are calculated as follows:

$$\delta_{ik} = \sum_{j=1, j \neq i}^{n} \left(p_{ij}^k - p_{ji}^k \right), \; i = 1,...,n, \; k = 1,...,m \tag{20}$$

The calculation results are presented in the form of a matrix

$$\Delta = \begin{bmatrix} & P_1 & ... & P_k & .... & P_m \\ A_1 & \delta_{11} & ... & \delta_{1k} & ... & \delta_{1m} \\ ... & ... & ... & ... & ... & ... \\ A_i & \delta_{i1} & ... & \delta_{ik} & ... & \delta_{im} \\ ... & ... & ... & ... & ... & ... \\ A_n & \delta_{n1} & ... & \delta_{nk} & ... & \delta_{nm} \end{bmatrix}.$$

For each FPR P_k, the values of these two indices are calculated:

- absolute deviation:

$$AD_k = \sum_{i=1}^{n} \sum_{j=1}^{n} \left| \delta_{ik} - \delta_{jk} \right|, \; k = 1,...,m \tag{21}$$

- standard deviation:

$$SD_k = \sqrt{\frac{1}{n} \delta_{ik}^2} \tag{22}$$

FPRs with larger AD_k and SD_k values are more important. The weights determined based on AD_k values are called ADM weights in [12], and the weights determined based on SD_k values are called SDM weights. In this paper, we use SDM weights.

The values of SDM weights are calculated using the expression (23)

$$\tilde{w}_k = \frac{\left(\frac{1}{n} \sum_{i=1}^{n} \delta_{ik}^2 \right)^{\frac{1}{2(p-1)}}}{\left[\sum_{l=1}^{m} \left(\frac{1}{n} \sum_{i=1}^{n} \delta_{il}^2 \right)^{\frac{p}{2(p-1)}} \right]^{\frac{1}{p}}}, k = 1,...,m, \; p > 1 \tag{23}$$

The normalized values of the SDM weights are calculated using the expression (24)

$$w_k = \frac{\left(\sum_{i=1}^{n} \delta_{ik}^2 \right)^{\frac{1}{2(p-1)}}}{\sum_{l=1}^{m} \left(\sum_{i=1}^{n} \delta_{il}^2 \right)^{\frac{1}{2(p-1)}}}, \; k = 1,...,m, \; p > 1 \tag{24}$$

From (24) it follows that the normalized values of w_k depend on the values of the parameter p. In [12] it is recommended to use smaller values of p. In the present paper, the value p = 2 is used. With this value of p, expression (24) is transformed into the form

$$w_k = \frac{\sqrt{\sum_{i=1}^{n} \delta_{ik}^2}}{\sum_{l=1}^{m} \left(\sum_{i=1}^{n} \delta_{il}^2 \right)}, \; k = 1,...,m \tag{25}$$

Note that for $p = \infty$ $w_k = \frac{1}{m}$, $k = 1,...,m$. In other words, the collective FPR is equal to the arithmetic mean of the individual FPRs.

Illustrative example 1. Let there be a set of alternatives $A = \{a_1, a_2, a_3, a_4\}$. The task of three experts is to assign their individual FPRs on this set of alternatives according to some criterion c_j. To solve this problem, the algorithm for constructing compatible FPRs presented above is used.

Expert E_1 performed the following initial assignments:

$$P_1^* = \begin{bmatrix} 0.50 & 0.53 & & \\ & 0.50 & 0.67 & \\ & & 0.50 & 0.73 \\ & & & 0.50 \end{bmatrix}.$$

The first task is to calculate the preference values in the lower left corner of the matrix. According to expression (18), we have

$$p_{31} = 1.5 - p_{12} - p_{23} = 1.5 - 0.53 - 0.67 = 0.30;$$
$$p_{41} = 2 - p_{12} - p_{24} - p_{34} = 2 - 0.53 - 0.67 - 0.73 = 0.07;$$
$$p_{42} = 1.5 - p_{23} - p_{34} = 1.5 - 0.67 - 0.73 = 0.10.$$

The remaining values are determined using the additivity property of FPR: $p_{ji} = 1 - p_{ij}$. We have

$$P_1 = \begin{bmatrix} 0.50 & 0.53 & 0.70 & 0.93 \\ 0.47 & 0.50 & 0.67 & 0.90 \\ 0.30 & 0.33 & 0.50 & 0.73 \\ 0.07 & 0.10 & 0.26 & 0.50 \end{bmatrix}.$$

Expert E_2 performed the following initial assignments:

$$P_2^* = \begin{bmatrix} 0.50 & 0.75 & & \\ & 0.50 & 0.80 & \\ & & 0.50 & 0.85 \\ & & & 0.50 \end{bmatrix}.$$

Let us carry out the calculations according to the above scheme.

$p_{31} = 1.5 - p_{12} - p_{23} = 1.5 - 0.75 - 0.80 = -0.05$;
$p_{41} = 2 - p_{12} - p_{24} - p_{34} = 2 - 0.75 - 0.80 - 0.85 = -0.40$;
$p_{42} = 1.5 - p_{23} - p_{34} = 1.5 - 0.80 - 0.85 = -0.15$.

$$P_2 = \begin{bmatrix} 0.50 & 0.75 & 1.05 & 1.40 \\ 0.25 & 0.50 & 0.80 & 1.15 \\ -0.05 & 0.20 & 0.50 & 0.85 \\ -0.40 & -0.15 & 0.15 & 0.50 \end{bmatrix}.$$

The initial estimates of expert E_2 are in the interval [-.40. 1.40], so these estimates must be transformed. According to procedure 2 of the algorithm, a = 0.40.

Let us calculate the transformed values according to procedure 4 of the algorithm.

$$p'_{12} = \frac{0.75 + 0.40}{1 + 2 * 0.40} = \frac{1.15}{1.80} = 0.64.$$

The remaining calculations are performed by analogy. Finally, we have

$$P'_2 = \begin{bmatrix} 0.50 & 0.64 & 0.80 & 1.00 \\ 0.36 & 0.50 & 0.67 & 0.80 \\ 0.20 & 0.33 & 0.50 & 0.69 \\ 0.00 & 0.20 & 0.31 & 0.50 \end{bmatrix}.$$

Using the initial assignments of expert E_3, the following FPR P_3 is formed

$$P_3 = \begin{bmatrix} 0.50 & 0.57 & 0.69 & 0.89 \\ 0.43 & 0.50 & 0.62 & 0.77 \\ 0.31 & 0.38 & 0.50 & 0.65 \\ 0.16 & 0.23 & 0.35 & 0.50 \end{bmatrix}.$$

We aggregate individual FPRs of experts. To do this, we first calculate the values δ_{i1} of the differences for the assignments of expert E_1 using (20).

$\delta_{11} = (0.53 - 0.47) - (0.70 - 0.30) - (0.93 - 0.07) =$
$= 0.06 + 0.40 + 0.86 = 1.32$;

$\delta_{21} = (0.47 - 0.53) + (0.67 - 0.33) + (0.90 - 0.10) =$
$= -0.06 + 0.34 + 0.80 = 1.08$.

By analogy, $\delta_{31} = -0.27$, $\delta_{41} = -2.13$.

The differences δ_{i2} and δ_{i3} for FPR P'_2, P_3 are calculated in a similar way. The resulting values of the differences are presented in the matrix Δ.

$$\Delta = \begin{bmatrix} & P_1 & P'_2 & P_3 \\ A_1 & 1.32 & 1.88 & 1.20 \\ A_2 & 1.08 & 0.66 & 0.64 \\ A_3 & -0.27 & -0.56 & -0.32 \\ A_4 & -2.13 & -1.98 & -1.52 \end{bmatrix}.$$

Using (25), we calculate the values of the FPR weights. First, we calculate the values of $\sqrt{\sum_{i=1}^{4} \delta_{ik}^2}$, $k = 1,2,3$.

$$\sqrt{\sum_{i=1}^{4} \delta_{i1}^2} = \sqrt{1.32^2 + 1.08^2 + (-0.27)^2 + (-2.13)^2} =$$
$$= \sqrt{1.74 + 1.17 + 0.08 + 4.54} = \sqrt{7.53} = 2.74.$$

By analogy,

$$\sqrt{\sum_{i=1}^{4} \delta_{i2}^2} = 2.86, \quad \sqrt{\sum_{i=1}^{4} \delta_{i3}^2} = 2.06.$$

As a normalizing divisor in (25) we will take the sum of the values calculated above: 7.66. We have the following values of the FPR weights:

$$w_1 = \frac{2.74}{7.66} = 0.36, \quad w_2 = \frac{2.86}{7.66} = 0.37, \quad w_3 = \frac{2.06}{7.66} = 0.27.$$

Using (19), we determine the collective FPR Pc. To do this, we calculate the weighted average values for all p_{ijk} .

$p_{12}^c = 0.36 * 0.53 + 0.37 * 0.64 + 0.27 * 0.57 = 0.58$.

The remaining values p_{ij}^c are calculated by analogy. As a result, we have

$$P^c = \begin{bmatrix} 0.50 & 0.58 & 0.68 & 0.93 \\ 0.42 & 0.50 & 0.66 & 0.83 \\ 0.28 & 0.35 & 0.50 & 0.67 \\ 0.06 & 0.17 & 0.30 & 0.50 \end{bmatrix}.$$

C. Selection of Optimal Alternatives Based on FPR

Historically, the first approach to selecting optimal alternatives in MCDM problems where experts' preferences are represented in the form of FPR was the approach proposed in [13], [14]. We will present this approach based on the data from their work [15].

The fundamental concept in MCDM problems is the concept of the Pareto set, which is formed by alternatives

that are not comparable in terms of criterion values. All these alternatives are called P-optimal.

By analogy with the concept of P-optimality, the concept of P-dominance can be introduced into consideration. If preferences in an MCDM problem are expressed in the form of FPR, these concepts can be expanded as follows.

Let P (or P^c) be an FPR reflecting fuzzy preferences (aggregated fuzzy preferences) on the initial set of alternatives according to some single criterion.

The following FPRs can be defined on the set of alternatives.

A fuzzy strict preference relation.

$$P^s = \frac{P}{P^{-1}} \tag{26}$$

with membership function values [13], [14]

$$\mu_{P^s}\left(a_i, a_j\right) = \max\left(\mu_P\left(a_i, a_j\right) - \mu_P\left(a_j, a_i\right), 0\right) \tag{27}$$

A fuzzy non-dominance relation.

If $\left(a_i, a_j\right) \in P^s$, an alternative a_j is strictly dominated by an alternative a_i , $\mu_{P^s}\left(a_j, a_i\right)$, $\forall a_i \in A$, denotes the value of the membership function on pairs of alternatives $\left(a_j, a_i\right)$ in which the alternative a_i is strictly dominated by all alternatives a_j . The complement of this FPR, $\bar{P}^s = 1 - P^s\left(a_j, a_i\right)$, $\forall a_i \in A$ includes the set of alternatives which are not strictly dominated by others. This set is formed by those alternatives that belong to the non-dominance FPR P^{ND} with the values of the membership function defined by expression [13], [14].

$$\mu_{P^{ND}}\left(a_i\right) = \min\left(1 - \mu_{P^s}\left(a_j, a_i\right)\right) = \\ = 1 - \max\left(\mu_{P^s}\left(a_j, a_i\right)\right) \tag{28}$$

The value $\mu_{P^{ND}}\left(a_i\right)$ reflects the degree to which the alternative a_i is not dominated by any of the alternatives of the set A.

The optimal alternative is the alternative a^{ND} that has the maximum value of the membership function $\mu_{P^{ND}}\left(a^{ND}\right)$ [13], [14].

$$a^{ND} = \left(a_i^{ND} \in A, \mu_{P^{ND}}\left(a_i^{ND}\right) = \max \mu_{P^{ND}}\left(a_i\right)\right) \tag{29}$$

If alternatives $a_i \in A$, $i = 1,...,m$, are evaluated by the values of a set of criteria $C = \left\{c_j \,/\, j = 1,...,n\right\}$, then the aggregated FPR P^G is defined as the intersection of the FPR Pj for each of the criteria [14]

$$P^G = \cap_{j=1}^{n} P_j \tag{30}$$

$$\mu_{P^G}\left(a_i, a_j\right) = \min_{1 \le j \le n} p_j\left(a_i, a_j\right), \ \forall a_i, a_j \in A \tag{31}$$

In this case, the set of alternatives $\left\{a_i^{ND}\right\}$ is Pareto optimal set.

Illustrative example 2. It is necessary to determine the optimal alternative based on the resulting FPR P^c from illustrative example 1.

Let us define a fuzzy relation of strict preference on FPR P^c. To do this, using expression (27), we calculate the values of the membership function for pairs of alternatives $\left(a_i, a_j\right) \in A$.

$$\mu_{P^s}\left(a_1, a_2\right) = \max\left(\mu_{P^c}\left(a_1, a_2\right), \mu_{P^c}\left(a_2, a_1\right), 0\right) = \\ = \max\left(0.58 - 0.42, 0\right) = \max\left(0.16, 0\right) = 0.16;$$

$$\mu_{P^s}\left(a_2, a_1\right) = \max\left(\mu_{P^c}\left(a_2, a_1\right) - \mu_{P^c}\left(a_1, a_2\right), 0\right) = \\ = \max\left(0.42 - 0.58, 0\right) = \max\left(-0.16, 0\right) = 0.$$

The remaining values $\mu_{P^s}\left(\cdot,\cdot\right)$ are calculated by analogy. We have the following FPR P^s

$$P^s = \begin{bmatrix} 0.00 & 0.16 & 0.30 & 0.87 \\ 0.00 & 0.00 & 0.35 & 0.66 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \end{bmatrix}.$$

Using (28), we determine the values of the membership function of alternatives to the set of non-dominated alternatives.

$$\mu_{P^{ND}}\left(a_1\right) = 1 - \max\left(\mu_{P^s}\left(a_2, a_1\right), \mu_{P^s}\left(a_3, a_1\right), \mu_{P^s}\left(a_4, a_1\right)\right) = \\ = 1 - \max\left(0.00, 0.00, 0.00\right) = 1.$$

$\mu_{P^{ND}}\left(a_i\right)$, $i = 2,3,4$, are calculated by analogy.

$\mu_{P^{ND}}\left(a_2\right) = 0.84$, $\mu_{P^{ND}}\left(a_3\right) = 0.63$, $\mu_{P^{ND}}\left(a_4\right) = 0.13$.

The optimal is alternative a_1 that strictly dominates all other alternatives.

Another, simpler method for determining the optimal alternative based on FPR is proposed in [12]. The idea of this method is similar to the idea implemented in the TOPSIS method. Let a set of alternatives $A = \left\{a_i \,/\, i = 1,...,n\right\}$ be given and let FPR P be defined on this set. Then, for each alternative a_i , the input and output preference flows are calculated

$$\phi^+\left(a_i\right) = \sum_{j=1, j \ne i}^{n} p_{ij} \ , \ i = 1,..,n \tag{32}$$

$$\phi^-\left(a_i\right) = \sum_{i=1, i \ne j}^{n} p_{ji} \ , \ j = 1,..,n \tag{33}$$

The net flow of preferences for an alternative a_i is defined as

$$\phi(a_i) = \phi^+(a_i) - \phi^-(a_i),\ i = 1,..,n \quad (34)$$

If the alternatives are evaluated by a set of criteria $C = \{c_j / j = 1,...,m\}$, then m values $\phi_j(a_i)$ can be calculated. These values are aggregated in a suitable way, for example by weighted averaging

$$\phi^G(a_i) = \sum_{j=1}^{m} w_j \phi_j(a_i), \quad (35)$$

where w_j is the weight of the j-th criterion.

Illustrative example 3. It is necessary to determine the optimal alternative based on the above method, using the FPR P^c from illustrative example 1.

Let us perform the necessary calculations using (33), (34) and (35).

$$\phi^+(a_1) = 0.58 + 0.68 + 0.93 = 2.19;$$
$$\phi^-(a_1) = 0.42 + 0.28 + 0.06 = 0.76;$$
$$\phi(a_1) = 2.19 - 0.76 = 1.43.$$

The remaining calculations are performed by analogy. As a result, we have

$$\phi(a_1) = 1.43;\ \phi(a_2) = 0.81;\ \phi(a_1) = 1.43;$$
$$\phi(a_4) = -1.90.$$

The optimal alternative is a_1 with the highest value of the pure preference flow $\phi(a_1) = 1.43$.

III. Results and Discussion

This article presents a method for analyzing and selecting decisions based on fuzzy preference relations (FPR). This method is very similar in its ideology to fuzzy versions of the AHP method. In all these methods, fuzzy results of pairwise comparisons of alternatives by preference for each criterion are used as initial data. The difference is that in all fuzzy versions of the AHP method, the results of pairwise comparisons are expressed in the form of fuzzy numbers. Instead, in the method based on FPR, the values of the membership function to FPR, reflecting the degrees of preference on pairs of alternatives, are used as estimating values.

This paper presents two approaches to selecting optimal decisions based on FPR. The first approach is based on performing various specific operations on FPR. This approach requires complex and extensive calculations; whereas the second approach requires simpler calculations and is more visual for participants in the process of evaluating and selecting decisions.

The article provides simple examples to illustrate the computational procedures. An example of constructing a compatible FPR on a large set of elements (criteria) is given in [16]. A hybrid approach including AHP and FPR is presented in [17]. In [18], a hybrid approach including fuzzy VIKOR and FPR is discussed.

Examples of applying FPR to solving practical problems are given in [19], [20].

It should be noted that the decision-making method based on FPR has not found such wide practical use as fuzzy versions of other well-known MCDM methods. However, this method has great potential for its wider use in practical MCDM problems.

Conclusions

Various versions of multi-criteria decision-making methods have become very widespread in almost all areas of human activity in recent decades. Unfortunately, these methods have not yet become widespread in Latvia.

The use of fuzzy versions of MCDM methods expands the possibilities for the successful application of the corresponding methods in conditions of extremely uncertain initial information.

The main factors for increasing the efficiency of using MCDM methods for solving practical problems are: (1) the availability of high-level specialists who can professionally select and use suitable MCDM methods in real choice situations; (2) increasing the confidence of potential users in the efficiency of using formal MCDM methods for solving their specific problems.

One of the objectives of this article is to popularize one of the specific methods of fuzzy MCDM in order to expand the scope of use of this and other methods for solving practical problems in various areas of economic and social life in Latvia.

References

[1] R. S. Stoll, Set Theory and Logic. San Francisco, CA: Dover Publications, 1979. [Assessed Dec. 11, 2024].

[2] E. F. Codd, "A Relational Model of Data for Large Shared Data Banks," Communication of the ASM, vol. 13, no. 6, 1970, pp. 377–387. [Assessed Dec. 08, 2024].

[3] L. A. Zadeh, "Similarity Relations and Fuzzy Orderings," Information Sciences, vol. 3, 1971, pp. 177– 200. Available: https://doi.org/10.1016/s0020-0255(71)80005-1. [Accessed December 10, 2024].

[4] S. Dutta and M. Chakraborty, "Fuzzy relation, fuzzy function over fuzzy sets: A retrospective," Soft Computing, vol. 19, no. 1, 2015, pp. 99–112. Available: https://doi.org/10.1007/s00500-014-1356-z. [Accessed December 12, 2024].

[5] S. E. Elmaghraby, "IV D. Fuzzy Relations," in Encyclopedia of Physical Science and Technology (Third Edition), Ramtech, Inc., Tarzana, California, USA, 2003. [Assessed Dec. 15, 2024].

[6] L. A. Zadeh, "The Linguistic Approach and Its Application to Decision Analysis," in Directions in Large-Scale Systems, Y. C. Ho et al. (Eds.), New York: Plenum Press, 1976, pp. 339-370. [Assessed Jan. 04, 2025].

[7] T. Tanino, "Fuzzy preference ordering in group decision making," Fuzzy Sets and Systems, vol. 12, 1984, pp. 117 – 131. Available: https://api.sematicscholar.org/CorpusID:122848934. [Accessed December 20, 2024].

[8] E. Herrera-Viedma, F. Herrera, F. Chiclana, and M. Lique, "Some issues on consistency of fuzzy preference relations," European

Journal of Operational Research, vol. 154, 2004, pp. 98 - 109. [Assessed Jan. 04, 2025].

[9] M. Xia and Z. Xu, "On Consensus in Group Decision Making Based on Fuzzy Preference Relations," in E. Herrera-Viedma et. al. (Eds.) Consensual Processes, STUDFUZZ 267, Springer Verlag, Berlin, Heidelberg, 2011, pp. 263–287. [Assessed Jan. 12, 2025].

[10] E. Herrera-Viedma, F. Chiclana, F Herrera, and S. Alonso, "Group Decision-Making Model With Incomplete Fuzzy Preference Relations Based on Additive Consistency," IEEE Transactions on Systems, Man, and Cybernetics, vol. 2, no. 1, 2007, 14 p.[Assessed January 12, 2025].

[11] V. Paneva and I. Popchev, "Aggregation of fuzzy preference relations to multicriteria decision making," Fuzzy Optimal Decision Making, vol. 6, 2007, pp. 351–365. Available: https://doi.org/10.1007/s.10700-007-9018-6. [Accessed January 9, 2025].

[12] Y.-M. Wang and Xh.-P. Fan, "Fuzzy preference relations: Aggregation and weight determination," Computers & Industrial Engineering, vol. 53, 2007, pp. 163–172. [Assessed Dec. 12, 2025].

[13] S.A. Orlovsky, "Decision making with a fuzzy preference relation," Fuzzy Sets and Systems, vol. 1, 1978, pp. 155-167. [Assessed Jan. 04, 2025].

[14] S. A. Orlovsky, Problem of Decision Making with Fuzzy Information. Moscow: Nauka, 1981. (in Russian). [Assessed Jan. 04, 2025].

[15] H. Borzęcka, "Multi-Criteria Decision Making Using Fuzzy Preference Relations," Operations Research and Decisions, no. 3, 2012, pp. 5–21. [Assessed Jan. 04. 2025].

[16] F. M. A. Alias and L. Abdullah. "Consistent Fuzzy Preference Relation Method and Its Application to Criteria Assessment of Quality of Life Among Population of Setiu Wetlands," Menemui Matematik (Discovering Mathematics), vol. 39, no. 2, 2017, pp. 52–60. [Assessed Dec. 05, 2024].

[17] J. Rezaei and R. Ortt. "Multi-criteria supplier segmentation using a fuzzy preference relations based AHP," European Journal of Operational Research, vol. 225, 2013, pp. 75–84. Available: http://dx.doi.org/10.1016/j.ejor.2012.09.037. [Accessed Jan. 15, 2025].

[18] H.-Th. Le and T.-Ch. Chu, "Ranking Alternative Using a Preference Relation-Based Fuzzy VIKOR Method," Axioms, 11, 2023. Available: https://doi.org/10.3390/axioms12121079. [Accessed January 21, 2025].

[19] N. Ibadov, "Contractor selection for construction project, with the use of fuzzy preference relation," Procedia Engineering, vol. 111, 2015, pp. 317–323. Available: https://doi.org/10.1016/j.proeng.2015.07.095. [Accessed February 3, 2025].

[20] N. Ibadov and J. Roslon, "Technology Selection for Construction Project, with the Use of Fuzzy Preference Relation," Archives of Civil Engineering, vol. LXI, no. 3, 2015, 105-118. Available: https://doi.org/10.1515/ace-2015-0028. [Accessed Febr. 4, 2025].

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 367-374

Integrating Digital Technologies to Enhance CSR Strategies for Retail Companies in Latvia

Velga Vevere
EKA University of Applied Science
Riga, Latvia
velga.vevere@gmail.com
Iveta Linina
Commerce Department
Turiba University
Riga, Latvia
iveta.linina@turiba.lv

Inga Shina
EKA University of Applied Sciences
Riga, Latvia
inga,shina@gmil.com
Rosita Zvirgzdina
Commerce Department
Turiba University
Riga, Latvia
rosita@turiba.lv

Malalgodapitiya Gamage Darika Nirujani Nanayakkara
EKA University of Applied Sciences
Riga, Latvia
madnn1991@gmail.com

***Abstract*—As sustainable practices grow in importance, Latvian companies must align their CSR strategies with environmental goals. Integrating digital technologies into CSR presents an opportunity for progress, innovation, and efficiency. Through this transformation, companies can benefit both themselves and the environment, reducing their ecological footprint and contributing to a sustainable future. Embracing this evolution in CSR demonstrates commitment to positive change and fosters collaboration among stakeholders. By combining sustainable practices with digital technologies, Latvian companies can lead in creating a greener business landscape. Adaptation and improvement of CSR strategies can make a lasting global impact on sustainable development. The goal of the research was to assess the ways in which retail companies in Latvia can utilize digital technologies to enhance their CSR strategies, with an emphasis on advocating for sustainable practices. To reach the goal the following tasks were set forth: (1) to research theoretical sources on CSR and digitalization, with a particular accent upon retail companies; (2) to work out empirical research methodology; (3) to carry out empirical research and interpret results. The main empirical research method employed was the online survey of retail customers (n=207). The findings suggest that digital technologies play a crucial role in improving companies' CSR capabilities. The findings show that opinions about the role of digital technology in CSR vary greatly depending on age and gender. Younger people, especially women, are very supportive of using digital tools in CSR, possibly because they are more familiar with technology and have a stronger awareness of environmental issues. On the other hand, the responses from older age groups show a mix of opinions, indicating the need for specific awareness campaigns and training to bridge the confidence gap. To effectively incorporate digital technologies into CSR efforts, retail companies need to customize their strategies to accommodate these demographic differences to promote widespread and inclusive adoption.**

Keywords*— *Digital Technologies; Retail Industry; Corporate Social Responsibility; Sustainability; Resource Optimization

I. INTRODUCTION

The topicality of this study lies in addressing the pressing need for Latvian companies to enhance their CSR (corporate social responsibility) strategies amidst slow progress and incomplete implementation of reforms, as highlighted by the 2023 European Semester reviews. Despite some advancements, with 54% progress on CSR-related recommendations, significant challenges remain in achieving comprehensive and effective CSR outcomes. This research is particularly relevant as it explores how digital technologies, such as AI (Artificial Intelligence), blockchain, and IoT (Internet of Things), can optimize CSR strategies to improve environmental sustainability, social responsibility, and economic resilience [1].

By focusing on Latvian companies especially on the retail industry, this study not only addresses local barriers and challenges but also aims to provide actionable insights and recommendations for leveraging technology to overcome these obstacles, making it a timely and impactful contribution to the field. It is important to note that the integration of these digital technologies has the potential to revolutionize the way these companies approach CSR, enabling them to streamline their processes, automate certain tasks, and enhance overall efficiency. For instance, AI can be used to analyse large volumes of data and identify patterns and trends related to CSR performance, helping companies gain valuable insights and make data-driven decisions. On the other hand, blockchain technology

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8579
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

can improve transparency and accountability in CSR initiatives by providing a decentralized and immutable ledger to track and verify social and environmental impacts. As for IoT, it enables real-time monitoring and reporting of sustainability metrics, facilitating proactive management and timely interventions to address emerging issues [2].

Digital technologies, such as mobile devices, data analytics, cloud computing systems, broadband internet, and various social media platforms, have rapidly emerged and gained prominence in the past several years. The widespread adoption of these digital technologies has led to significant transformations across various domains, including marketing and sales. However, when it comes to the realm of CSR (corporate social responsibility) practices, the impact of digital technologies has been relatively limited, with only a handful of companies leveraging these technologies to drive their CSR initiatives [3]. Nevertheless, it is important to recognize the potential of digital technologies in shaping and enhancing CSR practices. The development and advancement of digital technology have paved the way for the emergence of numerous applications and platforms that offer public value to citizens. For instance, mobile health applications have revolutionized healthcare services, e-government services have streamlined administrative processes, and consumer behaviour in the realm of mobile culture (m-culture) has opened new possibilities for engaging with the public. These applications, fuelled by digital technology, have the potential to contribute to the economic, environmental, social, and governance aspects of corporate social responsibility, benefiting both the community and the entities involved [4] – [5]. As a result, the relevance of utilizing digital technologies in CSR practices cannot be understated. In the absence of a well-defined strategy that integrates digital communications into key societal transformation and improvement areas, disparities and gaps in the provision of public value can arise, impeding overall growth. To address this challenge, countries have embraced the need for designing comprehensive strategies that align digital technology applications with meaningful societal and business outcomes. By strategically connecting digital technologies to CSR initiatives, countries can leverage the power of these technologies to drive positive changes in society and foster mutually beneficial relationships with various stakeholders [6].

Digital technologies have revolutionized numerous aspects of our lives, including marketing, sales, and healthcare. However, their impact on CSR practices has been relatively limited. It is crucial for businesses and societies to recognize the potential of digital technologies in enhancing CSR initiatives and driving positive societal change. By embracing these technologies and developing comprehensive strategies, countries can create an enabling environment for integrating digital technology applications into CSR practices, ultimately leading to improved public value and sustainable development [7].

Corporate Social Responsibility (CSR) has been defined as composed of three elements of alliance between workers, companies, and the government, with differing strategies observed in various nations. As articulated by Velga Vevere and Anna Svirina in the publication "Business Ethics and Corporate Social Responsibility," CSR entails a voluntary pledge to incorporate social and environmental considerations into business activities and engagements with stakeholders. Globally, there exist multiple CSR models, each emphasizing various degrees of government participation, extending from engagement at the national level to regulations at the enterprise level [8].

At the same time, the digital era creates new opportunities and challenges in communication of the CSR activities [9] – [10].

The goal of the current research is to identify how digital technologies can enhance CSR strategies for companies in Latvia, focusing on improving environmental sustainability, social responsibility and economic resilience.

II. MATERIALS AND METHODS

Corporate Social Responsibility (CSR) is crucial for companies as it involves actively considering social, environmental, and economic issues in their business operations and relationships with stakeholders. Prioritizing CSR not only ensures compliance with legal requirements but also entails going above and beyond to tackle societal problems through ethical and sustainable business practices. The European Commission [11] defines CSR as a commitment by companies to embrace their responsibilities and contribute to positive societal change. Carroll's [12] pyramid of CSR is a comprehensive framework that emphasizes four key areas that companies should address: economic responsibilities, which involve generating profits and providing a return on investment to shareholders; legal responsibilities, which entail compliance with laws and regulations; ethical responsibilities, which encompass adhering to ethical principles and values in decision-making processes; and philanthropic responsibilities, which encompass giving back to communities and engaging in social initiatives to make a positive impact. By integrating CSR into their core business strategies, companies can establish themselves as socially and environmentally responsible entities, enhance their reputation, and build trust among their stakeholders. This not only benefits society by addressing pressing issues such as climate change, inequality, and poverty but also fosters long-term sustainability and competitiveness for the companies themselves [13]. CSR serves as a guiding principle for companies to actively contribute to social progress and sustainability. By proactively addressing economic, legal, ethical, and philanthropic responsibilities, companies can create a positive impact on society while ensuring their long-term success in an interconnected and socially aware world [14].

The concept of corporate social responsibility (CSR) in Latvia has gained significant prominence since the country acceded to the European Union in 2004. Initially, CSR was primarily driven by the need to comply with EU directives, especially those of environmental protection, labour rights,

and sustainable business practices [15]. However, as time passed and the awareness of the importance of CSR grew, Latvian businesses started embracing a more comprehensive approach to CSR, drawing inspiration from global trends and the increasing consciousness of consumers. These factors have played a crucial role in shaping and expanding the scope of CSR practices within the country's corporate landscape, encompassing not only environmental and labour concerns but also ethical sourcing, community engagement, and philanthropy. As a result, Latvian companies have been actively implementing CSR initiatives that prioritize sustainable growth, social impact, and long-term value creation. By ensuring responsible and transparent business practices, they have not only met the legal requirements imposed by the EU but also become key stakeholders in the sustainable development of Latvia. This commitment to CSR has not only enhanced the reputation and competitiveness of Latvian businesses on both domestic and international fronts but has also contributed to the overall well-being of society and the environment. With the growing importance of CSR, it is expected that more Latvian companies will continue to embrace and further expand their initiatives, making a positive and lasting impact on various stakeholders and ensuring a sustainable future for the country. Between the years 2019 and 2022, Latvia witnessed a remarkable and praiseworthy 54% increase in the realm of CSR progress, as diligently assessed and evaluated through the lens of European Semester reviews. This notable growth is a testament to the dedication and zeal that both the Latvian government and businesses have exhibited towards embracing the essence of CSR. Yet, this surge in progress should not overshadow the pressing reality that sustains the need for even stronger and more effective strategies. It is imperative that the integration of CSR principles into corporate governance practices be further enhanced and strengthened in order to make lasting and impactful changes [16].

Notably, in Latvia, prominent retail chains like RIMI, MAXIMA, and LIDL have emerged as key players spearheading CSR initiatives. These retail giants have adeptly aligned their strategies with global trends while navigating and addressing unique local challenges. This transformative approach beautifully signifies their deepened commitment towards creating a positive impact on society and the environment. As the retail landscape continues to evolve, it becomes increasingly evident that CSR is no longer a mere buzzword but a fundamental aspect of responsible business practices. Industry leaders recognize that the integration of ethical and sustainable principles is not only crucial for meeting customer demands but also for fostering long-term success. By adopting and implementing robust CSR initiatives, retailers can not only enhance their brand reputation but also contribute positively to the communities they serve and safeguard the delicate ecological balance.

The reports and success stories from the leading retail chains [17] – [18]. underline the significant strides made by the industry in embracing CSR. As consumers become increasingly mindful of the environmental and social impacts of their purchases, retailers must prioritize CSR as a strategic imperative, thereby cementing their position as pillars of positive change within society and the global marketplace.

The development of digital technology in Corporate Social Responsibility (CSR) in Latvia demonstrates the incorporation of advanced methods and sustainable strategies to adhere to worldwide trends. Latvia's advancement towards digital transformation in CSR can be categorized into three phases: the commencement of digitalization, the assimilation of digital tools, and the compliance with the European Union's Digital Decade framework. In the first phase, the commencement of digitalization, Latvia recognized the significance of integrating digital technology into CSR practices. This initial step involved identifying the potential benefits and challenges of digitalization and establishing a foundation for further development. The second phase, the assimilation of digital tools, marked a significant shift in Latvia's approach to CSR. Digital tools and platforms were embraced to enhance communication, efficiency, and transparency in CSR initiatives. These tools empowered businesses and organizations to engage with stakeholders, facilitate collaboration, and track the impact of their CSR efforts. The final phase of Latvia's digital transformation in CSR revolves around compliance with the European Union's Digital Decade framework. This framework sets ambitious targets for the digitalization of various sectors, including CSR. Latvia's commitment to this framework ensures that its digital strategy aligns with EU guidelines and harnesses the full potential of digital technology to drive positive social and environmental change. By combining these three phases, Latvia has successfully leveraged digital technology to strengthen its CSR initiatives. The incorporation of advanced methods and sustainable strategies has not only positioned Latvia at the forefront of digital innovation but also enabled the country to contribute significantly to global CSR trends. Through continued dedication to digital transformation, Latvia will undoubtedly continue to shape the future of CSR in the digital era [19].

Digital technologies are highly essential tools that can be effectively utilized in the design and implementation of Corporate Social Responsibility (CSR) strategies. In general, the role played by these digital technologies is often overlooked and not adequately explained. The deployment and influence of digital technologies are often described superficially, failing to grasp their true potential. Simultaneously, it is of utmost importance to emphasize the purpose of the field extensively. To truly showcase a company's contribution to society, it becomes crucial to establish a comprehensive and interactive platform that visualizes and highlights these efforts. Furthermore, digital technologies can be utilized as a powerful instrument for analysing the breadth and depth of changes within CSR policies. They can expand the company's horizon, enabling a wider understanding of societal needs and facilitating the design of effective CSR actions. These technologies

provide the capability to utilize real-time or big data sources for performance monitoring, social investment evaluation, and the management of a dynamic portfolio of CSR initiatives. With these digital tools at hand, companies can greatly enhance their CSR endeavours, ensuring a more impactful and sustainable approach in their contributions to society [20]. In Latvia, companies have recognized the immense potential of AI-driven technology and are progressively utilizing it to carefully monitor their environmental impact and develop sophisticated waste management systems. By leveraging these digital platforms, organizations now have the unprecedented ability to foster enhanced transparency, establish robust relationships with stakeholders, and ultimately bolster corporate responsibility while instilling a heightened level of public confidence in their operations [21]. Corporate collaborations with government initiatives have promoted the harmonization of CSR activities with the digitalization objectives of the nation. An example of this is the use of digital reporting and data analysis tools to assist companies in assessing and enhancing their social and environmental footprint in a more efficient manner.

One of the major challenges in the implementation of a digital CSR strategy for companies is the need to demonstrate beneficial results for internal and external stakeholders. The reality is that with new digital tools, positive results can only be seen after a certain time. In addition, the costs can be significant, and expected outcomes may be hard to measure. Organizations may lack key team members, and differences in experience, attention, energy, engagement, and expectation are common. Investments in this area may also be made without prior consideration of how potential future approaches to stakeholder engagement might change as digital technology evolves. The issue is not just about changing communication technology but also about how society's use of technology and labour shapes expectations and needs [22].

The current research methodology was designed considering the developments and challenges. To investigate how digital technologies can enhance CSR strategies for the retail companies in Latvia, focusing on improving environmental sustainability, social responsibility, and economic resilience, this study utilized an online survey as the main method for gathering data. The purpose of the survey was to collect information about how retail companies in Latvia, including RIMI, MAXIMA, and LIDL, are using digital technologies to improve their Corporate Social Responsibility (CSR) strategies. The questions were created to understand different views on awareness, attitudes, and hopes regarding CSR actions and the use of digital methods. The survey allowed participants to provide detailed feedback and in-depth information on their shopping habits, brand preferences, shopping frequency, online purchasing behaviour, awareness regarding sustainable retail practices, and beliefs about corporate social responsibility (CSR) and the use of digital technologies in sustainable retail. The survey was created and shared using Google Forms, a user-friendly platform known for its simplicity, accessibility, and wide distribution capabilities, ensuring that the survey reached a diverse range of participants and collected comprehensive data. Furthermore, Google Forms automatically stores the data in Excel format, facilitating efficient data analysis. The sampling method was the snowball sampling one. The link to the survey was sent to a number of identified retail customers with a kind request to distribute to the target audience. To minimize the potential sampling bias, the original link was sent to a diverse set of respondents, who exhibited different demographic profiles (gender, age, education, income level, etc.). Thus, the total number of 207 responses was reached [23]. In our opinion, this number of responses allows us to conclude the main tendencies regarding the integration of digital technologies to enhance CSR activities in retail companies in Latvia.

The role of digital technologies in CSR formed a core theme of the survey. Respondents were asked whether they believe technologies like AI, blockchain, mobile applications, social media, or IoT can enhance CSR efforts, with follow-up questions exploring observed usage of such tools (e.g., apps promoting sustainability or digital waste management systems). The survey further investigates perceptions of these technologies' effectiveness in ensuring transparency and their influence on customer preferences, such as choosing stores that actively use technology for sustainability. Finally, it delves into trust and advocacy, assessing whether technology-driven CSR initiatives increase trust in the retailer and the likelihood of recommending such stores. To gauge future expectations, the survey concludes by asking respondents to rate the importance of adopting advanced digital technologies in CSR activities over the next five years, emphasizing the evolving role of innovation in retail sustainability.

Participants were requested to rate specific statements on a scale of 1 to 5, where 1 represented strong disagreement, 5 represented strong agreement, and 3 represented neutral attitude. These carefully crafted statements not only measured participants' attitudes towards CSR efforts, digital sustainability tools, and overall trust in technology-based retail practices, but also delved deeper into their motivations, preferences, and behaviours related to sustainable consumption. By including such nuanced statements in the survey, this study aimed to capture a holistic view of participants' opinions and perceptions on sustainable retail, enabling researchers to draw robust conclusions and insights from the collected data.

The survey included three sections. The initial portion aimed to gather comprehensive and detailed demographic details, encompassing a wide range of factors such as age range, income level, educational background, occupation, and geographic location. Moving on to the second part of the survey, it sought to assess not only the extent of respondents' knowledge about CSR initiatives carried out by retail chains but also their attitudes, opinions, and experiences related to these initiatives. In addition to exploring their awareness of CSR efforts undertaken by popular retail chains such as RIMI, MAXIMA, and LIDL, the questions delved into the participants' level of engagement with these stores and the frequency of their

visits. This comprehensive approach aimed to uncover valuable insights into the participants' shopping behaviour, enabling a deeper analysis of the correlation between their knowledge of CSR initiatives and their choices as consumers. This included initiatives such as waste reduction, recycling, and sustainability promotion. The questionnaire's third section assessed the impact of digital technologies on enhancing corporate social responsibility (CSR) initiatives. It extensively covered various aspects of technology, including the awareness and utilization of digital tools such as sustainability apps and waste management systems. Moreover, it aimed to evaluate the effectiveness of these tools in promoting transparency within organizations. Additionally, the section explored the influence of digital technologies on consumers' purchasing decisions. Respondents were asked about their preferences for shopping at stores that incorporate technology to achieve environmental sustainability. Furthermore, the section delved into the significance of digital innovations in the context of CSR over the next five years. To measure the respondents' awareness, credibility, and the potential influence of digital tools on their purchase intentions and trust in retailers, scaled questions were utilized in each subsection. Data was analysed by the means of descriptive statistics.

III. RESULTS AND DISCUSSION

The survey gathered data from individuals aged 18 and older, encompassing various socio-economic and professional backgrounds. The questionnaire covered several key areas, including awareness of CSR initiatives, the perceived importance of digital technologies in CSR, and preferences for technology-enhanced CSR practices. The respondents were grouped into different age brackets—18-24, 25-34, 35-44, 45-54, and 55+, ensuring a generationally diverse understanding of consumer attitudes and expectations. The examination of the distribution of age groups based on the survey data showed that the majority of survey takers are between the ages of 31 and 50, making up 40.1% of the total respondents. This indicated that middle-aged individuals were the main group involved in the CSR-related initiatives and technologies in retail settings. The age group of 18-30 made up 34.3% of respondents, showing significant participation from younger adults who are often the first to adopt technology and advocate for sustainability. Participants aged 51 and older comprised 15%, indicating a moderate level of engagement from older individuals. Lastly, those under 18 represented 10.6%, showing the least participation but still indicating interest in CSR activities among younger generations. These findings highlighted the importance of customizing CSR and technology strategies to accommodate the preferences and levels of engagement of middle-aged and younger adult consumers, who make up the largest groups.

Figure 1 presents the summary chart of attitudes to the CSR by age and gender.

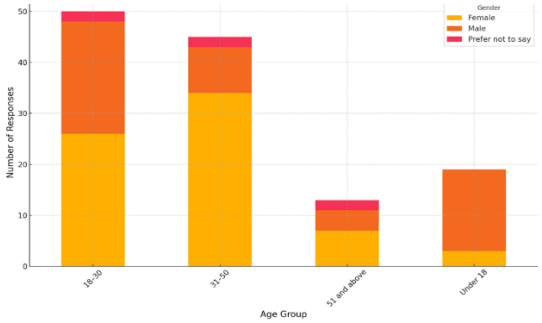


Fig. 1. Analysis of age group, gender vs CSR awareness

The chart provides valuable insights into the varying levels of awareness of Corporate Social Responsibility (CSR) among different age groups and genders, specifically focusing on the affirmative responses. It sheds light on intriguing patterns, such as the notably higher awareness levels observed in females aged 31-50, indicating a remarkable interest in engaging in CSR activities within this demographic. Surprisingly, males under the age of 18 exhibit a substantial level of awareness compared to their counterparts in other male age groups. Conversely, both genders in the 51-and-above age group exhibit relatively lower levels of awareness, suggesting the necessity for more targeted outreach endeavours. These significant findings underscore the critical importance of tailoring CSR communication strategies to suit the specific demographic groups, particularly with regards to older audiences and males within certain age ranges, to foster greater levels of engagement and awareness surrounding CSR initiatives.

The survey found that respondents were highly aware of the Corporate Social Responsibility (CSR) activities carried out by retail stores like Rimi, Maxima, and Lidl. Many participants mentioned initiatives such as the promotion of environmentally friendly bags and the support of local farmers as noteworthy CSR practices. However, while some respondents were able to identify specific efforts, others had limited knowledge of ongoing initiatives, indicating the need for improved communication and visibility. The findings emphasize the importance not only of implementing impactful CSR programs, but also of ensuring that they are accessible and transparent to the customer base. Enhanced digital tools could be key in bridging this gap and promoting greater engagement and trust among consumers.

The importance of CSR activities for the customers the results are depicted in Table 1.

The results appear to be relatively stable with a low spread, a slightly left-skewed distribution, and a more peaked shape than a normal distribution. The coefficient of variation suggests low dispersion relative to the mean, meaning the values do not fluctuate wildly. The results of the survey underscore the high level of importance for retail companies to engage in activities that have a positive impact on society and the environment. A large majority of participants rated this as extremely crucial, with most

giving it a score of 5 on a scale from 1 to 5. Survey takers pointed out that such initiatives not only build trust in the brand but also influence their shopping choices, leading them to favour retailers that prioritize societal and environmental responsibilities.

TABLE 1 IMPORTANCE OF CSR ACTIVITIES FOR CUSTOMERS

Descriptive statistics indicators					
Arithmetic mean	***Median***	***Mode***	***Standard deviation***	***Kurtosis***	***Coefficient of variation***
3,9	4	4	0,.64	3.751	0.199

Based on the survey results, most participants have noticed that retail chains like Rimi, Maxima, and Lidl are using digital tools to support their CSR efforts. These tools range from apps promoting sustainability to digital waste management systems. Survey respondents gave examples such as apps that encourage customers to recycle, digital platforms for reducing food waste, and IoT-based systems that monitor energy use in stores. These technologies are seen as improving CSR activities and also as a way to build customer trust and loyalty by showing a commitment to environmental and social sustainability. However, some respondents mentioned not noticing these technologies, highlighting the need for more visibility and customer education about these initiatives. This suggests that there is potential for these retail chains to better implement and communicate digital tools to ensure their impact is widely recognized and valued (see Table 2).

TABLE 2 VALUATION OF USE OF DIGITAL TECHNOLOGIES PROMOTING CSR ACTIVITIES

Descriptive statistics indicators					
Arithmetic mean	***Median***	***Mode***	***Standard deviation***	***Kurtosis***	***Coefficient of variation***
3,85	4	4	0.758	4.14	0.197

Based on survey feedback, digital technologies are seen as extremely successful in promoting transparency in a company's CSR endeavours. Most participants ranked their efficiency as top-notch, stressing that methods such as blockchain and IoT increase trust through the provision of up-to-date details on supply chain operations and sustainability projects. These tools empower consumers to validate assertions about ethical sourcing, waste minimization, and energy efficiency, promoting a feeling of responsibility. The data is fairly stable with low variability. The most common value is 4, and the median is also 4, indicating a balanced dataset. The distribution is peaked with more frequent extreme values (outliers). The low coefficient of variation confirms consistent data with little fluctuation. This indicates a trend among consumers where technology-driven environmental responsibility is playing a significant role in brand loyalty and trust. Retailers who adopt these strategies are in a good position to build stronger relationships with customers and establish a reputation for sustainability and innovation. Consumers believe that the use of technology in CSR, such as sustainability-promoting apps and blockchain for supply chain transparency, reflects a company's genuine dedication to environmental and social causes. This alignment of technological advancement with ethical standards not only increases trust but also reinforces the perceived honesty of retail brands like Rimi, Maxima, and Lidl.

The survey on perceptions of integrating digital technologies into corporate social responsibility (CSR) initiatives across different age groups and genders reveals a multitude of fascinating patterns (see Fig.2).

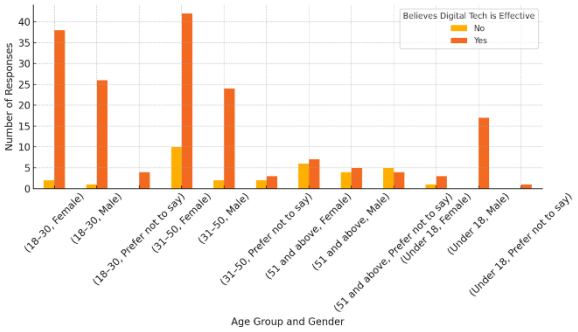


Fig. 2. Analysis of age group, gender vs CSR awareness

It becomes apparent that individuals aged 18-30, irrespective of their gender, wholeheartedly believe in the immense power of digital tools such as artificial intelligence (AI), the Internet of Things (IoT), and blockchain to significantly enhance CSR activities. This remarkable level of enthusiasm is particularly evident among females within this age bracket, as they overwhelmingly express their unwavering support for the utilization of digital technologies in CSR endeavours. Furthermore, males and those individuals who prefer not to disclose their gender within the same age group also demonstrate significant agreement, albeit slightly less pronounced. The results from this survey serve as a testament to the fact that younger individuals possess a heightened awareness regarding the tremendous potential of digital innovations to promote transparency, sustainability, and create a profound impact within the realm of CSR. It is, therefore, crucial for organizations to acknowledge and capitalize on this remarkable outlook among the younger generation to further drive positive change and advancements in the field of corporate social responsibility.

And also, 31-50 age group shows a wider range of responses. Even though most in this group also believe in the impact of digital technologies on CSR, a significant number of both women and men express doubts or a lack of support. This difference may be due to different levels

of familiarity or trust in these technologies. It is worth noting that while men in this age group show slightly less support compared to women, overall, there is recognition of the potential benefits of digital integration in CSR. These results highlight the significance of demographic factors in the development and execution of technology-based CSR initiatives.

Therefore, these findings show that opinions about the role of digital technology in CSR vary greatly depending on age and gender. Younger people, especially women, are very supportive of using digital tools in CSR, possibly because they are more familiar with technology and have a stronger awareness of environmental issues. On the other hand, the responses from older age groups show a mix of opinions, indicating the need for specific awareness campaigns and training to bridge the confidence gap. To effectively incorporate digital technologies into CSR efforts, retail companies need to customize their strategies to accommodate these demographic differences to promote widespread and inclusive adoption.

IV. CONCLUSIONS

The integration of digital technologies into corporate social responsibility (CSR) strategies offers a transformative opportunity for retail companies operating in Latvia. These technologies, including mobile applications, social media, artificial intelligence (AI), blockchain, and the Internet of Things (IoT), have already shown significant benefits. It helped to enhance transparency, improve efficiency, and deepen consumer engagement. Through the implementation of these digital tools, retail companies of Rimi, Maxima, and Lidl are able to optimize their resource utilization, enhance supply chain transparency, with cultivate community trust.

The results of the survey disclose the intriguing patterns regarding awareness of CSR activities, such as the notably higher awareness levels observed in females aged 31-50, indicating a remarkable interest in engaging in CSR activities within this demographic. Surprisingly, males under the age of 18 exhibit a substantial level of awareness compared to their counterparts in other male age groups. Conversely, both genders in the 51-and-above age group exhibit relatively lower levels of awareness, suggesting the necessity for more targeted outreach endeavours. These significant findings underscore the critical importance of tailoring CSR communication strategies to suit the specific demographic groups, particularly concerning older audiences and males within certain age ranges, to foster greater levels of engagement and awareness surrounding CSR initiatives.

Most of the respondents have noticed that retail chains like Rimi, Maxima, and Lidl are using digital tools to support their CSR efforts. These tools range from apps promoting sustainability to digital waste management systems. Survey respondents gave examples such as apps that encourage customers to recycle, digital platforms for reducing food waste, and Internet of Things-based systems that monitor energy use in stores. These technologies are seen as improving CSR activities and also as a way to build customer trust and loyalty by showing a commitment to environmental and social sustainability.

Digital technologies are seen as extremely successful in promoting transparency in a company's CSR endeavours. Most participants ranked their efficiency as top-notch, stressing that methods such as blockchain and IoT increase trust through the provision of up-to-date details on supply chain operations and sustainability projects.

Future Trends in Digital CSR. Looking ahead, the future of CSR in Latvia's retail sector lies in adopting advanced technologies like advanced mobile apps, AI-driven analytics, enhanced blockchain applications, and sophisticated data analytics. These innovations are expected to improve efficiency, enable risk prediction, and foster greater consumer engagement in sustainability initiatives. By embracing these trends, retail companies in Latvia can ensure that their CSR strategies remain impactful, relevant, and aligned with both societal expectations and global sustainability goals.

REFERENCES

[1] European Commission, "2023 Country Report – Latvia" Comission Staf Working Document, 2023. [Online] Available at: https://economy-finance.ec.europa.eu/system/files/2023-05/LV_SWD_2023_614_en.pdf [Accessed February 15, 2023].

[2] P. G. Cardinali and P. Giovanni, "Responsible digitalization through digital technologies and green practices," Corporate Social Responsibility and Environmental Management, vol. 29(4), pp. 984–995, 2022.

[3] K. S. Al-Omoush, B. Ribeiro-Navarrete and W. C. McDowell, "The impact of digital corporate social responsibility on social entrepreneurship and organizational resilience", Management Decision, vol. 62 (8), pp. 2621-2640, 2024.

[4] M. Karwowski and M. Raulinajtys‐Grzybek, „The application of corporate social responsibility (CSR) actions for mitigation of environmental, social, corporate governance (ESG) and reputational risk in integrated reports", Corporate Social Responsibility and Environmental Management, vol. 28(4), pp. 1270-1284, 2021.

[5] M. Ahmad, Q. Wu, and S. Ahmed, (2024). "Does CSR digitalization improve the sustainable competitive performance of SMEs?" Sustainability Accounting, Management and Policy Journal, vol. 15(1), pp. 119–147, 2024.

[6] C. N. X. Chen, X. Chen, X. Li, Y. Li and X. Wang, "Digital transformation of value chains and CSR performance", Sustainability, vol. 14 (16), 10245, 2022. [Online] Available: https://www.mdpi.com/2071-1050/14/16/10245 [Accessed January 10, 2025].

[7] J. Hwang, "Corporate Social Responsibility (CSR) in the Digital Age: Investigating the challenges and future insights", GSC Advanced Research and Reviews, vol. 21(01), pp. 503-518, 2024.

[8] V. Vevere and A. Svirina, Business Ethics and Corporate Social Responsibility. Riga: EKA University of Applied Sciences, 2020.

[9] L. Illia, S. Romenti, B. Rodríguez-Cánovas, G. Murtarelli & C. E. Carroll, "Exploring corporations' dialogue about CSR in the digital era", Journal of Business Ethics, vol. 146(1), pp. 39-58, 2017.

[10] G. Tomaselli & M. Melia, "The role of interactive technologies for CSR communication", Journal of International Scientific Publications: Economy & Business, vol. 8, pp. 324-340, 2014.

[11] European Commission, "Corporate Social Responsibility: a new definition, a new agenda for action" [Online] Available:

https://ec.europa.eu/commission/presscorner/detail/en/memo_11_730 [Accessed January 10, 2025].

[12] A. Carroll, "The Pyramid of Corporate Social Responsibility: Toward the Moral Management of Organizational Stakeholders", Business Horizons, vol. 34(4), pp. 39-48, July 1991.

[13] T. T. Le, "Corporate social responsibility and SMEs' performance: Mediating role of corporate image, corporate reputation, and customer loyalty", International Journal of Emerging Markets, vol. 18(10), pp. 4565-4590, 2023.

[14] A. Elalfy, N. Palaschuk, D. El-Bassiouny, J. Wilson and O. Weber, "Scoping the evolution of corporate social responsibility (CSR) research in the sustainable development goals (SDGs) era", Sustainability, vol. 12(14), 5544, 2020. [Online] Available: https://www.mdpi.com/2071-1050/12/14/5544 [Accessed January 10, 2025].

[15] A. Petersons and G. King, Gundar, (2009). "Corporate social responsibility in Latvia: A benchmark study", Baltic Journal of Management, vol. 4, pp. 106-118., 2009.

[16] O. Ņikadimovs, (2023). "Corporate Social Responsibility–Assessment of Facilitating and Impeding Factors for Small and Medium-sized Enterprises in Latvia", European Integration Studies, vol. 17, 2023. [Online] Available: file:///C:/Users/velga/Downloads/33542-Article%20Text%20-126225-1-10-20230915.pdf [Accessed December 20, 2024].

[17] "Rimi Corporate Responsibility Report," 2021 [Online] Available: https://www.rimibaltic.com/rimi-corporate-responsibility-report-2021 [Accessed January 10, 2025].

[18] "Maxima Consolidated Annual Report", 2022. [Online] Available: https://www.maximagrupe.eu/uploads/MG%2520Consolidated%2520Annual%2520Report%25202022.pdf [Accessed January 10, 2025].

[19] O. Ņikadimovs, (2023). "Corporate Social Responsibility–Assessment of Facilitating and Impeding Factors for Small and Medium-sized Enterprises in Latvia", European Integration Studies, vol. 17, 2023. [Online] Available: file:///C:/Users/velga/Downloads/33542-Article%20Text%20-126225-1-10-20230915.pdf [Accessed December 20, 2024].

[20] P. G. Cardinali and P. Giovanni, "Responsible digitalization through digital technologies and green practices," Corporate Social Responsibility and Environmental Management, vol. 29(4), pp. 984–995, 2022.

[21] H. Nwariaku, B. Fadojutimi, L.Gertrude, L. Lawson, J. Jumoke, J. Udom and T. Olajide, "Blockchain technology as an enabler of transparency and efficiency in sustainable supply chains", Electronic Research Archive, 1779-1789, 2024. [Online] Available: https://www.researchgate.net/publication/383201302_Blockchain_technology_as_an_enabler_of_transparency_and_efficiency_in_sustainable_supply_chains [Accessed December 19, 2024].

[22] [6] C. N. X. Chen, X. Chen, X. Li, Y. Li and X. Wang, "Digital transformation of value chains and CSR performance", Sustainability, vol. 14 (16), 10245, 2022. [Online] Available: https://www.mdpi.com/2071-1050/14/16/10245 [Accessed January 10, 2025].

[23] J. T. Chan, "Snowball Sampling and Sample SeleCtion in a SoCial network," in Econometrics of networks. Advances in Econometrics, vol. 42, 2020, pp. 61–80.

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 375-382

Data Centre Monitoring Model Utilizing Artificial Intelligence, Machine Learning and Anomaly Detection Algorithms

Roberts Volkovičs
Vidzeme University of Applied Sciences
Valmiera, Latvia
roberts.volkovics@va.lv

***Abstract* - In this article the review is created of architectures of popular data centre monitoring tools and corresponding information processing techniques are summarised. Pros and cons analysis of the monitoring tools is done and novel approach is offered by utilizing Artificial Intelligence (AI), Machine Learning (ML) and Anomaly Detection (AD) algorithms to achieve research goals and prove hypothesis that data centre level monitoring model could be built using combined AI, ML and AD techniques. Oracle performance metric data are collected to perform the information analysis from such angles the most modern enterprise monitoring tools do not provide yet.**

Keywords — Data Centre, Monitoring, Tools and Techniques, Artificial Intelligence, Machine Learning, Anomaly Detection, Algorithms, Model.

I. Introduction

As the first enterprise grade data centre monitoring tool Oracle Enterprise Manager or Cloud Control will be described in the review.

In Oracle documentation [1] we can find the architecture diagram of Oracle Enterprise manager, see "Fig. 1".

As diagram shows, Oracle Enterprise Manager consists of several components, such as "Oracle Database Management Repository", "Oracle Management Service or OMS", "JVMD Engine", "Cloud Control Console" and "Oracle Management Agents with Plug-ins".

Each of the mentioned components serves for dedicated purpose. For example, The Oracle Management Repository (Management Repository) is a storage location where all the information collected by the Management

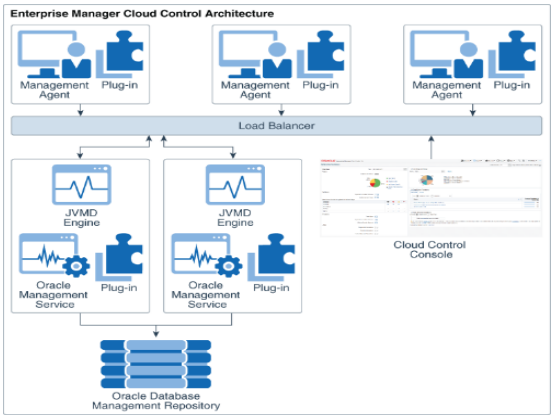


Fig. 1 Oracle Enterprise Manager architecture.

Agent gets stored. It consists of objects such as database jobs, packages, procedures, views, and tablespaces [1].

The OMS uploads the monitoring data it receives from the Management Agents to the Management Repository. The Management Repository then organizes the data so that it can be retrieved by the OMS and displayed in the Enterprise Manager Cloud Control console. Since data is stored in the Management Repository, it can be shared between any number of administrators accessing the Enterprise Manager Cloud Control [1].

Oracle Enterprise Manager is one of the best monitoring tools in the market with very rich built-in functionality to monitor Oracle software products starting from Oracle database, Oracle Linux operating system, Oracle Middleware and many more.

Oracle Enterprise manager as we can see in "Fig. 1" has as well a rich offer of different Plug-ins which support

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8565
© 2025 The Author(s). Published by RTU PRESS.
This is an open access article under the Creative Commons Attribution 4.0 International License.

the monitoring of products from other vendors, for example, IBM's Db2 database.

In case one would like to have a rich set of standard monitoring functionality for Oracle centric environment then Oracle Enterprise manager or Cloud Control could be very sound choice to star with.

In "Fig. 2" we can see Zabbix monitoring tool architecture diagram [2].

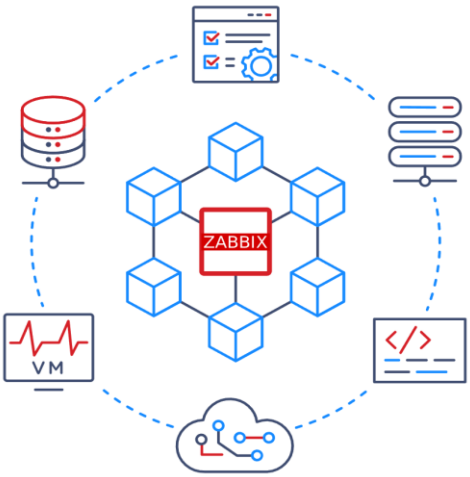


Fig. 2 Zabbix architecture.

Zabbix monitoring tool from practical perspective is much more suitable for general purpose monitoring if we compare it to Oracle Enterprise Manager. Zabbix monitoring tool consists of such components as: "Server", "Agent", "Agent 2", "Proxy", "Java gateway", "Sender", "Get", "Js" and "Web service".

The server performs the polling and trapping of data, it calculates triggers, sends notifications to users. It is the central component to which Zabbix agents and proxies report data on availability and integrity of systems [2].

The agent gathers operational information locally and reports data to Zabbix server for further processing. In case of failures (such as a hard disk running full or a crashed service process), Zabbix server can actively alert the administrators of the machine that reported the failure [2]. Zabbix agent 2 is a new generation of Zabbix agent and may be used in place of Zabbix agent [2].

Zabbix proxy is a process that may collect monitoring data from one or more monitored devices and send the information to the Zabbix server, essentially working on behalf of the server. All collected data is buffered locally and then transferred to the Zabbix server the proxy belongs to [2].

From the description of Zabbix components above we can conclude that from the architecture perspective Oracle Enterprise Manager and Zabbix are similar if we emphasize facts that both monitoring tools have centralized server which could be configured in cluster mode for high availability and both monitoring tools utilize agents for data collection from remote targets. For sure Zabbix as a general-purpose monitoring tool has less built in functionality for Oracle product monitoring, but it has the Oracle template for "Agent 2" which could very well be used for Oracle database monitoring [3].

In "Fig. 3" we can see architecture diagram of Cacti monitoring tool [4].

As one can notice Cacti has the simplest architecture diagram from the all three tools mentioned so far. It basically has only two components: "Cacti server" and "server to monitor". In reality "Cacti server" is to some extent analogical to Oracle Enterprise Manager and Zabbix from the perspective that all three of the mentioned have relational database as persistent data store and browser based graphical user interface.

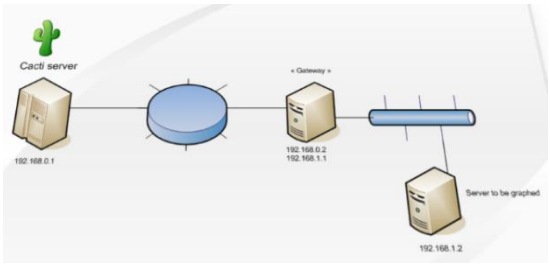


Fig. 3 Cacti architecture.

However, Cacti monitoring tool is different from perspective that it has no or we can say it has much less built-in functionality for specific vendor product monitoring and it is agent less. It as well has plugins.

Cacti monitoring tool differs from the perspective of how it stores the collected data. Cacti utilizes RRDTools Round Robin Archives (RRAs) as data sources for graph generation and that is the unique feature of Cacti. As it is stated by Cacti documentation, Cacti is a robust performance and fault management framework and a frontend to RRDTool - a Time Series Database (TSDB) [4].

Additional information on RRDTool could be found from the RRDTool documentation [5], but the main difference here is that data from monitored devices are stored in the RRA files and this file format is dedicated to store time series data, in this case database serves more as information processing tool.

We can mention other monitoring tools here such as Nagios [6], for example, but we already have figured out some pattern, that monitoring tools are similar at some extent as they have the same goal to store and process time series data about monitored objects which could be different software metrics from different vendor products or sensor data from IOT devices. Some of the monitoring tools will focus on support of specific vendor products, for example, Oracle Enterprise Manager, but some of the monitoring tools focus especially on the general-purpose monitoring tasks.

It is obvious that monitoring tools with the main aim to support specific vendor products or to support general purpose monitoring could not have built in functionality for all sorts of real-life scenarios and both types support some level of customization.

In the rest of this article the novel approach of data centre monitoring is described for which the author of the article has created the model based on AI algorithms, machine learning and anomaly detection techniques allowing to focus more on monitoring at data centre level rather than monitoring at specific target level in the data centre. The model will consider existing monitoring targets and human behaviour as the targets are getting monitored for metrics already. Each of the target metric could be displayed in more than one resulting graph and graphs could be created by different persons. This will serve as a weight factor for metrics as metrics get displayed greater number of times in regular graphs of individual monitoring targets as more weight those metrics have in graphs reporting the overall situation in the data centre.

II. Materials and Methods

For demonstration purposes of the model the attention is drawn on two of the Oracle database performance metrics “consistent_gets” and “db_block_gets”. The sum of "db_block_gets" plus "consistent_gets" is considered as logical reads of database blocks from either the buffer cache or process private memory [7].

In “Fig. 4” one can see the example of histograms for

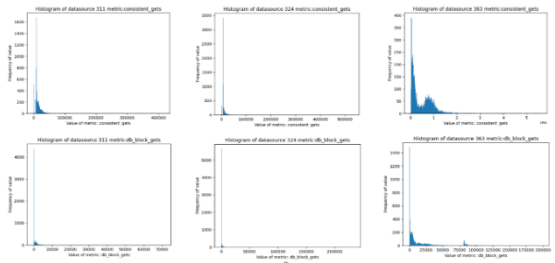


Fig. 4 Histograms of performance metrics related to "logical reads."

performance metrics “consistent_gets” and “db_block_gets” from three different data sources. One data source in “Fig. 4” represents on database in the data centre. In some cases, one database could be presented to different persons via different graphs visualizing different combinations of performance metrics. In such situations, one performance metric is part of different data sources, and it will serve as a weighting factor in the end results, as it could be considered as a factor of higher importance.

In the scope of this research hypothesis is considered that it is possible to construct a model that is based on AI algorithms, machine learning techniques, and anomaly detection techniques for data centre level monitoring of data centre systems. The purpose of data centre level monitoring of data centre systems is to provide novel ways of metric processing allowing to analyse the information from perspective which currently available tools in the market do not provide yet.

In “Fig. 4” it is visible, that chosen histograms of performance metrics “consistent_gets” and “db_block_gets” do not have a shape of normal distribution, uniform distribution, or some other popular distribution. Therefore, as good choice of anomaly detection techniques for processing these metrics naturally would be AI algorithms which support processing of data from timeseries performing anomaly detection utilizing techniques based on timeseries which are independent of data distributions. As there are plenty of monitoring targets and huge number of metrics, we will choose AI algorithms which support unsupervised machine learning.

To further construct the model, a set of algorithms were chosen which by theory are capable to solve the previously defined task: “Empirical Cumulative distribution-based Outlier Detection or ECOD”, “Local Outlier factor or LOF”, “Isolation Forest or IForest”, “Outlier Detection Using the Local Correlation Integral or LOCI”.

The premise of the Isolation Forest algorithm is that anomalous data points are easier to separate from the rest of the sample. To isolate a data point, the algorithm recursively generates partitions on the sample by randomly selecting an attribute and then randomly selecting a split value between the minimum and maximum values allowed for that attribute [8].

The local outlier factor is based on a concept of a local density, where locality is given by k nearest neighbours, whose distance is used to estimate the density. By comparing the local density of an object to the local densities of its neighbours, one can identify regions of similar density, and points, that have a substantially lower density than their neighbours, are outliers [9].

The existing unsupervised machine learning approaches often suffer from high computational cost, complex hyperparameter tuning and limited interpretability, especially when working with large, high-dimensional datasets. To address these issues, we present a simple yet effective algorithm called ECOD (Empirical Cumulative distribution-based Outlier Detection), which is inspired by the fact that outliers are often the "rare events" that appear in the tails of a distribution. In a nutshell, ECOD first estimates the underlying distribution of the input data in a nonparametric fashion by computing the empirical cumulative distribution per dimension of the data. ECOD then uses these empirical distributions to estimate tail probabilities per dimension for each data point. Finally, ECOD computes an outlier score of each data point by aggregating estimated tail probabilities across dimensions [10].

LOCI is highly effective for detecting outliers and groups of outliers (a.k.a. micro-clusters). In addition, it offers the following advantages and novelties: (a) It provides an automatic, data-dictated cut-off to determine whether a point is an outlier—in contrast, previous

methods force users to pick cut-offs, without any hints as to what cut-off value is best for a given dataset. (b) It can provide a LOCI plot for each point; this plot summarizes a wealth of information about the data in the vicinity of the point, determining clusters, micro-clusters, their diameters, and their inter-cluster distances. None of the existing outlier-detection methods can match this feature, because they output only a single number for each point: its outlierness score. (c) Our LOCI method can be computed as quickly as the best previous methods [12].

Additionally, to theoretical aspects of previously mentioned AI algorithms we will use the Python PYOD library as the building block for the model. Python PYOD library has implementations of previously mentioned algorithms [13], [14], [15], [16], [17]. Implementations are done using other Python open-source projects such as Python scikit-learn [18].

The model for data centre level monitoring will use previously described Cacti monitoring tool as a basis and add to it the component based on AI algorithms and machine learning with capabilities to detect anomalies in the stream of monitoring data. Machine learning process will be done on historic data of performance metrics. Historic performance data are collected with the help of existing Cacti database model adjusting it as necessary to collect and store the data for longer term, by default Cacti database model keeps only small set of temporary data which could not be used by machine learning process. The

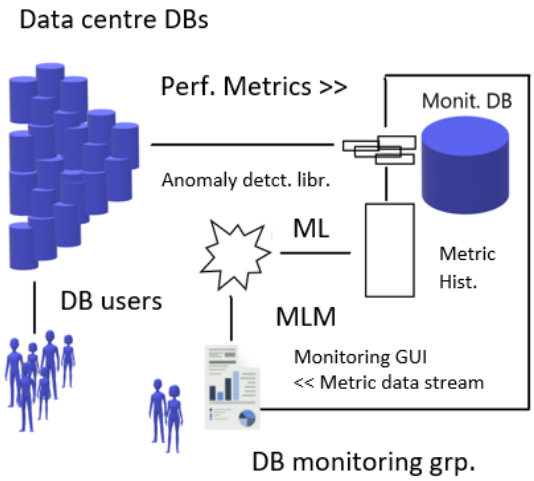


Fig. 5 Architecture of model "Data Centre monitoring".

architecture of the model is visible in “Fig. 5”

As one can see in “Fig. 5” data centre hosts many databases (at the left side), metrics from database servers are collected and stored temporarily in the monitoring database (at the right side). Monitoring database holds historic data of incoming stream of monitoring metrics. Historic data are used as input for machine learning algorithms which analyse the data to create the modules for each metric individually which help later as basis in anomaly detection process in incoming data stream of monitoring metrics. As it is visible in “Fig. 4” such metrics as “consistent_gets” and “db_block_gets” may differ by such characteristics as the shape of the histogram of their historic data depending on the nature of the usage of the databases. That means we must have separate machine learning process and resulting module for each metric for every database.

Data structure of historical table for metrics “consistent_gets” and “db_block_gets” is visible in “Fig. 6”.

Example of monitoring metric timeseries data displayed in descending order by values is visible in “Fig. 7”.

shape: (753_488, 4)

local_data_id	rrd_name	time	value
i64	str	str	f64
582	consistent_gets	2024-08-28 11:15:00	9.19
582	db_block_gets	2024-08-28 11:15:00	1.21
587	consistent_gets	2024-08-28 11:15:00	9.19
587	db_block_gets	2024-08-28 11:15:00	1.21
182	consistent_gets	2024-08-28 11:15:00	3.016667
…	…	…	…
602	db_block_gets	2024-09-19 16:30:01	86046.916667
606	consistent_gets	2024-09-19 16:30:01	700846.313333
606	db_block_gets	2024-09-19 16:30:01	86046.916667
610	consistent_gets	2024-09-19 16:30:01	700846.313333
610	db_block_gets	2024-09-19 16:30:01	86046.916667

Fig. 6 Structure of metric history table.

Using all the components described previously the model was developed in Python programming language in following steps:

1. historical metric collection from incoming data stream (data point per 5 minutes for each metric);
2. unsupervised machine learning process for each metric (in total for 20 Oracle database) with:
   a. 1 day of data points (288)
   b. 3 days of data points (864);
   c. 7 days of data points (2016);
3. unsupervised machine learning process for each metric produced a module as output which could be used for real-time anomaly detection in incoming monitoring data stream:
   a. “1days” learning process modules;
   b. “3days” learning process modules;
   c. “7days” learning process modules;
4. all the modules: “1days”, “3days” and “7days” are applied for each metric of data to produce comparable results;
5. the binary result of anomaly detection is summarized to gain overall results from all 20 databases for each metric in data centre.

III. Results and Discussion

Several novel results and approaches of monitoring and possibilities to gain even positive economic impact on data centre monitoring process were discovered during the one-month long period of using the model in practice in a data centre.

Example of outlierness level over data centre Oracle database performance metrics related to logical reads is shown in “Fig. 8” for “1days” unsupervised ML period.

Example of outlierness level over data centre Oracle database performance metrics related to logical reads is shown in “Fig. 9” for “3days” unsupervised ML period.



Fig. 8 Outlierness level over Data Centre "1days".

Graphs in “Fig. 8” for “1days” learning period and “Fig. 9” for “3days” learning period display four sub graphs for period of the last day:

1. DC outlierness level for last “15 min” period for logical reads in scoring points out of maximum possible 350 scoring points;
2. DC outlierness level for last “30 min” period for logical reads in scoring points out of maximum possible 700 scoring points;
3. DC outlierness level for last “60 min” period for logical reads in scoring points out of maximum possible 1400 scoring points;
4. Example database “VIP” exact values for performance monitoring metrics “consistent_gets” and “db_block_gets” for period of the last day.

Monitoring for outlierness level and storing the results of the outlierness level for long term allows to represent the information visually and perform analysis and make further discussions finding options for research direction.

Obviously, it is possible to establish certain standards for outlierness level and react involving human experts in case outlierness level exceeds previously agreed thresholds.

In case of situation when outlierness level exceed thresholds, experts could figure out the causing reason for that and create, for example, knowledge base for further analysis of information and possible automation options of data centre management.

One option to establish thresholds for the level of outlierness is described in “RRDtool” documentation [5]. It is based on existing historic data and statistics methods built in “RRDtool” function “PREDICT”.

Prediction done using the function “PREDICT” about outlierness level that could be expected for next period of three days based on the outlierness level in previous seven days is shown in figures “Fig. 10” for outlierness scoring

```
shape: (6_370, 2)
```

rrd_name	value
str	f64
consistent_gets	5.5970e6
consistent_gets	5.4860e6
consistent_gets	5.4118e6
consistent_gets	5.3510e6
consistent_gets	4.9734e6
…	…
consistent_gets	14089.496667
consistent_gets	14083.41
consistent_gets	14081.263333
consistent_gets	14075.053333
consistent_gets	14074.55

Fig. 7 Example of monitoring metrics timeseries

done by algorithm “IForest”, “Fig 11” for outlierness scoring done by algorithm “LOF” and “Fig 12” for outlierness scoring done by algorithm “ECOD”. By the red colour (please, see the arrows in Fig. 10 when reading



Fig. 9 Outlierness level over Data Centre "3days".

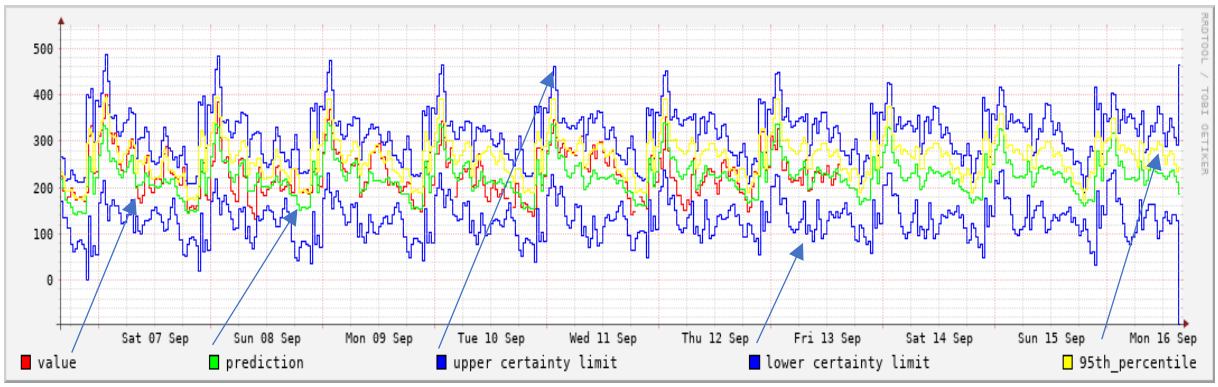


Fig. 10 Prediction "3days" IForest level of outlierness.

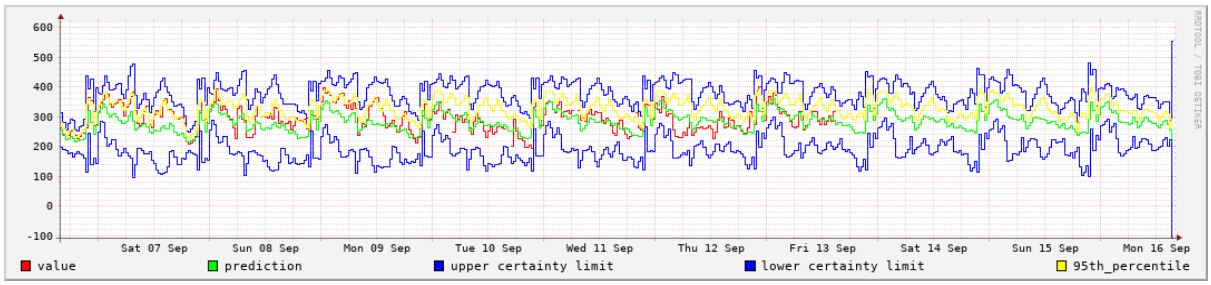


Fig. 11 Prediction "3days" LOF level of outlierness.

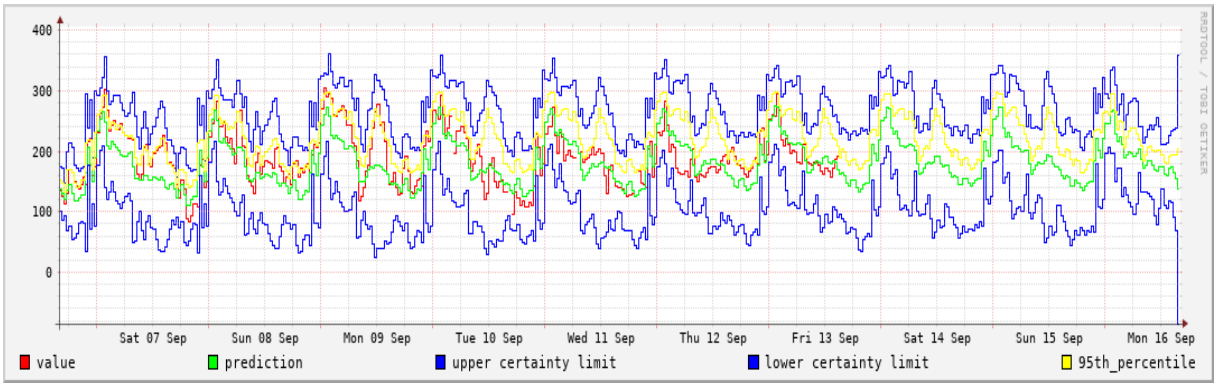


Fig. 12 Prediction "3days" ECOD level of outlierness.

printed grayscale variant) the current value of outlierness scoring is shown, by the green value predicted value is shown, blue colour shows lower and upper certainty levels and yellow shows 95th percentile. All colours except red are present in graphs 3 days after the current day of graph generation "Friday 13th of September" and could be considered as prediction. At the same time such prediction could be considered as a threshold level exceeding which human experts are involved to verify situation.

IV. Conclusions

The research hypothesis was proved as it is possible to construct a model based on AI algorithms, machine learning techniques and anomaly detection techniques for data centre level monitoring of data centre systems.

The results of model are visible in "Fig. 8" and "Fig. 9" which show us level of outlierness which is the result of processing Oracle performance metric timeseries data by AI algorithms using unsupervised ML techniques. Following algorithms were used during the research: "IForest", "LOF", "ECOD" and "LOCI" to achieve the results. One of the algorithms "LOCI" did not provide any anomaly scoring results, so we assume it either not good choice for our type of timeseries data or there is a bug in Python PYOD library. The other three: "IForest", "LOF", "ECOD" produced slightly different results for each particular data point, but in case we do not focus on particular data points, but on longer timeseries as it is visible in "Fig. 10", "Fig. 11" and "Fig. 12", the results are very similar and they provide similar predictions based on historic data. Additionally, it is worth to mention the performance of algorithms during unsupervised ML process. As previously mentioned, we can assume "LOCI" did not provide useful results in our case, from the rest "IForest" and "LOF" were significantly faster than "ECOD", due to that it was possible to complete unsupervised ML process for periods of "1days" and "3days" during reasonable amount of time. In the process of anomaly detection in real time data all three algorithms performed fast enough for the scope of the task.

Conclusion could be made, that it is possible to establish a knowledge base of cases when thresholds are exceeded and continue the work on actions advised by the experts on how to handle certain situations.

Outlierness level monitoring at data centre level could help as well to identify certain situations which are not identifiable by monitoring individual objects which could help to react faster on certain type of theoretically possible cases touching field of IT security where quite often experts deal with situations that have never happened before and that are not visible in the monitoring done by traditional approaches.

As it is visible in Oracle 21c documentation [7], there exist more than 500 performance metrics. In Oracle 21c documentation all the metrics are divided in following classes: "User", "Redo", "Enqueue", "Cache", "OS", "Real Application Clusters", "SQL", "Debug", "Instance level" [7]. For example, a class "SQL" represents a statistic that relates to SQL statements and caching. That provides wide field for further research based on the model developed in the scope of this research and author hopes to continue his work on it.

V. Acknowledgments

This research was funded by the European Commission, Research Executive Agency grant number 101079206, "Twinning in Environmental Data and Dynamical Systems Modelling for Latvia" (TED4LAT).

VI. References

[1] Oracle Enterprise Manager, "Enterprise Manager Cloud Control Architecture." *Copyright © 1995, 2024, Oracle and/or its affiliates*. [Online]. Available: https://docs.oracle.com/en/enterprise-manager/cloud-control/enterprise-manager-cloud-control/13.5/emcon/enterprise-manager-cloud-control-architecture.html [Accessed: Sep. 19, 2024].

[2] Zabbix documentation, "Zabbix features." *Policy© 2001-2024 by Zabbix LLC. All rights reserved.* [Online]. Available: https://www.zabbix.com/features [Accessed: Sep. 19, 2024].

[3] Zabbix documentation, "Zabbix integrations Oracle." *Policy© 2001-2024 by Zabbix LLC. All rights reserved.* [Online]. Available: https://www.zabbix.com/integrations/oracle [Accessed: Sep. 19, 2024].

[4] Cacti documentation, "What is Cacti?" *Copyright © 2004-2021 The Cacti Group, Inc. - Cacti is the registered trademark The Cacti Group, Inc.* [Online]. Available: https://www.cacti.net/info/cacti [Accessed: Sep. 19, 2024].

[5] RRDtool documentation, “RRDtool documentation” *OETIKER+PARTNER AG* [Online]. Available: https://oss.oetiker.ch/rrdtool/doc/rrdtool.en.html [Accessed: Sep. 19, 2024].
[6] Nagios documentation, “Nagios documentation” *Copyright © 2009-2023 Nagios Enterprises, LLC. All rights reserved.* [Online]. Available: https://www.nagios.org/documentation/ [Accessed: Sep. 19, 2024].
[7] Oracle Database Reference 21, “Statistics Descriptions.” *Copyright © 1995, 2024, Oracle and/or its affiliates*. [Online]. Available: https://docs.oracle.com/en/database/oracle/oracle-database/21/refrn/statistics-descriptions-2.html [Accessed: Sep. 20, 2024].
[8] Wikipedia, “Isolation forest,” [Online] Available: https://en.wikipedia.org/wiki/Isolation_forest [Accessed: Sep. 20, 2024].
[9] Wikipedia, “Local outlier factor,” [Online] Available: https://en.wikipedia.org/wiki/Local_outlier_factor [Accessed: Sep. 20, 2024].
[10] Zheng Li, Yue Zhao, Xiyang Hu, Nicola Botta, Cezar Ionescu, George H. Chen, “ECOD: Unsupervised Outlier Detection Using Empirical Cumulative Distribution Functions, ” 2022, https://arxiv.org/abs/2201.00382
[11] Wikipedia, “Empirical distribution function,” [Online] Available: https://en.wikipedia.org/wiki/Empirical_distribution_function [Accessed: Sep. 20, 2024].
[12] S. Papadimitriou, H. Kitagawa, P. B. Gibbons and C. Faloutsos, "LOCI: fast outlier detection using the local correlation integral," Proceedings 19th International Conference on Data Engineering (Cat. No.03CH37405), Bangalore, India, 2003, pp. 315-326, doi: 10.1109/ICDE.2003.1260802.
[13] Pyod 2.0.2 documentation, “Python library for detecting anomalous/outlying objects in multivariate data,” [Online] Available: https://pyod.readthedocs.io/en/latest/ [Accessed: Sep. 20, 2024].
[14] pyod.models.lof module, “Local Outlier Factor (LOF). Implemented on scikit-learn library,” [Online] Available: https://pyod.readthedocs.io/en/latest/pyod.models.html#module-pyod.models.lof [Accessed: Sep. 20, 2024].
[15] pyod.models.loci module, “Local Correlation Integral (LOCI),” [Online] Available: https://pyod.readthedocs.io/en/latest/pyod.models.html#module-pyod.models.loci [Accessed: Sep. 20, 2024].
[16] pyod.models.iforest module, “IsolationForest Outlier Detector. Implemented on scikit-learn library,” [Online] Available: https://pyod.readthedocs.io/en/latest/pyod.models.html#module-pyod.models.iforest [Accessed: Sep. 20, 2024].
[17] pyod.models.ecod module, “Unsupervised Outlier Detection Using Empirical Cumulative Distribution Functions (ECOD),” [Online] Available: https://pyod.readthedocs.io/en/latest/pyod.models.html#module-pyod.models.ecod [Accessed: Sep. 20, 2024].
[18] scikit-learn, “scikit-learn machine learning library,” [Online] Available: https://scikit-learn.org/ [Accessed: Sep. 20, 2024].

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 383-388

Pollution Detection Model Utilizing Anomaly Detection Techniques Performing Analysis of Satellite Data

Roberts Volkovičs
Modelling of sociotechnical systems
Vidzeme University of Applied Sciences
Valmiera, Latvia
roberts.volkovics@va.lv

***Abstract*—In this article review was created of nowadays popular way in science of working on climate change topics by processing and performing analysis of open data from Earth orbiting satellites. Open data from satellites are provided by The European Space Agency or ESA, National Aeronautics and Space Administration or NASA via portals and cloud services under their management and by other organizations via such cloud service as Creodias, for example. Open data from satellites are available for research for other topics as well, but in the scope of this article the topic of climate change is in the focus by achieving research goal and proving hypothesis that it is possible to build the pollution detection model and pollution location detection model by utilizing anomaly detection techniques and performing analysis of satellite data.**

Keywords — Analysis, Anomaly Detection (AD), Location Detection, Model, Pollution Location, Satellite Data.

I. Introduction

Climate change and related topics are very popular in science nowadays and many researches are working in this field with the aim to improve the overall situation that is constantly worthening regarding climate on the Earth. As the evidence to situation worthening such phenomena could be mentioned as increasing global air temperature, increasing global water temperature in the oceans, weather anomalies like heavy storms and other.

Author of the article works on different topic related to anomaly detection and has found that open data from satellites provide good basis for experiments with anomaly detection techniques in the area of big and dense data. This research in the field of climate change was done performing analysis of satellite data with the aim to create the model capable to detect pollution or source of pollution using anomaly detection techniques. The hypothesis of the research: "it is possible to build a model for analysis of satellite sensor data for pollution detection or pollution location detection utilizing anomaly detection techniques."

II. Materials and Methods

During this research an open data from The European Space Agency or ESA "Copernicus" [1] project was used to perform the analysis to achieve the research goal and prove the hypothesis, that it is possible to construct the model based on anomaly detection techniques and algorithms, that could be utilized for pollution detection and pollution location detection on Earth.

National Aeronautics and Space Administration or NASA, has prepared a guide on how to access "Copernicus" project open data [2]. Besides the option to download "Copernicus" project's data from several portals, NASA provides an option to download "Copernicus" project's data as well and there are options to request data in different formats. For that purpose, there is "Earth data Search" tool available online [3]. Additional information on "Sentinel" project satellites, for example, products, naming conventions could be found in "Senti Wiki" portal [4].

"Sentinel" project has 6 types of satellites with several satellites in for each type going around the Earth by different orbits as demonstrated in "Fig. 1".

All the satellites of "Sentinel" project provide following "Copernicus" project services:

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8566
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

- The Copernicus Atmosphere Monitoring Service (CAMS) provides continuous data and information on atmospheric composition. The service describes the current situation, forecasts the situation a few days ahead, and analyses consistently retrospective data records for recent years. The Copernicus Atmosphere Monitoring Service supports many applications in a variety of domains including health, environmental monitoring, renewable energies, meteorology, and climatology [5];



Fig. 1. Sentinel satellites

- The Copernicus Marine Service (or Copernicus Marine Environment Monitoring Service) is the marine element of Copernicus, the Earth observation component of the European Union's Space programme. It provides free, regular, and systematic authoritative information on the state of the Blue (physical), White (sea ice) and Green (biogeochemical) ocean, on a global and regional scale [6];
- The Copernicus Land Monitoring Service (CLMS) provides geospatial information on land cover and its changes, land use, vegetation state, water cycle and Earth's surface energy variables to a broad range of users in Europe and across the World in the field of environmental terrestrial applications [7];
- The Copernicus Climate Change Service (C3S) supports society by providing authoritative information about the past, present and future climate in Europe and the rest of the World [8];
- The Copernicus service for Security applications aims to support European Union policies by providing information in response to Europe's security challenges [9];
- The Copernicus Emergency Management Service (Copernicus EMS) provides all actors involved in the management of natural disasters, man-made emergency situations, and humanitarian crises with timely and accurate geo-spatial information derived from satellite remote sensing and completed by available in situ or open data sources [10].

In the scope of this article, the main attention is paid to "Sentinel-5P" mission which provides open data for "The Copernicus Climate Change Service (C3S)" service.

Sentinel-5p TROPOMI sensor applications are encompassing the air quality and pollution, the ozone-layer monitoring, the climate change, and the aviation safety. All these applications are presented in depth, with the specification of the corresponding product types [8].

"The Copernicus data space ecosystem" [11] is one of the portals where open data from different satellites are made available; similar services for different organization satellites are provided by "Creodias" [12], which is cloud service provider for Earth observation data.

In case to retrieve "raw" data from satellites the Copernicus service or the Creodias service could be utilized. To avoid computation on mapping "raw" satellite data to Earth area, in scope of the research, data were requested and downloaded locally from NASA "Earth Search Data" service [3]. These data are mapped to the Earth area and instead of representing exact results of satellite sensor scan over particular Earth area at specific moment in time, the data represent (in one NCDF4 file) one week of moving average for each day of observations over the Earth area. To prove the hypothesis of the research NCDF4 files over five-year long period are processed.

Central and South America was chosen as the region of choice for the research, because it is known to the science that winds in stratosphere usually are bidirectional in this region: with east-wind or west-wind component of direction.

The winds in the stratosphere and mesosphere are usually estimated from temperature data collected by satellites. The winds at these high levels are assumed to be geostrophic. Overall, in the midlatitudes, they have a westerly component in the winter and an easterly component in the summer [13].

The phenomenon of winds in the stratosphere and mesosphere having east-wind or west-wind component of direction has been so stable in long term that even some changes in this behaviour are considered as anomaly by some researchers who are monitoring this phenomenon closely.

In article [14], the graphical data representation of described phenomenon could be found as demonstrated in "Fig. 2".

Based on phenomenon described and rules of logic and probability, it could be assumed, that any kind of pollution or pollution location, if it exists at all, must show up after analysis of satellite data when performing data representation in graphical diagram as horizontally (Easterly-Westerly) oriented regions of lower/higher probability areas or polygons of research metric or variable visual representation. For this research, visual representation of research metric or variable serves as the main method for proving hypothesis.

As research metrics or variables density of ozone in stratosphere from two different altitudes were used.

As a pollution factor freon gas will be considered, which reacts with ozone molecules repeatedly turning ozone in oxygen and causing free atom of oxygen to construct other chemical elements in different chemical reactions. Such a pollution must be visible as anomalies in long term geospatial data, especially very close to pollution location, in case properly visualized.

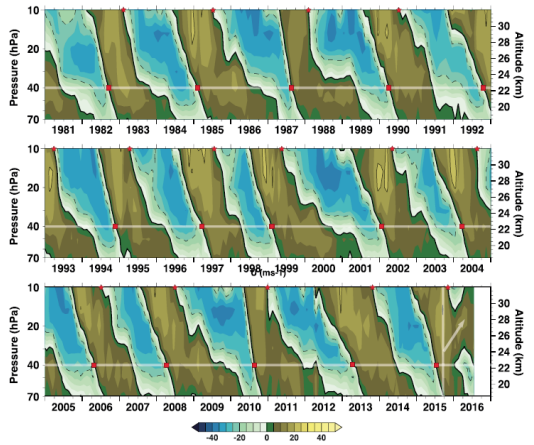


Fig. 2. Phenomenon East and West component of wind alternation [14].

All the mentioned factors combined were joined in the plan of the research to process 5 years of "Sentinel-5" data utilizing the model for pollution detection based on anomaly detection techniques. The model was created as program written in MATLAB using MATLAB modules for NCDF4 file processing, geospatial data processing, anomaly detection techniques, visual representation and regular functionality for file and variable processing in software program cycles the same way as in programs written in other programming languages.

Calculations are done considering rules of statistics - utilizing variable scaling techniques and anomaly scoring, and considering that in normal conditions density of ozone in stratosphere has normal probability distribution.

In "Fig. 3" the web interface of portal Creodias is visible, allowing to choose the region of interest for which to request and download satellite data. To calculate the distribution of the sample of ozone density the distant region in the ocean was chosen assuming there is the minimum of impact of human caused pollution.

In "Fig. 4" the web interface of portal Creodias allowing to pick the data from satellite is demonstrated.

In the "Fig. 5" the histogram of variable of ozone density is visible.

The histogram visible in the "Fig. 5" is in almost perfect form of bell, which suggests that the density of the ozone in normal circumstances has normal probability distribution.

Normal probability distribution is the most frequently occurring distribution for most measurable metrics in nature, like air temperature in a certain season, a time of a day and an area.

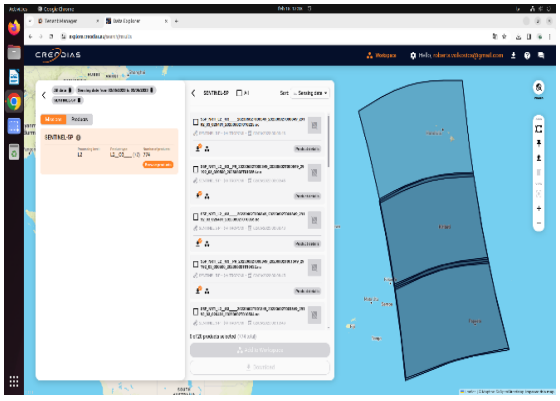


Fig. 3. Creodias, choosing the region of interest

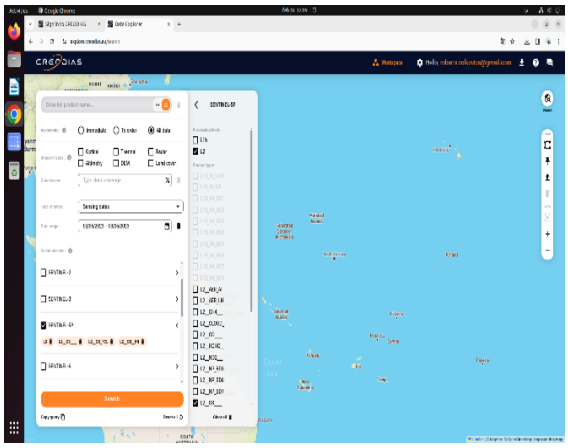


Fig. 4. Creodias choosing the product of interest

That allows to perform statistical calculations and anomaly detection assuming that ozone density during normal conditions has normal probability distribution.

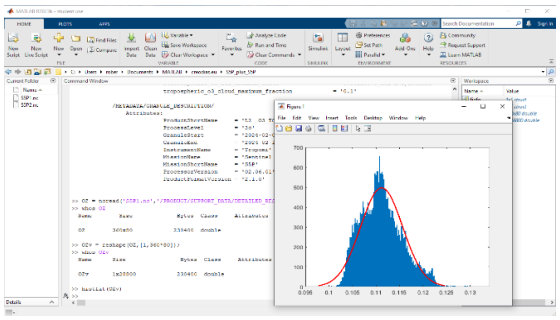


Fig. 5. Histogram of ozone density

In the "Fig. 6" the screenshot of MATLAB displaying the structure of NCDF4 file is visible.

Statistical operations with variables having normal distributions allow to perform such calculations as:

- anomaly detection based on z-score methodology;
- addition of average values of the same variable at two different altitudes;
- scaling for scoring processing of anomaly detection.

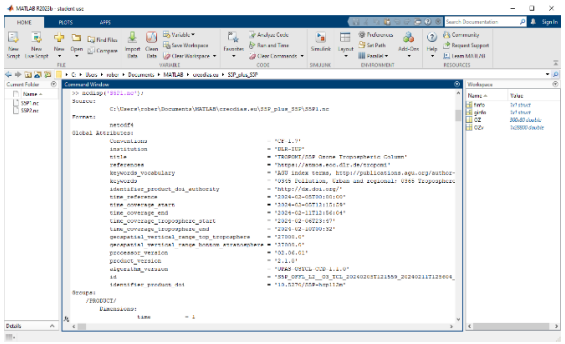


Fig. 6.. NCDF4 structure from "Sentinel5"

Normal distribution is one of the most widely spread distributions in nature and many statistics methods were created based on this type of distribution and are only available for it.

III. Results and Discussion

After processing the data, the list of graphical visualizations was created showing the overall anomaly level over region of interest for the years 2019, 2020, 2021, 2022, 2023.

More than 330 files for each year were processed by anomaly detection techniques calculating the minimum level of ozone density, the maximum level of ozone density and the normal level of ozone density.

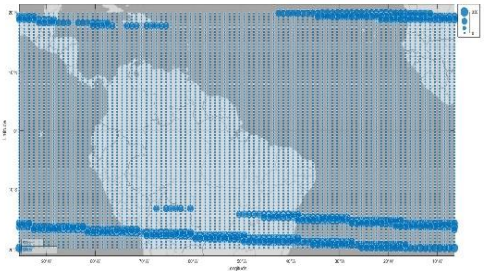


Fig. 7. 2019. Anomaly scoring category minimums ozone density

The minimum level of ozone density for the year 2019 is visible in "Fig. 7"

As visible in "Fig. 7", for the year 2019 the minimums of ozone density tend to draw horizontal line at the top and at the bottom of the graph.

In Fig. 8, the maximum ozone density is displayed for the year 2019.

As demonstrated in "Fig. 8", the maximums tend to create horizontal areas in the middle of the geographical region.

In the "Fig. 9", overall results are displayed for all three scoring categories: minimums, maximums, and normal level of anomalies of ozone density for the year 2019.

Light blue colour represents anomaly scoring level for minimums, green for maximums and regular blue for both minimums and maximums having normal level.

In the "Fig. 10", the minimums of ozone density are displayed for the year 2020.

In the "Fig. 11", the minimums of ozone density are displayed for the year 2021.

In the "Fig. 12", the minimums of ozone density are displayed for the year 2022.

In the "Fig. 13", the minimums of ozone density are displayed for the year 2023.

In the "Fig. 14" the map of populated places from "Latin America and the Caribbean (LAC) Population Database" is visible [15.]

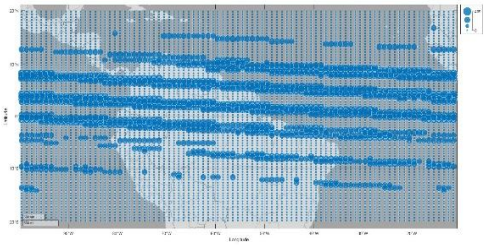


Fig. 8. 2019. anomaly scoring category maximums ozone density

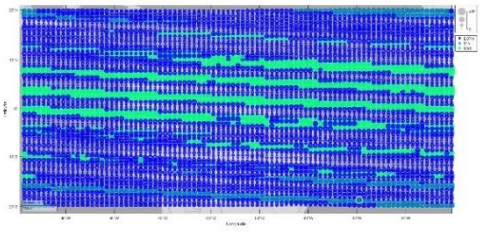


Fig. 9. 2019. anomaly scoring all categories ozone densitv

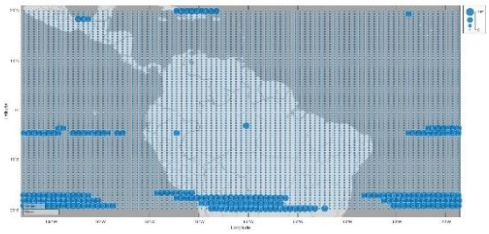


Fig. 10. 2020. anomaly scoring category minimums ozone density

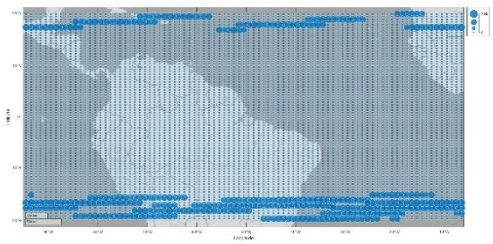


Fig. 11. 2021. anomaly scoring category minimums ozone density

At some extent, figures: "Fig. 7", "Fig. 10", "Fig. 11", "Fig. 12", "Fig. 13" are following the same pattern and clearly demonstrate horizontally oriented areas of ozone

minimum very close to most populated places visible in map from "Fig. 14".

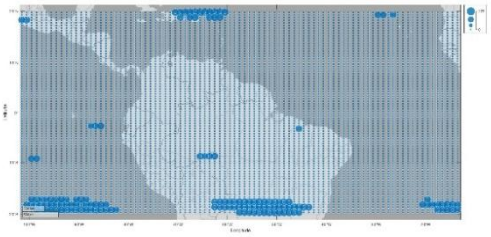


Fig. 12. 2022. anomaly scoring category minimums ozone density

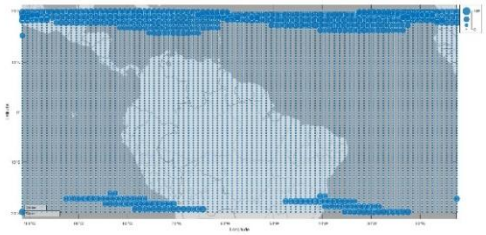


Fig. 13. 2023. anomaly scoring category minimums ozone density

As previously discussed, such minimums of ozone density could be caused by pollution of freon gas and the close location to populated places could be direct cause of the pollution.

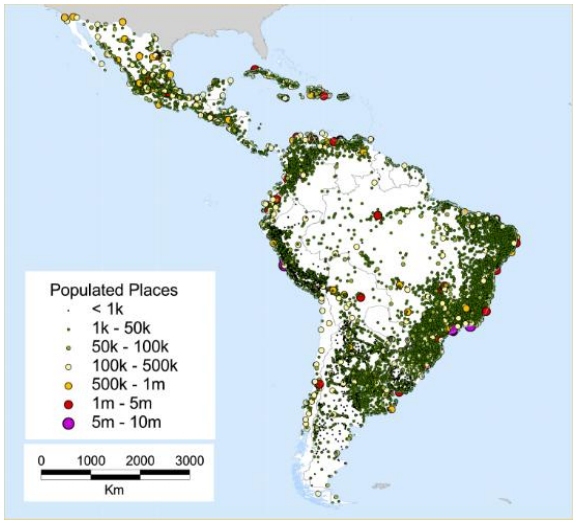


Fig. 14. Central and South America populated places [15]

It should be considered that winds near earth could very well affect direction of how freon gas lifts until stratosphere, but still it could be assumed that the location of pollution could be detected by this approach to certain precision of geographical area.

IV. Conclusions

After analysis and processing of open data from "Sentinel-5" project data sets [16] and [17], it was possible to generate graphical representation of anomaly scoring level our outlierness for specific geographic region for 5 years long period. Since geographic region is in tropic area of Earth where wind directions in stratosphere mostly have only east and west components, it is possible to conclude that horizontally oriented lines, areas, or polygons representing anomaly scoring category minimums in particular geographical areas and those are most likely very close to freon gas pollution sources.

Areas with anomaly scoring category minimums are very close in geographic map with those areas of highest density of human population like large cities with many million inhabitants which most likely is the cause of freon gas pollution as it was used some time ago for such devices as refrigerators, conditioners etc.

Luckily humanity has agreed to not produce anymore such type of devices with freon gas components and situation with ozone layer density started to improve recently.

The goal of the research is achieved by proving hypothesis that it is possible to build the model with capability of pollution detection performing analysis of satellite data and proving hypothesis by graphical representation of anomaly scoring results.

Acknowledgments

This research was funded by the European Commission, Research Executive Agency grant number 101079206, "Twinning in Environmental Data and Dynamical Systems Modelling for Latvia" (TED4LAT).

References

[1] Copernicus, "Europe's eyes on Earth." [Online]. Available: https://www.copernicus.eu/en [Accessed: Sep. 19, 2024].
[2] National Aeronautics and Space Administration, "TUTORIAL FOR DATA DOWNLOAD FROM THE COPERNICUS OPEN ACCESS HUB," *National Aeronautics and Space Administration*, 2024. [Online]. Available: https://appliedsciences.nasa.gov/sites/default/files/2021-10/Part2_Data-Download_EN.pdf [Accessed: Sep. 19, 2024].
[3] National Aeronautics and Space Administration, "Earth data Search," *National Aeronautics and Space Administration*, 2024. [Online]. Available: https://search.earthdata.nasa.gov/search [Accessed: Sep. 19, 2024].
[4] Copernicus, "Senti Wiki," [Online]. Available: https://sentiwiki.copernicus.eu/web/sentiwiki [Accessed: Sep. 19, 2024].
[5] Copernicus, "The Copernicus Atmosphere Monitoring Service (CAMS)," [Online]. Available: https://www.copernicus.eu/en/copernicus-services/atmosphere [Accessed: Sep. 19, 2024].
[6] Copernicus, "The Copernicus Marine Service," [Online]. Available: https://www.copernicus.eu/en/copernicus-services/marine [Accessed: Sep. 19, 2024].
[7] Copernicus, "The Copernicus Land Monitoring Service (CLMS)," [Online]. Available: https://www.copernicus.eu/en/copernicus-services/land [Accessed: Sep. 19, 2024].
[8] Copernicus, "The Copernicus Climate Change Service (C3S)," [Online]. Available: https://www.copernicus.eu/en/copernicus-services/climate-change [Accessed: Sep. 19, 2024].
[9] Copernicus, "The Copernicus service for Security applications," [Online]. Available: https://www.copernicus.eu/en/copernicus-services/security [Accessed: Sep. 19, 2024].

[10] Copernicus, "The Copernicus Emergency Management Service (Copernicus EMS)," [Online]. Available: https://www.copernicus.eu/en/copernicus-services/emergency [Accessed: Sep. 19, 2024].
[11] Copernicus, "The Copernicus data space ecosystem," [Online]. Available: https://dataspace.copernicus.eu/ [Accessed: Sep. 19, 2024].
[12] Creodias, "CREODIAS offers a cloud computing solution for EO data processing," [Online]. Available: https://creodias.eu/ [Accessed: Sep. 19, 2024].
[13] Britannica, "Winds in the stratosphere and mesosphere," [Online]. Available: https://www.britannica.com/science/climate-meteorology/Winds-in-the-stratosphere-and-mesosphere [Accessed: Sep. 24, 2024].
[14] P. A. Newman, L. Coy, S. Pawson, and L. R. Lait, "The anomalous change in the QBO in 2015–2016," *Geophys. Res. Lett., 43, 8791–8797*, 2016. [Online serial]. Available: https://dx.doi:10.1002/2016GL070373 [Accessed: Sep. 24, 2024].
[15] Centro Internacional de Agricultura Tropical (CIAT), United Nations Environment Program (UNEP), Center for International Earth Science Information Network (CIESIN), Columbia University, and the World Bank (2005), "Latin America and the Caribbean (LAC) Population Database," [Online]. Available: https://gisweb.ciat.cgiar.org/population/report.htm [Accessed: Sep. 24, 2024].
[16] "2018-04-30 to 2020-07-07 Sentinel-5P TROPOMI Tropospheric Ozone Column V1 (S5P_L2__O3_TCL)", [Online]. Available: https://dx.doi.org/10.5270/S5P-8aqg6um [Accessed: Sep. 24, 2024].
[17] "2018-04-30 ongoing Sentinel-5P TROPOMI Tropospheric Ozone Column V2 (S5P_L2__O3_TCL)", [Online]. Available: https://dx.doi.org/10.5270/S5P-hcp1l2m [Accessed: Sep. 24, 2024].

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 389-394

Model for Processing Historical Timeseries and Establishing Ruleset for Anomaly Detection in Current Sensor Data and General-Purpose Forecasting for Smart Farming in Latvia

Roberts Volkovičs
Modelling of sociotechnical systems
Vidzeme University of Applied Sciences
Valmiera, Latvia
roberts.volkovics@va.lv

***Abstract*—In this article the model is created for establishing ruleset for further anomaly detection in data from smart farming sensors which could be utilized in data cleaning, data analysis and general-purpose forecasting. Model is based on assumption that processes related to smart farming are tied to nature in particular area, for example, Latvia. In case we have historical data for some metric, for example, air temperature, then we can build such a model as long-term knowledge of phenomena provides the basement for such a model to be successful, for example, we know that in Latvia there are four repeating seasons spring, summer, autumn, and winter, but there are even shorter cycles as twelve months with certain known characteristics for each month and day night cycles. Air temperature is more affected by day and night cycles during summer season, less in other seasons.**

Created model will show calculations based on air temperature, but similar approach could be utilized for other metrics which depend on location and seasonality of nature, such as soil moisture level, sunlight, etc. In case, approach is applied elsewhere it is assumed that rulesets are regenerated based on local historical timeseries data.

Keywords — Anomaly Detection, Data Analysis, Forecasting Techniques, Historical Timeseries, Sensor Data, Smart Farming.

I. INTRODUCTION

Sometimes researchers perform analysis of timeseries data which come from sensors, for example, sensors of smart farming field. As a smart farming we understand the type of farming that takes an advantage of information technologies in order to maximize efficiency or product yield [1]. As an industry agriculture usually focuses on generation of profit the same way as all the other industries, therefore we can imagine that quite frequently due to the aim of finding the right balance between profit and quality of data and precision of measurements smart farming does not make a focus on quality of sensors, rather it tends to cover fields with many sensors which are affordable. This leads to situation that researchers processing the data need to focus a lot on data cleaning, smoothing and removal of anomalies before the actual analysis of interest is possible.

In this article the model is created which could help smart farming researches to define the ranges of normal data, the ranges of anomalous data and the ranges of most likely data values will take according to long term historical timeseries covering the same seasonality or period so many times that it is possible to utilize statistics and visualization techniques to define the previously mentioned ranges.

Once we have well defined approach and model to process certain case in one location of the world based on historical timeseries of metric, the same could be used elsewhere, based on historical timeseries of that location.

The goal of this research is to build the model allowing to utilize historical time series data to establish ruleset for classifying data points as anomalous or normal, therefore we can state that the hypothesis of this research is that it is possible to build a computational model based on historical timeseries data allowing to classify data points in anomalous and normal, and allowing to predict the most

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8569
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

likely data values for season based on previous values for that season.

II. Materials and Methods

As the basement to establish the ruleset to define ranges of normal data and ranges of anomalous data for air temperature in Latvia during particular season, month or day, the open data from 26 Latvian Road Meteo Stations [2] are analysed. It covers the period of more than 10 years which is sufficient as it has enough data points to make the model statistically correct and calculation results and assumptions statistically significant.

All 26 of Latvian Road Meteo Stations have similar characteristics:

1. Data points with values of air temperature are collected each minute;
2. Some data points have no value, some have anomalous value due to sensor error;
3. Overall data quality of 26 Latvian Road Meteo Stations is much higher than quality of data provided by sensors from the fields of smart agriculture;
4. Removing anomalous data and aggregating the rest to closest hour, and by using linear interpolation method from Python Pandas library [3], we can get approximated and correct value of air temperature of approximated hour over territory of Latvia;
5. 20 years of historical timeseries from the same meteo stations could provide statistically correct results for other metrics as well, not only air temperature, but that is out of scope of this research as the focus and aim of the research is to build a model allowing researcher to process such information in standardized way.

As a computational platform the Python programming language will be used focusing on such Python libraries as matplotlib [4], numpy [5], pandas [3], plotly [6], statsmodels [7].

This research will focus on visualization techniques as proof for calculation results as millions of data points will be processed to achieve the aim of the research and there is no other way to demonstrate the proof of this model working other than visualization.

It is assumed that readers can use techniques from statistics and probability behind the scenes on intuitive level as verification of results of visualization.

III. Results and Discussion

As the first step, the data were processed to gain air temperatures in Latvia over the previous 3-year period. Calculation result could be seen in Fig. 1 bellow.

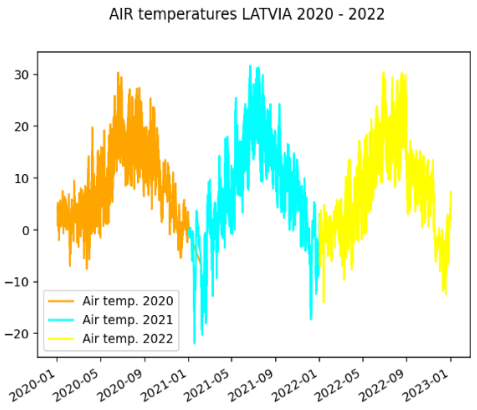


Fig. 1. Air temperatures in Latvia years: 2020, 2021 and 2022.

Fig. 1 demonstrates, that the previous 3-year period of data proves that air temperature data have periodicity over 1-year period and seasonality. Air temperature data do have as well day-night cycles - visualized later during the scope of this article.

Second step, the model allows to adjust the area of most likely values. That could be done by specifying how many timeseries above minimum and bellow maximum values we will consider creating the group of normal data as the rest will create the group of anomalous data, this approach could be compared to Bell-Curve of normal distribution as statistically we can decide the proportion of data point values constructing normal data and proportion of data point values constructing anomalous data.

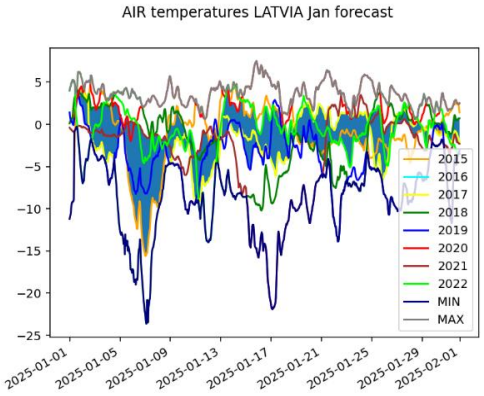


Fig. 2. Air temperature Latvia period from 2015 to 2023.

The Bell-Curve moves over time, like moving average window. That as well means that proportion of data points with normal data is always the same as well of proportion of data points with anomalous data. However, timeseries themselves my cross the border of normal and anomalous data many times during the period of our interest.

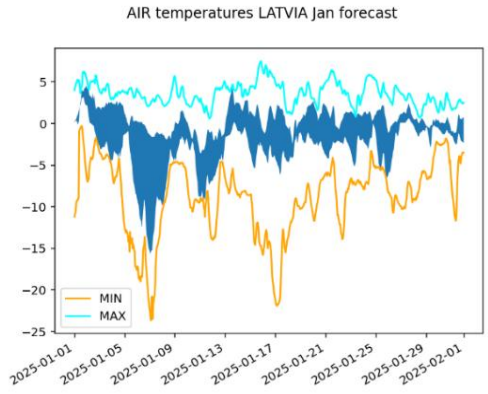


Fig. 3. Air temperature Latvia min/max range most likely range calculated from 2015 to 2023.

As Fig. 2 demonstrates, historical timeseries allow us to create the forecast for January of 2025 utilizing data from period from year 2015 until 2023. For each year data are presented in different colour. The blue area always contains several timeseries inside the area and some timeseries outside the area, as previously mentioned the amount of timeseries inside the area and the amount of timeseries outside the area could be parametrized, but the area itself shows the range of values air temperature most likely should be, based on historic values and proportion of values inside the area is static.

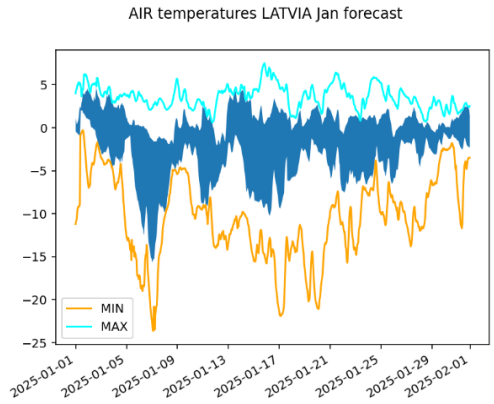


Fig. 4. Air temperature Latvia min/max range most likely range calculated from 2013 to 2015.

Additionally, to values of timeseries from particular year and the area of most likely values, the Fig. 2 shows us the minimum and maximum values based on historical data. Most likely, the values outside the range from min to max could be considered as novelties our outliers, depending on the fact how much historical data we have.

As more historical data we add to the model as more precise the model gets with tendency to expand the range from min to max and expand the range of the most likely values.

In Fig. 3 we see the same data as in Fig. 2, just individual timeseries are removed, but the range from min to max values and the range of the most likely values remains in the graph.

In Fig. 3 the graph is computed based on the period 2015 – 2023 for January, this can be used as a forecast of air temperature based on historic data.

Therefore, we have adjusted the values to timeline to the year of 2025. The same will be done for all the other graphs in this article.

As we see in Fig. 4, after adding a couple of years of timeseries data we slightly expand the range from minimum to maximum and we slightly expand the range of the most likely values.

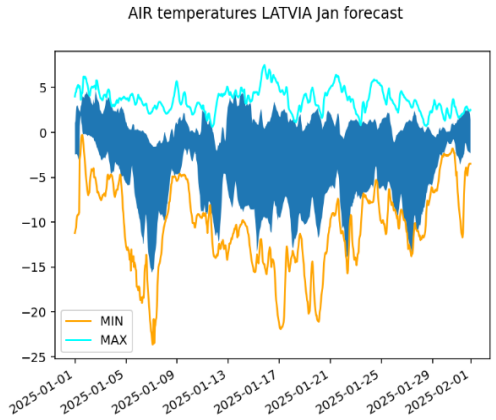


Fig. 5. Air temperature Latvia January min/max range most likely range calculated from 2011 to 2023.

For the scope of this model the decision was made to utilize data from the period of the beginning of the year 2011 to the beginning of the year 2023, for the generation of the ruleset data. In such a way generated graph for January is visible in Fig. 5.

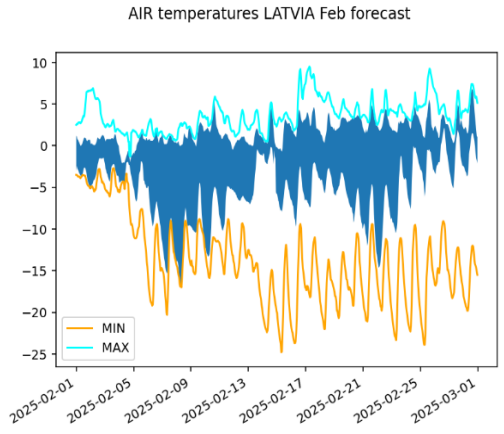


Fig. 6. Air temperature Latvia February min/max range most likely range calculated from 2011 to 2023.

On a modern computer computation necessary to generate the graph takes approximately 5 minutes, therefore it makes sense in the later phase to create some type of aggregation of the results which could be used further by smart agriculture needs.

In such a way complexity of model could be hidden behind the scenes and the work could be reutilized.

In Fig. 6 minimum to maximum range temperatures for February are shown.

To make the results complete, the graphs for the rest of months of the year will be computed.

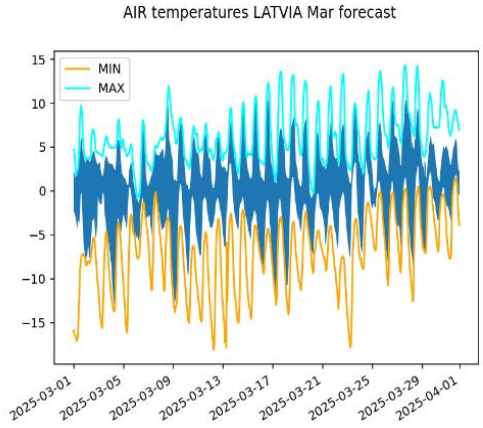


Fig. 7. Air temperature Latvia March min/max range most likely range calculated from 2011 to 2023.

In Fig. 7, the minimum to maximum range temperatures for the month of March can be found.

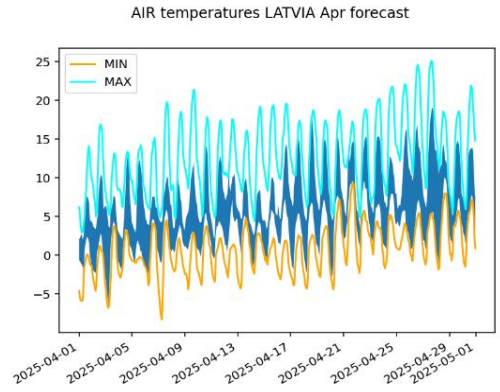


Fig. 8. Air temperature Latvia April min/max range most likely range calculated from 2011 to 2023.

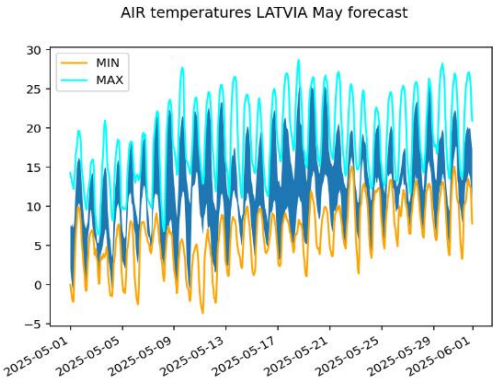


Fig. 9. Air temperature Latvia May min/max range most likely range calculated from 2011 to 2023.

In Fig. 8 minimum to maximum range temperatures for April are visualized.

In Fig. 9, one can find the minimum to maximum range of temperatures for May.

In Fig. 10, the graph of minimum to maximum range temperatures from Jun is shown.

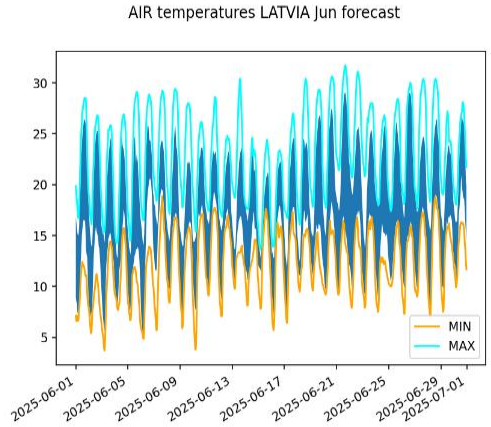


Fig. 10. Air temperature Latvia June min/max range most likely range calculated from 2011 to 2023.

In Fig. 11 minimum to maximum range temperatures for July are visible.

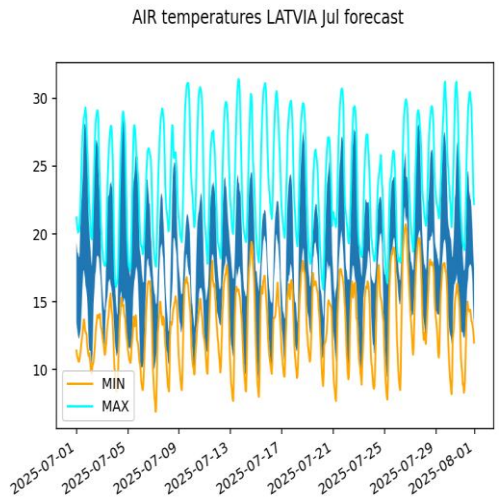


Fig. 11. Air temperature Latvia July min/max range most likely

In Fig. 12 minimum to maximum range temperatures for August can be seen.

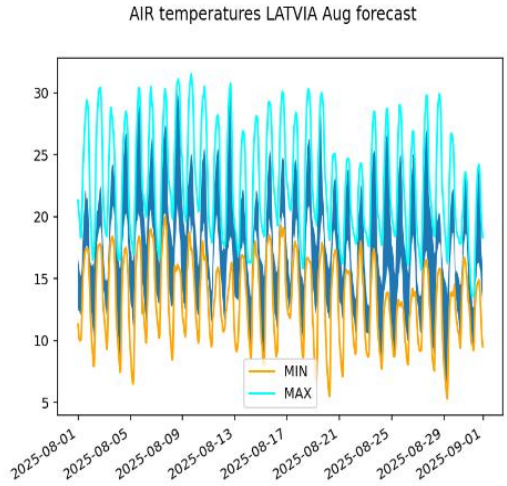


Fig. 12. Air temperature Latvia August min/max range most likely range calculated from 2011 to 2023.

As previously described, air temperatures are very strongly affected by the day/night cycles from March to middle of October. See, Fig. 7 – Fig. 14.

In Fig. 13 minimum to maximum range temperatures for September can be seen.

In Fig. 14 the graph of minimum to maximum range temperatures for October is presented.

In Fig. 15 one can find minimum to maximum range temperatures for November.

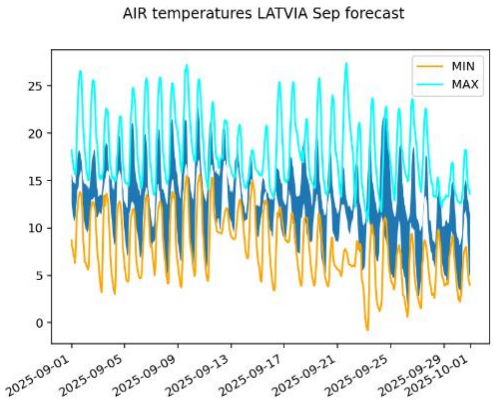


Fig. 13. Air temperature Latvia September min/max range most likely range calculated from 2011 to 2023.

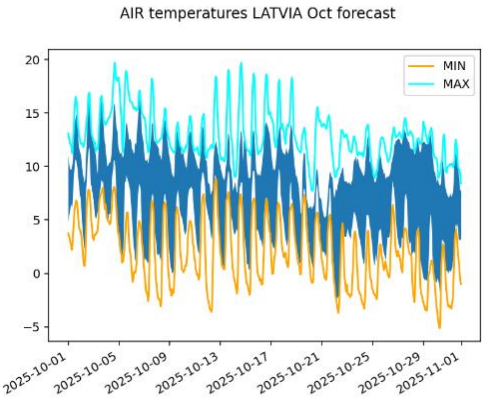


Fig. 14. Air temperature Latvia October min/max range most likely range calculated from 2011 to 2023.

In Fig. 16 minimum to maximum range temperatures for December are visualized.

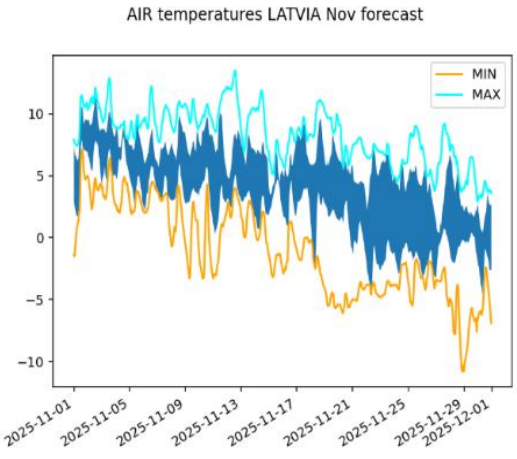


Fig. 15. Air temperature Latvia November min/max range most likely range calculated from 2011 to 2023.

As we see in Tab. 1, it is possible to perform visual analysis or mathematical analysis of long-term historical timeseries and create a parameter table which could be used in further data cleaning, anomaly detection and

removal, and forecasting in different real-world smart agriculture scenarios processing output from huge number of low-cost sensors.

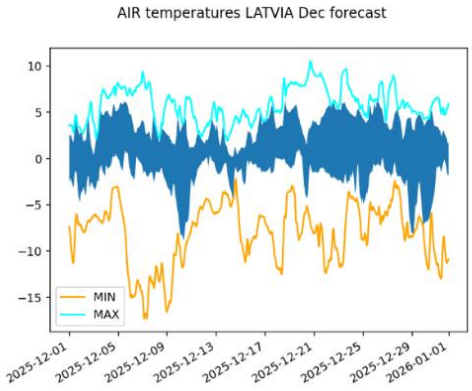


Fig. 16. Air temperature Latvia December min/max range most likely range 2011 – 2023.

TAB. 1 AIR TEMPERATURES MIN/MAX RANGE MOST LIKELY RANGE BY MONTH

Air temperatures MIN, MAX, Expected range by Month				
Month	**MIN**	**MAX**	**Exp. LOW**	**Exp. HIGH**
January	-23	7	-15	4
February	-25	7	-15	5
March	-15	12	-12	10
April	-6	22	-5	15
May	-3	25	0	23
June	4	32	5	25
July	5	32	8	26
August	5	30	7	28
September	0	25	3	22
October	-5	19	-2	15
November	-10	14	-3	10
December	-16	10	-8	6

Main parts of the Python code utilized to generate all the figures from Fig. 1 to Fig. 15 are demonstrated below.

```
...
...
# Calculation of INNER area MIN
# calculated from timesries 2011 - 2022
innerMinJan = at_Jan.groupby('datums').
  apply(lambda grp: grp.nsmallest(3,
'AT').max())
...
...
# Calculation of INNER area MAX
# calculated from timesries 2011 - 2022
innerMaxJan = at_Jan.groupby('datums').
  apply(lambda grp: grp.nlargest(3, 'AT').min())
...
...
# Draw the MIN January line:
# calculated from timesries 2011 - 2022
plt.plot(minJan, c=line_color_Jan, label='MIN')
line_color_Jan = line_color_list_Jan.pop()
...
...
# Draw the MAX January line:
# calculated from timesries 2011 - 2022
plt.plot(maxJan, c=line_color_Jan, label='MAX')
...
...
# Draw the INNER January AREA:
# For example INNER 8 timepoints out of 12
# calculated from timesries 2011 - 2022
plt.fill_between(X, Y11.flatten(),
Y21.flatten())
plt.legend()
...
...
```

Fig. 1. to Fig. 15 were generated using Python library "matplotlib" utilizing interface "pyplot": "plt.plot" and "plt.fill" calls and calculations were done utilising Python Pandas mathematical functions, grouping, etc.

IV. CONCLUSIONS

During this research we have proved that it is possible to create a model that could be used for low-cost smart agriculture sensor data cleaning and anomaly detection utilizing the method of long term historical timeseries data processing.

It is frequently possible to find existing data in the area of interest which could be treated as more reliable than data from smart agriculture sensors and utilize that to compute parameter table according to this model which later could help with cleaning of data from smart agriculture sensors.

ACKNOWLEDGMENTS

This research was funded by the European Commission, Research Executive Agency grant number 101079206, "Twinning in Environmental Data and Dynamical Systems Modelling for Latvia" (TED4LAT).

REFERENCES

[1] Wikipedia, "Smart farming," [Online]. Available: https://en.wiktionary.org/wiki/smart_farming [Accessed: Jan. 22, 2025].
[2] Latvian Government Open Data, "Historical data of road weather stations 2001-2020," [Online]. Available: https://data.gov.lv/dati/dataset/celu-meteo-staciju-vesturiskie-dati-2001-2019-gadi [Accessed: Feb. 09, 2025].
[3] Pandas, "Python Pandas – data analysis library," [Online]. Available: https://pandas.pydata.org [Accessed: Feb. 09, 2025].
[4] Matplotlib, "Matplotlib: Visualization with Python," [Online]. Available: https://matplotlib.org [Accessed: Feb. 09, 2025].
[5] NumPy, "The fundamental package for scientific computing with Python," [Online]. Available: https://numpy.org [Accessed: Feb. 09, 2025].
[6] Plotly, "Plotly Open Source Graphing Library for Python," [Online]. Available: https://plotly.com/python [Accessed: Feb. 09, 2025].
[7] Statsmodels, "Statistical models, hypothesis tests, and data exploration," [Online]. Available: https://www.statsmodels.org/stable/index.html [Accessed: Feb. 09, 2025].

Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume II, 395-399

Modeling and Numerical Solution of Liquid Filtration Processes in Multilayer Oil Fields

Ibrohim Yuldoshev
Digital Technologies and Artificial Intelligence Research Institute
International Agriculture University
Tashkent, Uzbekistan
ibrohimyuldoshev95@gmail.com

Dilmurod Tuhtanazarov
International Islamic Academy of Uzbekistan
Tashkent, Uzbekistan

Turdali Jumayev
International Islamic Academy of Uzbekistan
Tashkent, Uzbekistan

Anvarjon Mahkamov
International Islamic Academy of Uzbekistan,
Tashkent, Uzbekistan

***Abstract*-The paper presents the physic and mathematic models for fluid filtration in the multilayered strata with poorly permeable and well permeable layer. Developed computational algorithm and program for the intermediate model. Shows computer experiment compared the results with other modules for the development of a multilayered reservoir field. Based on analysis numerical results is that the approval of the interim model is optimal in terms of efficiency of computer time and memory consumption of computer technology.**

Keywords-mathematic models, fluid filtration, reservoir field.

I. INTRODUCTION

Many oil and gas condensate fields are a set of deposits, i.e. they are multilayered. In some cases, it is advisable to subdivide the productive horizon into separate units, especially if they are separated from each other by consistent interlayers, such as clay.

For the theory and practice of developing multilayer fluids in fields, it is important to establish the permeability, low permeability or impermeability of the separating bridges. In some cases, this question can be answered using exploratory well data.

If the following conditions are met simultaneously:

1) the distribution of initial reservoir pressures by horizons obeys the barometric formula:

2) gas-water contacts are at the same elevation:

3) the compositions of the fluids in all horizons are the same, then we can reliably say that a hydrodynamic connection has manifested itself at least over geological time. In such cases, when carrying out forecast calculations, one should keep in mind the possibility of a hydrodynamic connection manifesting itself during the development of a multi-layer field.

If the specified conditions are not met, and if the initial pressure in the horizons is distributed according to the hydrostatic law, we can confidently speak of the isolation of the productive horizons from each other. With the specified identification, we should keep in mind the possibility of the absence of a hydrodynamic connection between the layers and the presence of a hydrodynamic connection in the area of water content. Then one of the listed conditions can be met.

Many studies have been conducted on modeling the processes of oil extraction from multi-layer oil fields. The mathematical modeling of fluid filtration in multicomponent fluids including water, gas, and oil as well as in heterogeneous multilayer porous media is the main topic of this research article. It explains the difficulties in resolving multidimensional, nonlinear partial differential equations and looks at several simplifications for the creation of useful models. The scientific work considers existing models of systems incorporating faults, two- and three-phase flows, nanoporous rocks, and man-made substances. Unsteady filtering processes in two-layer systems, whose dynamics rely on permeability, diffusion, and layer thickness, are given special consideration. The study provides methods for improving oil and gas extraction procedures and advances knowledge of the condition of liquids in porous media [1,2,3].

In this study, a mathematical model for examining liquid filtration in horizontal wells in a sealed type of

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol2.8594
© 2025 The Author(s). Published by RTU PRESS.
This is an open-access article under the Creative Commons Attribution 4.0 International License.

formation is developed. The finite element technique (FEM) was used to examine the effects of permeability, deformation, and anisotropy on well performance. Numerical models demonstrate that variables like vertical permeability and isotropy angle have a major impact on flow rate. The software tools and algorithms that have been developed offer useful applications for improving drilling tactics and raising reservoir productivity. A 30.8% increase in productivity during field application demonstrated the model's efficacy in boosting oil and gas extraction [4,5].

Let there be a three-layer interacting layer with a region D, the middle one is highly permeable, and two extreme ones are poorly permeable (Fig. 1). It is required to determine a continuous function of pressure $P_i(x,y,z,t)$ satisfying a system of differential equations

$$\left.\begin{array}{l}\frac{\partial}{\partial x}\left(K_1(x,y,z)\frac{\partial P_1}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_1(x,y,z)\frac{\partial P_1}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_1(x,y,z)\frac{\partial P_1}{\partial z}\right)=M_1(x,y,z)\frac{\partial P_1}{\partial t}\\ \frac{\partial}{\partial x}\left(K_2(x,y,z)\frac{\partial P_2}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_2(x,y,z)\frac{\partial P_2}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_2(x,y,z)\frac{\partial P_2}{\partial z}\right)=\\ =M_2(x,y,z)\frac{\partial P_2}{\partial t}+F(x,y,z,t)\\ \frac{\partial}{\partial x}\left(K_3(x,y,z)\frac{\partial P_3}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_3(x,y,z)\frac{\partial P_3}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_3(x,y,z)\frac{\partial P_3}{\partial z}\right)=M_3(x,y,z)\frac{\partial P_3}{\partial t}\end{array}\right\} \quad (1)$$

under the initial

$$P_i(x,y,z,0)=\varphi_i(x,y,z) \quad (2)$$

and boundary conditions

$$\left.\frac{\partial P_i}{\partial n}\right|_{\Gamma}=0 \quad (3)$$

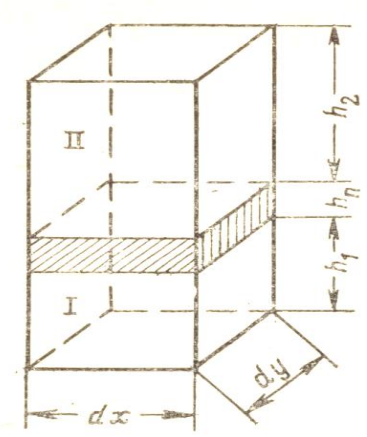


Fig. 1. Elementary volume in the presence of a well-permeable bridge between the layers

Here P_i - is the pressure, K_i, M_i, F_i -are the given functions of their arguments, $i=1,2,3$, n -is the external normal to G, G- is the surface of the filtration region under consideration D [6,7]. As a function $\varphi_i(x,y,z)$, a constant value is often taken that characterizes the undisturbed state of the formation at the initial moment of time, neglecting the weight of the liquid column within the thickness of the i-th interlayer. According to the Hantusch model, instead of solving problem (1)-(3), we have a more simplified problem

$$\left.\begin{array}{l}\frac{\partial}{\partial x}\left(K_2\frac{\partial \vartheta_2}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_2\frac{\partial \vartheta_2}{\partial y}\right)=M_2\frac{\partial \vartheta_2}{\partial t}+F(x,y,t)-q_2;\\ \vartheta_2\big|_{t=0}=\varphi_2(x,y);\ P_i\big|_{t=0}=\varphi_i(x,y,z);\ P_1\big|_{z=h_1-0}=\vartheta_2\big|_{z=h_1+0};\\ P_3\big|_{z=h_2+0}=\vartheta_2\big|_{z=h_2+0};\ q_2=q_1+q_3;\ q_i=\frac{K}{h_i-h_{i-1}}\left.\frac{\partial P_i}{\partial z}\right|_{z=h_i};\\ \vartheta_2=\frac{1}{h_2-h_1}\int P_2(x,y,z,t)dz.\end{array}\right\} \quad (4)$$

where q_i is the flow, $i=1,3$.

Thus, instead of the spatial initial problem (1)-(3), a comparatively simple quasi-three-dimensional problem (4) was obtained. In the work [5-8], the problem in this formulation is considered, the methods of solution in test data are given, the results are obtained and analyzed. However, researchers still face difficulties in solving the problem according to the obtained model, taking up more memory and time. For this purpose, we use a somewhat simplified model than the Hantush model, an intermediate model [1, 8].

In the task (4), averaging the movements by spatial variables to determine the values of the flow between layers and the change in the pressure value in the bridges, we obtain the so-called material balance model

$$\frac{\partial}{\partial z}\left[K_i(z)\frac{\partial \vartheta_i}{\partial z}\right]=M_i\frac{\partial \vartheta_i}{\partial t};\ h_{i-1}<z<h_i;\ t>0. \quad (5)$$

$$\vartheta_i\big|_{t=0}=\varphi_i(z);\ z\in[h_{i-1},h_i]. \quad (6)$$

$$\left.\frac{\partial \vartheta_i}{\partial z}\right|_{z=h_0,h_3}=0;\ \vartheta_i\big|_{z=h_1,h_2}=\overline{\vartheta_2}. \quad (7)$$

$$\vartheta_i=\int_0^1\int_0^1 P_i(x,y,z,t)dxdy;\ i=1,3.$$

here, $\overline{\vartheta_2}=\sum_{l=1}^{N_x}\sum_{j=1}^{N_y}\frac{\vartheta_{2l,j}}{N_x\cdot N_y}$, where N_x, N_y is the number of nodes along X, Y.

The change in the pressure field in a well-permeable formation is determined by solving the equation

$$\frac{\partial}{\partial x}\left(K_2\frac{\partial \vartheta_2}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_2\frac{\partial \vartheta_2}{\partial y}\right)=M_i\frac{\partial \vartheta_2}{\partial t}+F(x,y,t)-q_{n2} \quad (8)$$

with the corresponding initial and boundary conditions.

II. MATERIALS AND METHODS

To solve the problem numerically, we move on to dimensionless variables:

$$\overline{K}=\frac{K}{K_x},\ \overline{\mu}=\frac{\mu}{\mu_x},\ \overline{x}=\frac{x}{L_x},\ \overline{y}=\frac{y}{L_y},\ \overline{z}=\frac{z}{L_z},\ \overline{P}=\frac{P}{P_x},$$

$$Q=A\sum_{i=1}^{N}\delta(x-x_i,y-y_i)q_i,$$

$$A=\frac{L_x\mu_x}{K_xP_xL_yL_z},\ t=\tau\frac{K_x}{\mu_xL_x^2},\ Qp_x=\frac{L_x\mu_x}{K_xP_xL_yL_z}q_{n2}. \quad (9)$$

For ease of notation, we omit the dashes above the variables.

Here is the q_{n2}-function of the flow entering as a uniformly distributed internal drain [9].

Thus, the complicated original problem (4) is reduced to a sequential solution of the one-dimensional (5) and two-dimensional problem (8).

To solve the problem (8), we use the method of the longitudinal-transverse scheme [10,11] and the flow version of the sweep method.

For this, we cover the given two-dimensional region with a uniform grid:

$$\omega_{x,y}=\{(x_i=i\cdot h_x,\ h_x=\frac{1}{N_x}\ \ y_j=j\cdot h_y,\ h_y=\frac{1}{N_y}\ ),\ i=\overline{1,N_x},\ j=\overline{1,N_y},\ \}$$

In equation (8) we introduce variables in the form for applying the flow sweep:

$$w_x=K\frac{\partial \vartheta_2}{\partial x},\ w_y=K\frac{\partial \vartheta_2}{\partial y}.$$

Then (8) takes the following form:

$$\frac{\partial w_x}{\partial x}+\frac{\partial w_y}{\partial y}=m\frac{\partial \vartheta_2}{\partial t}+Q-q_{n2} \quad (10)$$

The finite difference form of equation (10) when calculated using the longitudinal-transverse scheme is as follows:

$$\left(w_{x\ i+\frac{1}{2},j}^{k+\frac{1}{2}}-w_{x\ i-\frac{1}{2},j}^{k+\frac{1}{2}}\right)=m_{i,j}\frac{h_x}{\tau}\vartheta_{2i,j}^{k+\frac{1}{2}}+\frac{h_x}{\tau}F_i;\ F_i=\tau\cdot\left(Q_{i,j}-\left(q_{n2}+\frac{w_{y\ i,j+\frac{1}{2}}^{k}-w_{y\ i,j-\frac{1}{2}}^{k}}{h_y}\right)\right)-m_{i,j}\vartheta_{2i,j}^{k};$$

$$\left(w_{y\ i,j+\frac{1}{2}}^{k+1}-w_{y\ i,j-\frac{1}{2}}^{k+1}\right)=m_{i,j}\frac{h_y}{\tau}\vartheta_{2i,j}^{k+1}+\frac{h_y}{\tau}F_j;\ F_j=\tau\cdot\left(Q_{i,j}-\left(q_{n2}+\frac{w_{x\ i+\frac{1}{2},j}^{k+\frac{1}{2}}-w_{x\ i-\frac{1}{2},j}^{k+\frac{1}{2}}}{h_x}\right)\right)-m_{i,j}\vartheta_{2i,j}^{k+\frac{1}{2}}. \quad (11)$$

In equation (5) we introduce variables in the form for applying the flow sweep [12,13]:

$$w_z=K\frac{\partial \vartheta_i}{\partial z},\ i=1,3.$$

Then (5) takes the following form:

$$\frac{\partial w_z}{\partial z}=m\frac{\partial \vartheta_i}{\partial t},\ i=1,3 \quad (12)$$

Finite difference form of equation (12):

$$\left(w_{z\ j+\frac{1}{2}}^{k+1}-w_{z\ j-\frac{1}{2}}^{k+1}\right)=m_j\frac{h_z}{\tau}\vartheta_{ij}^{k+1}+\frac{h_z}{\tau}F_i,\ F_i=-m_j\vartheta_{ij}^{k},\ i=1,3. \quad (13)$$

In parameterized form, the boundary conditions can be written as:

$$\left[\lambda\frac{\partial \vartheta_i}{\partial n}+(1-\lambda)\vartheta_i\right]_\Gamma=\gamma,\ i=1,2,3.$$

The parameter λ takes the value 0 or 1 (for $\lambda=0$ the first boundary condition, for $\lambda=1$ the second boundary condition).

To calculate (11) and (13) using the flow sweep method [13-14], we use the following algorithm:

$$\left.\begin{aligned}
&\alpha_N=\frac{-\lambda_2}{0.5\cdot\lambda_2+(1-\lambda_2)},\quad \beta_N=\frac{\lambda_2-0.5\cdot\lambda_2*F_N}{0.5\cdot\lambda_2+(1-\lambda_2)},\\
&j=(N_x-1)...0,\quad j=(N_y-1)...0,\\
&\alpha_j=\frac{\frac{h^2}{\tau}-\alpha_{j+1}}{1+\frac{h^2}{\tau}-\alpha_{j+1}},\quad \beta_j=\frac{\beta_{j+1}-F_j\left(\frac{h^2}{\tau}-\alpha_{j+1}\right)}{1+\frac{h^2}{\tau}-\alpha_{j+1}},\\
&\vartheta_{i0}=\frac{\frac{h}{\tau}\cdot\lambda_1\cdot\beta_0-\gamma_1\cdot\left(\alpha_0-\frac{h^2}{\tau}\right)-0.5\frac{h}{\tau}\lambda_1\cdot F_0\cdot\left(\alpha_0-\frac{h^2}{\tau}\right)}{\left((1-\lambda_1)-0.5\cdot\frac{h}{\tau}\lambda_1\right)\cdot\left(\alpha_0-\frac{h^2}{\tau}\right)+\frac{h}{\tau}\lambda_1},\\
&j=0...(N_x-1),\quad j=0...(N_y-1),\\
&\vartheta_{i\,j+1}=\left(\frac{\alpha_{j+1}}{\frac{h^2}{\tau}-\alpha_{j+1}}\right)\cdot\left(\beta_{j+1}-\vartheta_{i\,j}\right)+\beta_{j+1},\ i=1,2,3.
\end{aligned}\right\} \quad (14)$$

III. RESULTS AND DISCUSSION

To verify reliability, the results obtained for the developed algorithms have been compared with the results of trial functions.

The limits of applicability of this model and estimates of the values of $\|P_i - \vartheta_i\|_c$; $\|\vartheta_i - W_i\|_c$; $\|P_i - W_i\|_c$; are given in [14,16].

To analyze the results of the intermediate model and compare them with the calculation results obtained using the Hantusch model, the following initial data were taken as the basis for the calculations:

$P_i|_{t=0} = 100$ atm; $m_1 = m_2 = m_3 = 0.2$; $k_2 = 0.2$; $k_1 = k_3 = 0.05$; $h_0 = 0$; $h_1 = 1/12$; $h_2 = 11/12$; $h_3 = 1$; $\varphi_i = 1$; $\mu = 2$; $\Delta x = 0.01$; $\Delta y = 0.01$; $\Delta z = 0.02$;

$\tau = \frac{Lx \cdot Lx}{86400}$; $Lx = 1000м$; $Ly = 1000м$; $Lz_2 = 100м$; $Lz_1 = Lz_3 = 50м$.

The values of the selections and the coordinates of the well locations are given in Table 1.

TABLE 1. WELL DATA.

№	X, m	У, m	$10^3 * \frac{m^3}{day}$	№	X, m	У, m	$10^3 * \frac{m^3}{day}$
1	200	200	10	9	600	200	10
2	200	400	10	10	600	400	10
3	200	600	10	11	600	600	10
4	200	800	10	12	600	800	10
5	400	200	10	13	800	200	10
6	400	400	10	14	800	400	10
7	400	600	10	15	800	600	10
8	400	800	10	16	800	800	10

The pressure distributions of the highly permeable formation and the values of the flow from the bridge are symmetrical relative to the average formation due to the symmetry of the location of the selected points (wells). Therefore, their values in a quarter of the field are given in Tables 2 and 3, respectively. For a complete presentation of their values, Fig. 2 presents them as a map of isolines at the time $T = 720$ days.

TABLE 2. VALUES OF HIGHLY PERMEABLE FORMATION.

X / Y	X=0	X=100	X=200	X=300	X=400	X=500
Y=500	0.998	0.996	0.994	0.994	0.993	0.993
Y=150	0.998	0.996	0.992	0.993	0.991	0.993
Y=400	0.998	0.996	0.980	0.993	0.979	0.993
Y=350	0.998	0.996	0.992	0.993	0.991	0.993
Y=300	0.998	0.997	0.994	0.994	0.993	0.994
Y=250	0.998	0.997	0.993	0.994	0.992	0.993
Y=200	0.998	0.997	0.981	0.994	0.980	0.994
Y=150	0.999	0.997	0.994	0.995	0.993	0.995
Y=100	0.999	0.998	0.997	0.997	0.996	0.996
Y=50	0.999	0.999	0.998	0.998	0.997	0.997
Y=0	0.999	0.999	0.998	0.998	0.998	0.998

TABLE 3. FLOW VALUES.

X / Y	X=0	X=100	X=200	X=300	X=400	X=500
Y=500	0.0000	0.0037	0.0072	0.0073	0.0084	0.0075
Y=150	0.0000	0.0039	0.0089	0.0077	0.0101	0.0079
Y=400	0.0000	0.0042	0.0242	0.0081	0.0254	0.0084
Y=350	0.0000	0.0039	0.0088	0.0076	0.0100	0.0078
Y=300	0.0000	0.0036	0.0069	0.0070	0.0081	0.0073
Y=250	0.0000	0.0036	0.0084	0.0071	0.0095	0.0073
Y=200	0.0000	0.0035	0.0232	0.0069	0.0242	0.0072
Y=150	0.0000	0.0027	0.0069	0.0055	0.0077	0.0057
Y=100	0.0000	0.0017	0.0035	0.0036	0.0042	0.0037
Y=50	0.0000	0.0010	0.0020	0.0023	0.0025	0.0024
Y=0	0.0000	0.0037	0.0072	0.0073	0.0084	0.0075

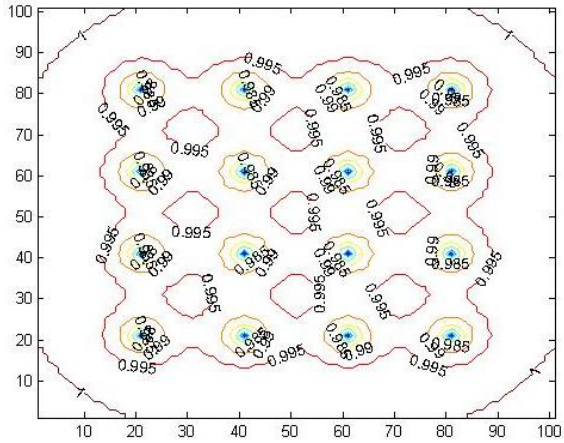


Fig.2. Isobar of a well-permeable reservoir

Now let's see how the pressure value around the well changes over time. Considering the symmetry of the results, let's look at one of the neighboring points to the well at different values of the viscosity coefficient (table 4) for two models

TABLE 4. DIFFERENT VALUES OF THE VISCOSITY COEFFICIENT FOR TWO MODELS.

t day	Intermediate model		Hantush's model		Intermediate model		Hantush's model	
	$\mu = 2$				$\mu = 5$			
200	0.991	0.985	0.991	0.985	0.987	0.982	0.982	0.967
400	0.989	0.983	0.989	0.982	0.979	0.963	0.979	0.963
540	0.987	0.981	0.987	0.981	0.977	0.961	0.977	0.961
720	0.985	0.979	0.986	0.980	0.975	0.959	0.975	0.960

The following conclusions can be drawn from the given values. For both models in the considered example, the pressure values are almost the same. Therefore, with such data, it is advisable to use PM using a small amount of memory and less calculation time.

IV. CONCLUSIONS

This research comprehensively addresses the complexities of modeling and solving fluid flow dynamics in multilayer oil and gas fields, particularly under conditions involving hydrodynamic connections between layers. The study focuses on simplifying the intricate problem of pressure distribution and flow calculations in multilayer reservoirs using an intermediate model (IM) and comparing its efficacy with the more computationally intensive Hantush model.

In conclusion, this study demonstrates that the intermediate model is a robust and efficient alternative to traditional methods for simulating fluid flow in multilayer reservoirs. Its balance of accuracy, computational efficiency, and adaptability makes it an invaluable tool for optimizing the development and management of oil and gas fields. Future research can further enhance the model by incorporating more complex geological features and real-time data integration, enabling even more precise and dynamic field management.

V. ACKNOWLEDGMENTS

We express our deep gratitude to the Research Institute of Digital Technologies and Artificial Intelligence and the International Islamic Academy of Uzbekistan for their constant support and provision of necessary resources during this research. We express our sincere gratitude to our colleagues at the International Agricultural University in Tashkent for their valuable feedback and insights that have enriched this work. We also note that the main work of the scientific community in Uzbekistan in the field of modeling liquid filtration has given great impetus to our research. Finally, we sincerely thank our families for their constant encouragement and patience.

VI. REFERENCES

[1] N. Ravshanov, Yu. N. Islomov, M. Kukanova, “Numerical modeling of the filtration problem of oil and gas in three-layer porous medium,” Uzbek journal “Calculation and applied mathematics problems”,Tashkent, no 1, 2016, pp. 29-45.

[2] N. Azhikhanov, K. Bisembaeva, B.Temirov, N. Zhunissov, “Mathematical Model of Fluid Filtration to Horizontal Well in Tight Heterogeneous Formation,” Global Journal of Pure and Applied Mathematics. ISSN 0973-1768, vol 12, no. 1, pp. 201-212, 2016.

[3] Yu.P.Korotaev, S.N.Zakirov, Theory and design of development of gas and gas condensate fields, M.: Nedra, 1981, p. 294.

[4] S. N. Zakirov, B. B. Lapuk, Design and development of gas fields, M.: Nedra, 1974, p. 374.

[5] V. N. Shchelkachev, M.A.Gusein-zade, “Influence of permeability of the roof and bottom of the formation on the movement of fluid in it,” oil industry, no. 2, 1953.

[6] M. S. Khantush, New in the theory of flow. In the collection: Issues of hydrogeological calculations, Moscow: Mir, 1964.

[7] N. Mukhitdinov, Gas-hydrodynamic study of nonlinear filtration of liquid and gas, Tashkent: Fan, 1977, p. 152.

[8] A. A. Samarsky, Introduction to the theory of difference schemes, Moscow: Nauka, 1971, p. 455.

[9] D. S. Tukhtanazarov, “Development of mathematical models of fluid filtration in multilayer formations,” Uzbek journal “Problems of Informatics and Energy,” Tashkent, no. 3-4, 2014.

[10] E. I. Parmuzin, & V. P. Shutyaev, “Numerical solution of the problem on reconstructing the initial condition for a semilinear parabolic equation,” Russian Journal of Numerical Analysis & Mathematical Modelling, vol 21, no. 4. 2006.

[11] I.Alimov, D.S.Tukhtanazarov, “Computational algorithms for solving two-dimensional hydrodynamic problems using sweep methods,” Uzbek journal “Problems of informatics and energy,” Tashkent, no. 5-6, p. 53, 2013.

[12] D. Tuhtanazarov, I. Xolmatova & K. Abdulbosit, “Model And Algorithm For Solving One-Dimensional Two-Phase Of Filtration Task,” in 2019 International Conference on Information Science and Communications Technologies, pp. 1-5, IEEE, November 2016.

[13] S. Mirzaev, D. Tukhtanazarov, K. Karimova, & N.Samadov, “Software for Determining Residual Oil Reserves in Oil Deposit Development,” in IOP Conference Series: Materials Science and Engineering, vol. 883, no. 1, p. 012119, IOP Publishing, July 2020.

[14] D. Tuhtanazarov, M.Xodjayeva, T. Jumayev, A. Mahkamov, “Computational algorithm and program for determining the indicators of wells based on processing of information of oil fields,” AIP Conference Proceedings, 2432, 060021, 2022.

[15] D. Tuxtanazarov, T. Jumayev, A. Mahkamov, & I. Yuldoshev, “Algorithm and program for calculating the coefficient of oil recovery using reserves when oil is displaced from fields,” in AIP Conference Proceedings, vol. 3244, no. 1, AIP Publishing, November 2024.

[16] N. Ravshanov, I. Kholmatova, & D. Tukhtanazarov, (2024, November). “Mathematical modeling of two-phase (oil-water) filtration in a porous medium”. in AIP Conference Proceedings, vol. 3244, no. 1, AIP Publishing, November 2024.