Modeling the Technology of the Varna Ferry Complex Operation Using the Queueing Theory

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ABSTRACT - The article focuses on the analysis and optimization of the technological process at the Ferry Complex for freight transportation, connecting maritime and railway transport. A key feature of this complex is the presence of railway networks with different track gauges, which necessitates specialized operations such as bogie exchange and additional shunting activities, leading to specific challenges in managing technological operations. To optimize technological operations or the required infrastructure at the terminal yards, mathematical modeling and simulations are considered. These simulations include optimization algorithms for resource allocation, heuristic and metaheuristic approaches for the distribution of freight flows, and bogie exchange. The simulations allow for the assessment of the impact of changes in technological processes and support decision-making to improve the complex's performance, as well as its infrastructure, depending on the volume of freight flows, including hazardous materials cargo. The Ferry Terminal is modeled as a complex system, composed of various interacting technological subsystems, which are formalized as queueing systems. This approach allows for the use of well-known analytical formulas from Queueing Theory to represent the technological process. Formulas are derived to determine the duration of technological operations depending on the type of cargo (hazardous or not), the dwell time of the wagons in the complex, and the number of requests per subsystem. This enables the optimization of the technical equipment at the terminal, based on the size of the processed wagon flow. The model is developed for the Varna Ferry Complex, which handles a large volume of freight and involves specific logistics processes related to the handling of freight wagons. The complex includes a bogie exchange facility where wagons undergo the process of replacing running gear to meet the requirements of different track gauges. The technological operations are formalized, evaluated, and various subsystem parameters are determined. As a result, depending on the size of the wagon flow, the technological process or technical equipment of the complex can be optimized. Modernization and optimization of the complex will lead to improved capacity and competitiveness, providing greater flexibility and efficiency in freight handling.

Keywords – ferry complex, mathematical modelling, queueing theory

I. Introduction

The Ferry Complex Varna (FBK-Varna) holds a strategic geographical position on the Bulgarian Black Sea coast, making it a key logistics hub for freight transport between Europe and the Black Sea basin countries. Located at the crossroads of Asia and Europe, the complex plays an essential role in regional and international trade, enabling combined sea and land freight transport [1].

In recent years, there has been anincreasing trend in freight transport across the Black Sea, driven by global economic processes and regional efforts to improve transport connectivity. Despite the challenges posed by the military conflict in Ukraine, the anticipated stabilization of the region is expected to lead to the restoration of the ferry connection between FBK-Varna and Odessa—a historically significant transport artery that has handled substantial freight volumes.

To address the expected growth in freight traffic and ensure efficient resource management [2][3] at FBK-Varna, the application of scientific methods for analyzing and optimizing operational processes is necessary [4][5]. In this context, queuing theory (QT) offers a powerful tool for modeling the technological operations within the ferry complex [6][7][8][9].

This paper determines the dwell time of railway wagons at FBK-Varna based on the chosen operational technology and the development of an analytical simulation model based on QT. The study provides valuable insights into optimizing transport flows, reducing cargo dwell time, and improving the overall logistical efficiency of the complex. By utilizing QT, service

parameters can be analyzed, system load forecasts can be made, and strategies for process efficiency improvement can be proposed [10][11][12].

In order to develop a model of the ferry complex, the freight flows that passed through the complex over the last six years were studied [1] and the operating technology was examined, taking into account the specifics of the station [13].

II. MATERIALS AND METHODS

The ferry complex can be viewed as a queuing system consisting of several subsystems.

To model the ferry complex, a subsystem approach is used, aiming to determine the wagon dwell time and the required technical equipment based on the magnitude of handled wagon flows. The layout follows a fully sequential scheme—reception yard, shunting facility for train decomposition and composition, a bogie exchange facility with tracks for different rail gauge widths, a pre-ferry yard with broad-gauge tracks, and movable bridges for ferry loading and unloading [13]. This sequential layout and the representation of the station as a QT system facilitate the modeling, as depicted in Fig. 1.
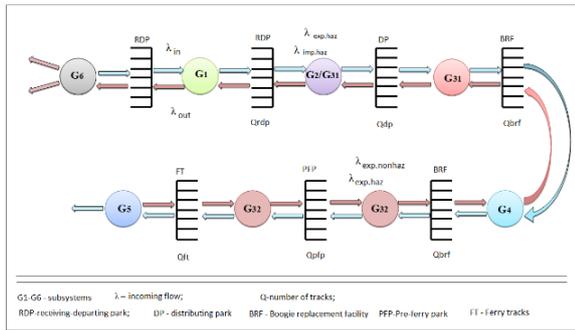

Fig.1 Structural diagram of the Ferry Complex - Varna as a QT system

Depending on the activity being performed, the station consists of six subsystems and each of them is characterized by an input flow λ_{Gi}; service intensity μ_{Gi}, service devices S_{Gi}, service time t_{Gi}^{ser}; probability of expected service P_{Wi}, expected service time W_{Gi} and number of requests in the system n_{Gi} [14][15][16]. In order to determine the stay of the wagons in the station, the processing and expected processing times for the different subsystems must be determined [6][17]. The six technological subsystems G_i involved are:

- Subsystem G_1 - technological system for processing freight trains upon arrival and departure. Freight trains are accepted on the tracks in the POP, the train locomotive is uncoupled, commercial and technical inspection are performed, documents are processed and prepared for decomposition. The same is done when accepting wagons (import). They are prepared for departure. In addition to the operations described, a full test of the brake system is performed on the composed

train. The special feature of the station, as well as all the border stations, is that customs checks and document processing are also performed. This subsystem is multi-channel, because there may be more than one brigade for servicing trains, but the number of brigades depends on the size of the served wagon flows for export to the ferry and for import in the opposite direction. Therefore, we assume that subsystem G1 is M/G/s (Poisson input flow/random service time/s service devices). The incoming flow of trains for one day (24 hours) in the subsystem is determined by:

$$\lambda = \lambda_{imp} + \lambda_{exp} = \frac{N_{imp} + N_{exp}}{24}, \qquad (1)$$

where: $\lambda_{imp}, \lambda_{exp}$ is the intensity of incoming flow;

$N_{imp} + N_{exp}$ – is the train from import and export

And the service time of the trains is determined by:

$$t_{G_1}^{ser} = \frac{\lambda_{imp} t_{imp} + \lambda_{exp} t_{exp}}{\lambda_{G_1}} \frac{24}{24 - T_{const}}, \qquad (2)$$

The service intensity is determined by:

$$\mu_{G_i} = \frac{1}{t_{G_i}^{ser}} \quad [\text{trains/hour}] \qquad (3)$$

Waiting time in queue in subsystem M/G/1:

$$W_{M/G/s} = \frac{Pw(1 + v_{in}^2)}{2.S.\mu(1 - \chi)}, \quad [\text{h/train}] \qquad (4)$$

Where $\qquad \chi = \frac{\lambda_{G_1}}{\mu_{G_i}.s} \qquad (5)$

The total waiting time of one request in subsystem G1 is sum of waiting times in queue and service time:

$$t_{G1} = W_{G1} + t_{G_1}^{ser}, \quad [\text{h/train}] \qquad (6)$$

- Subsystem G_2/G_{31} - operations of decomposing, composing and shunting with wagons with bogies with standard gauge. The shunting device for decomposing and composing is one, but the servicing shunting locomotives are two, because parallel operations of the shunting device and servicing the workshop for changing bogies can be performed. This system is single-channeled, determined by the number of shunting devices. The incoming flow into the train system for 1 day is determined by the formulas:

$$\lambda_{haz} = \lambda_{import}^{haz.} + \lambda_{export}^{haz} \qquad (7)$$

$$\lambda_{nonhaz} = \lambda_{import}^{nonhaz} + \lambda_{export}^{nonhaz.}, \qquad (8)$$

where haz/nonhaz – determines the cargo type (hazardous or non-hazardous)

The train service time for 1 day (24 hours) $t_{G2/G31}^q$ is determined:

$$t_{G2/G31}^{ser}=$$
$$\frac{\lambda_{imp}t_{comp}+\lambda_{exp}t_{decomp}+\lambda_{haz}t_{load}+\lambda_{nonhaz}t_{load}}{\lambda_{imp}+\lambda_{exp}} * \frac{24}{24-T_{inc}},$$
[h/train] $\qquad$ (9)

$$W_{G2/31} = \frac{\rho^2(\upsilon_{inc.}^2+\upsilon_{q.}^2)}{2\mu(1-\rho)(1-(1-\rho)\upsilon_{inc.})}, \quad [h/train] \qquad (10)$$

- Subsystem G_{32} – shunting operations with wagons with wide gauge bogies. The subsystem includes shunting operations, such as feeding the wagons to the boogie replacement facility (BRF) and the specialized track for changing the bogies; pulling the wagons with the changed bogies into the Pre-ferry park (PFP); unloading and loading operations of ferry ships. There are two locomotives in this subsystem and two shunting brigades work, due to the specifics of the loading and unloading activity: when unloading the ships – first the wagons are pulled from the middle track, then the wagons are pulled from the two symmetrically located tracks simultaneously with the help of two shunting locomotives and finally the remaining two tracks again simultaneously. The reverse process is done similarly. This system is multi-channel and depends on the locomotives used, which cannot be less than two. Therefore, we assume that the G_{32} subsystem is M/G/s (Using same formulas as for G1).

- Subsystem G_4 – changing the bogies of the wagons, which are prepared for loading on the ship or for movement on the railway line. The bogies of the wagons with dangerous goods are changed on a specialized track for changing bogies, by feeding three wagons at a time. The remaining wagons with goods are fed ten wagons at a time. This subsystem is the most interesting, because there is a specialization of the tracks depending on the type of cargo, but the service brigade is now one. That is why it will be considered as a single-channel one with servicing priority requests, which are dangerous goods.

$$W_{haz} = \frac{\rho_{haz}^2(\upsilon_{ibx}^2+\upsilon_{ioo}^2)}{2.\mu(1-\rho_{haz}).[1-(1-\rho_{haz})\upsilon_{bx}]} \quad [h/train] \quad (11)$$

$$W_{nonhaz} =$$
$$= \frac{\rho_{haz}^2(\upsilon_{ibx}^2 + \upsilon_{ioo}^2)}{2.\mu(1-\rho_{haz})(1-\rho_{nonhaz}).[1-(1-\rho_{haz})\upsilon_{bx}]}$$
(12)

$$W_{G4} = W_{haz} + W_{nonhaz} \quad [h/train] \qquad (13)$$

✓ Subsystem G_5 - technological system for sending a train from a ferry, by sailing the loaded ship by sea. The peculiarity is that these transports are at a large time interval depending on a relatively constant scheduled movement of the ferry. Only the waiting time for departure will be considered, because the loading and unloading of ships as service time is taken into account in subsystem G4. The system will be considered as a single-channel with service intensity depending on the capacity of the ships and the intervals of their arrival. The subsystem is assumed to be M/M/1 and the waiting time for service is:

$$W_{G5} = \frac{\rho}{\mu(1-\rho)}, [h/train] \qquad (14)$$

- Subsystem G_6 - technological system for sending wagon traffic along the railway network of the individual [d] adjacent sections. It consists of [d] technological systems. For each section, moving transit trains will have priority and the waiting time for departure to the railway network will be determined by the formulas for G_4.

The stay of wagons at the station is determined as the sum of the processing and waiting times for service

$$T_{ferri} = \sum_{i-1}^{6}(t_{i.proc} + t_{i.proc.q}) \quad (15)$$

III. RESULTS AND DISCUSSION

The model was applied to a realistic freight flow forecast for 2025 and the following input data: statistical data on the duration of technological operations, two shunting locomotives for each gauge, priority service for wagons with dangerous goods in the bogie change shop (G4), ferries with a capacity of 5 tracks of 10 wagons arriving regularly every day. The specific consideration does not take into account the delays of the ferries due to schedule disruptions due to bad weather or other reasons. The volumes of the incoming flow are for 1 year M = 9689 wagons, of which:

A. M imp = 5 997 wagons:
a) average number of wagons in the composition– $m_{c\,import} = 10$;
b) 76% wagons with non-hazardous cargo – $M_{imp\,nonhaz} = 4\,558$;
c) 24% wagons with hazardous cargo - $M_{imp\,haz} = 1\,439$.

B. M exp = 3 692:
C.
a) average number of wagons in the composition – $m_{c\,export} = 17$;
b) 76% wagons with non-hazardous cargo – $M_{export\,nonhaz} = 2\,806$;
c) 24% wagons with hazardous cargo – $M_{exp\,haz} = 1\,439$.

We determine the input parameters for the station in the number of trains per day:

$$N = \frac{M}{365m_c}, tr/day \qquad (16)$$

$$N_{imp} = \frac{M_{import}}{365m_{c\,import}} = 1,64\,tr/day,$$

$$N_{exp} = \frac{M_{exportc}}{365m_{c\,export}} = 0,60\,tr/day,$$

$$N = N_{import} + N_{export} = 2,24\,tr/day,$$

Dimensioning of subsystem G1 – subsystem for processing trains by arrival and departure

- The incoming flow of trains for 1 day (24 hours) in the system (7):

$$\lambda = \lambda_{imp} + \lambda_{exp} = \frac{N_{imp} + N_{exp}}{24},$$

where:

λ_{imp}; λ_{exp} – intensity of incoming flow for import and export.

$\lambda_{imp} = \frac{N_{imp}}{24} = 0,07$ train/day;

$\lambda_{exp} = \frac{N_{exp}}{24} = 0,03 \; train/day,$

$\lambda_{G1} = 0,093 \; train/hour,$

- the time for servicing trains for 1 day (24 hours) in the system $\overline{t}\,^q_{G1} = 6,89 \; h/train$ by the formulas (2):

$$\overline{t}_{G1} = \frac{\lambda_{imp} t_{imp} + \lambda_{exp} t_{exp}}{\lambda_{G1}} * \frac{24}{24 - T_{const}} \; , h/train$$

where:
T_{const} = 2,20 h.;
t_{imp} = 5,75 h;
t_{exp} = 7,517 h;

We determine the intensity of service (3)

$\mu_i = \frac{1}{t\,^{ser}_{Gi}} = 0,144$, train/h

Number of service brigades S = 1. and the probability that the arriving train will wait for service $P_w = \chi = 0,648$. Waiting time in queue (4):

W_{G1} =2,42 h/train

The total waiting time of one request in subsystem G1 (6):

t_{G1} =9,31 h/train

In the same way we determine the parameters for the remaining subsystems and the results are given in Table1.

TABLE 1 TIMES IN SMO

	G_1	$G_{2/31}$	G_{32}	G_4	G_5	G_6
t_{ser}	6.89	4.69	5.63	2.13	2.50	0.80
W	2.42	1.99	2.89	7.70	12.84	5.11
t_{Gi}	9.31	6.67	8.52	9.83	15.34	5.91

In cases where we determine the dwell time of export wagons, the times in subsystems G1, G2, G3, G4, and G6 are summed. However, for import wagons, subsystem G6 is replaced by subsystem G5. Export wagons stay at the station is 49.68 hours and imported wagons remain at the station is 40.25 hours.

IV. CONCLUSION

The Ferry Complex in Varna can be considered a queuing system due to its complex operations, high volume of serviced clients and cargo, and sophisticated infrastructure that ensures effective and coordinated service. Using mathematical modeling and creating a QT model allows for simulating different scenarios involving unexpected changes in cargo flow type and volume, identifying bottlenecks under increased freight traffic.

Model validation showed that the total dwell time for export wagons before departure from Varna Ferry Terminal is approximately 50 hours per wagon, while import wagons remain for 41 hours per wagon. This aligns with reality since trains can be dispatched inland when a complete trainset is ready, whereas export wagon dispatch depends on ferry availability and sea transport conditions.

The longest process is the bogie exchange for hazardous cargo wagons, as only three wagons at a time can be processed on the specialized track due to safety regulations, compared to ten wagons for other types of cargo.

Applying the model for different volumes helps determine the required number of shunting locomotives and crews to ensure proper freight flow management. The model also provides recommendations for improving the complex's throughput and necessary infrastructure.

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