Abstract: This article concerns the problem of estimating the throughput and forecasting the operation of a coal transshipment complex that comprises a marine coal terminal and a railway station. Scenario modeling is employed to address this issue. The mathematical model of the transshipment complex has the form of a queuing network, which allows us to take into account the impact of random factors on the arrival of trains and departure of vessels from the system and their handling. In the model, we use the batch marked Markovian arrival process (BMMAP), which allows for the batch arrival of several types of requests, to describe the arrival of different categories of trains. Various queuing systems model particular structural elements of the complex to consider peculiarities of their work. We investigate the coal transshipment complex, which includes one of the largest and most modern coal export terminals in Russia. Based on the results of a numerical study, we estimate its current and maximum throughput, find bottlenecks in the system structure, and forecast its performance after the planned modernization. We also discuss the advantages and limitations of the model presented and its potential extension.

Keywords: mathematical model; queuing theory; bulk terminal; traffic flow; simulation; computational experiment

1. Introduction

Global coal consumption in the period from 1980 to 2020, according to IEA (International Energy Agency, https://www.iea.org, accessed on 3 June 2024), doubled to 7.5 billion tons. In 2023, this indicator exceeded 8.5 billion tons. In the future, a further increase in demand is expected for this energy resource. Only in China, India, and Indonesia, according to the Global Energy Monitor, 58.8 GW of generating capacity was commissioned in 2023 (Boom and Bust Coal 2024. https://globalenergymonitor.org/report/boom-and-bust-coal-2024/, accessed on 3 June 2024), and it is planned to build new stations based on modern “clean” technologies. In particular, the joint application of the HELE (high efficiency low emission) and CCS (carbon capture and storage) principles makes it possible to increase the thermal efficiency of coal-fired thermal power plants to 45%, and reduce carbon dioxide emissions by up to 90% (HELE. https://www.futurecoal.org/sustainable-coal/high-efficiency-low-emissions-hele, accessed on 3 June 2024).

Russia, one of the largest coal exporters, plans to increase shipments from 213 million tons in 2023 to 259 million tons by 2035 (the program for the development of the Russian coal industry for the period up to 2035; https://docs.cntd.ru/document/565123539?marker=65601O (in Russian), accessed on 3 June 2024). The main volume of export supplies comes from the largest coal basins in Siberia by rail and then is shipped by waterway to countries in the Asia–Pacific region. As a result, the marine terminals of the Russian Far East and the associated railway stations are high-loaded and need to increase transshipment capacities. Thus, an urgent task is to develop a mathematical model that allows us to describe the
operation of the port infrastructure and associated ground transport as a joint system. Such a model should necessarily take into account the impact of random factors (for example, weather) on the vessel movement and loading and unloading operations [1,2].

Several mathematical models are known to consider the effect of random factors on the operation of maritime transport facilities; these include probabilistic statistical models [3], network models [4], and stochastic programming models [5,6]. However, since the 1980s, queuing theory (QT) has traditionally been considered the most suitable tool for describing internal logistics operations in a port [7]; in particular, to determine the required fleet of transshipment equipment at the berths of container [8] and bulk marine terminals [9].

Let us note that queuing systems (QSs), as a rule, are not used for modeling individual events [10]. QSs are well suited for studying objects that regularly repeat similar operations, and the incoming material flow and its further processing are stochastic [10,11]. At the same time, such models can be adapted to almost any transport facility in a relatively short time. Therefore, queueing theory (explicitly or implicitly) formed the basis of many methods and tools for designing marine infrastructure [1,2,7].

One of the first significant works concerning the application of QT for marine terminal planning appears to be the article by Edmond and Maggs [8]. This (and some other papers) deals with simple Markov QSs suitable for analytical research, i.e., single-phase QSs, in which the arrivals and services are stationary Poisson processes. In ref. [9], Kos et al. apply QT to describe the operation of marine bulk terminals intending to handle bulk cargo. The authors use single-phase QSs with stationary Poisson incoming flow and deterministic service time to simulate a vessel loading system. Recent studies (see, for example, [12–14]) apply a similar approach.

When using single-phase QSs with stationary or deterministic Poisson flow, researchers face the fact that the description of the arriving flow and the process of its servicing is unjustifiably simplified. Therefore, to simulate the operation of marine terminals, it is better to use more complex (non-Markov) QSs. Kozan [15] and Dragović [16] point out that cargo arrives on vessels in batches, so it is advisable to use QS with group request flow. Zhang et al. [17] present an approach based on the vacation queue model, which reduces the idle time for external trucks at the gate of the container terminal and internal trucks at the warehouse. Na Li et al. [18] propose a method for optimizing the loading and unloading of external trucks in a warehouse based on a QS with three-level queuing. Incoming traffic flows significantly affect the marine terminal operation. At the same time, their internal structure is heterogeneous and several routes for the movement of goods are possible. To take into account these features, open queuing networks (QNs) are most often used [19]. Some of the pioneer studies in this direction appear to be works by Sacone and Siri [20] and Legato et al. [21] on modeling the transshipment of containers between three modes of transport and on optimizing the operation of gantry cranes in a warehouse. Roy and de Koster [22] study the effectiveness of different warehouse configurations. Non-stationary QN is applied in [23–26] to take into account daily fluctuations in the intensity of transport arrivals. The movement of cargo inside terminals is also described by open multiphase QSs [27–29]. However, this approach deals with only one direction of transshipment from ground transport to a sea carrier or vice versa.

Note that it is not always possible to consider the peculiarities of cargo transshipment in marine terminals with a complex internal structure by using open queuing networks. Therefore, closed and semi-open QNs are helpful for a detailed description of logistic processes. Canonaco et al. [30] propose a model for managing berth crane operations that has the form of a closed QN with blocking. It describes internal trucks stopping on the embankment if the crane queue is overcrowded. Papers [31,32] apply a similar approach to simulate the movement of internal trucks between the pier and yard blocks. Furthermore, semi-open QNs allow one to describe the transportation of containers inside a terminal with a limited number of internal trucks [33–35]. In such models, some requests come from an external source, and the other part circulates inside the system.
Although QT is a useful mathematical tool for analyzing marine transport systems, there are some gaps in the current studies. There is a lack of research on the complex modeling of marine terminals, considering all existing subsystems, different types of transport, and the two directions of movement of material flows within the system. Models of particular subsystems are usually considered from the standpoint of inventory stock management. There are also techniques for designing new and modernizing existing seaports, which are developed by large companies and are expensive and time-consuming to implement. Our task is to develop model algorithmic and software tools for conducting a comprehensive analysis of the transport system. These tools should be highly versatile and adaptable while also being cost-effective and time-efficient to implement. Of course, the model does not capture the intricate properties of the object, and the conclusions drawn from the simulation results are preliminary; nevertheless, they are valuable and can provide a foundation for more in-depth research.

We have previously described complex transport systems based on QT [36] and developed a methodology for modeling railway stations [37] and sections of the railway network [38,39]. A key point is the use of the batch Markovian arrival process (BMAP) to represent incoming transport flow.

This paper focuses on expanding the methodology to a new type of facility: a coal transshipment complex, including a marine bulk terminal and a railway station. Increasing the complexity of an object requires significant modification of the model. Firstly, we apply the BMMAP (batch marked Markovian arrival process) model to describe the arrival of trains. Secondly, stacker reclaimers and a warehouse are considered independent as two nodes, due to which two directions of coal movement are taken into account. As a result, we obtain the models generalizing both our previous results and some known marine bulk terminal models (see [13,26]).

We consider a coal transshipment complex, including one of the largest marine bulk terminals in Russia, as an object of simulation, estimate its current throughput, and perform a scenario analysis and forecasting.

The article is organized as follows. Section 2 describes the research object. Section 3 presents the construction of the mathematical model. Section 4 focuses on the results of its numerical study and their interpretation. Section 5 includes conclusions and outlines possible directions for further research.

2. Subject Model

A coal transshipment complex is a port technological complex designed for the transshipment of coal and has specialized systems to reduce the emission of coal dust. Its main functions are the organization of an efficient process of transshipment of bulk materials between land and sea modes of transport and temporary storage of coal to eliminate inevitable inconsistencies between different modes of transport. We can distinguish two subtypes of such systems: import and export terminals. At import systems, dry bulk materials (cargo) are supplied at the seaside and leave the complex at the landside. At export systems, it is the other way around.

2.1. Object of Study

We consider an export coal transshipment complex (hereinafter “complex”), which includes two independent subsystems: Daltransugol JSC and Toki marshaling station. Daltransugol JSC is a marine coal terminal located in Vanino port. In 2023, it handled 21 million tons of coal, which was 9.9% of Russia’s total coal exports. The main volume of exports was sent to countries in the Asia–Pacific region, in particular to China, India, and Vietnam. In 2024, it is planned to process 23 million tons of coal and increase throughput to 40 million tons per year by 2030 [40,41]. Figure 1 shows the location map and photo of Daltransugol JSC (see [41]).
The complex includes the following elements directly involved in coal transshipment [40,41]: receiving yard and coal yard at Toki station, railway yards Terminal 1 and Terminal 2, railway cargo yard, conveyor system, open coal warehouse, and berthing cargo yard. Figure 2 shows the complex based on open-source satellite images.

Figure 1. Location map and photo of Daltransugol JSC.

Figure 2. Scheme of the coal transshipment complex.

2.2. Description of Structural Elements

Trains arrive at the receiving yard with six tracks at Toki station, where locomotive uncoupling, then technical and commercial inspections are carried out, and Daltransugol JSC locomotives are coupled to coal trains. According to the regulations, the time required to complete all operations is 60–110 min. Empty cars from Daltransugol JSC arrive at the coal yard of Toki station, where trains are formed and dispatched. Most of the Russian railway network is electrified. There are relatively small areas with diesel locomotives. In particular, such locomotives move coal trains from Toki station to Daltransugol JSC and back.

Terminal 1 and Terminal 2 are connected to Toki by two routes, with an average running time of 10 min. They include 10 and 7 tracks, respectively, with an effective length of 71–75 gondola cars. The 10th track of Terminal 1 has two portable complexes for crushing frozen coal, with a capacity of 150 cars per day each.
The railway cargo yard (hereinafter “cargo yard”) consists of two unloading complexes, which includes a thrust path, a building for rail car thawing, a car dumper, and a crushing machine (crusher). The car dumper handles two cars at a time, with a maximum output of 34 cars per hour. However, according to data for 2022, the unloading time for a train of 70 gondola cars is 210–220 min or 6 min per pair. Crusher productivity is 3500 tons/hour.

The conveyor system includes conveyor belts located both outdoors and indoors. In particular, the coal transfer between belts is performed at closed transfer stations to reduce the amount of coal dust. The productivity of one belt averages 4200 tons/hour.

The coal warehouse (hereinafter “warehouse”) consists of five open areas with a total capacity of 1.2 million tons. Based on the results of an analysis of open-source satellite images in February 2024, we estimate its filling at 20–25%. Four stacker reclaimers (hereinafter “SR”, see Figure 3) transfer coal from the conveyor system to the warehouse and back; the productivity of each is up to 7000 tons/hour.

![Stacker reclaimer in the warehouse.](image_url)

The berthing cargo yard includes the berth itself for two vessels and two ship-loading machines of the conveyor type. The throughput capacity of each machine is 4200 tons/hour.

2.3. Traffic Flows

Between 2022 and 2023, 15 trains arrived at Toki station per day: 12.5 coal, 0.5 freight, and 2 passengers. In 2024, the number of coal and freight trains is expected to increase by 0.5 per day. The number of cars in a passenger train is constant and equal to 15. Coal trains have from 67 to 71 cars. The distribution of the number of cars in a coal train was evaluated by experts from the field of railway transport based on the weight standards of the trains and the technical characteristics of the Toki and Terminal 1 stations. Table 1 shows the distribution.

### Table 1. Distribution of the number of cars in a coal train.

<table>
<thead>
<tr>
<th>Number of Cars (k)</th>
<th>0–66</th>
<th>67</th>
<th>68</th>
<th>69</th>
<th>70</th>
<th>71</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability (g1(k))</td>
<td>0</td>
<td>0.05</td>
<td>0.08</td>
<td>0.27</td>
<td>0.46</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Russian railways transport coal using two types of cars, which differ in capacity. The capacity of 65% of cars is 68–69 tons, and the other 35% of cars accommodate 72–73 tons. The number of cars of the first and second types arriving at Toki station is unavailable in
open sources. Therefore, we assume that one car holds 70 tons of coal on average, which is the mathematical expectation.

We use the online services marinetrack.com and vesselfinder.com to collect statistics on vessel traffic from 6 February 2024 to 16 April 2024. During this time, 26 carriers were sent from Daltransugol JSC, which was 11.5 per month. Table 2 shows the time (in hours) at the berth \( t_1 \) and the time interval (in hours) between successive departures of two carriers \( t_2 \).

Table 2. Statistics on arrivals and departures of carriers at Daltransugol JSC.

<table>
<thead>
<tr>
<th>No</th>
<th>( t_1 )</th>
<th>( t_2 )</th>
<th>Deadweight</th>
<th>No</th>
<th>( t_1 )</th>
<th>( t_2 )</th>
<th>Deadweight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26</td>
<td>-</td>
<td>76,620</td>
<td>14</td>
<td>48</td>
<td>51</td>
<td>75,680</td>
</tr>
<tr>
<td>2</td>
<td>34</td>
<td>34</td>
<td>75,200</td>
<td>15</td>
<td>136</td>
<td>52</td>
<td>91,443</td>
</tr>
<tr>
<td>3</td>
<td>46</td>
<td>86</td>
<td>81,200</td>
<td>16</td>
<td>72</td>
<td>30</td>
<td>75,772</td>
</tr>
<tr>
<td>4</td>
<td>86</td>
<td>99</td>
<td>75,400</td>
<td>17</td>
<td>98</td>
<td>111</td>
<td>170,000</td>
</tr>
<tr>
<td>5</td>
<td>56</td>
<td>57</td>
<td>99,050</td>
<td>18</td>
<td>51</td>
<td>264</td>
<td>79,252</td>
</tr>
<tr>
<td>6</td>
<td>44</td>
<td>97</td>
<td>91,440</td>
<td>19</td>
<td>41</td>
<td>10</td>
<td>73,729</td>
</tr>
<tr>
<td>7</td>
<td>67</td>
<td>33</td>
<td>170,000</td>
<td>20</td>
<td>87</td>
<td>125</td>
<td>72,495</td>
</tr>
<tr>
<td>8</td>
<td>81</td>
<td>48</td>
<td>73,600</td>
<td>21</td>
<td>69</td>
<td>36</td>
<td>174,766</td>
</tr>
<tr>
<td>9</td>
<td>38</td>
<td>14</td>
<td>72,500</td>
<td>22</td>
<td>33</td>
<td>45</td>
<td>75,765</td>
</tr>
<tr>
<td>10</td>
<td>43</td>
<td>60</td>
<td>174,766</td>
<td>23</td>
<td>28</td>
<td>84</td>
<td>74,577</td>
</tr>
<tr>
<td>11</td>
<td>75</td>
<td>20</td>
<td>75,320</td>
<td>24</td>
<td>43</td>
<td>34</td>
<td>93,237</td>
</tr>
<tr>
<td>12</td>
<td>29</td>
<td>108</td>
<td>76,100</td>
<td>25</td>
<td>49</td>
<td>32</td>
<td>173,541</td>
</tr>
<tr>
<td>13</td>
<td>68</td>
<td>32</td>
<td>174,766</td>
<td>26</td>
<td>67</td>
<td>176</td>
<td>75,318</td>
</tr>
</tbody>
</table>

We find out that the loading of a bulk carrier with a deadweight is 72 to 175 thousand tons (see Table 2), and the average time between the sequential departure of two vessels is 58.25 h. Unfortunately, we have not managed to find data on the capacity of the holds in open sources. Therefore, we assume that this value is 65% of the deadweight; then, its minimum capacity of the vessel is 47 thousand tons, the average is 66 thousand tons, and the maximum is 114 thousand tons.

3. Mathematical Model

The modeling purpose is to determine the current and maximum throughput of the complex and to predict its load in the future. Let us firstly consider only one direction of coal transfer from the receiving yard to a vessel. We also describe the operation of Daltransugol JSC only in summer to eliminate additional time for crushing frozen coal.

In models of technical objects based on QT, the incoming material flow and the process of servicing by the system are usually described separately. In the case considered, since bulk terminals have a complex hierarchical structure, it is advisable to split the service into two stages. The first is to identify the key elements and describe their operation in terms of QT. The second is to construct routes of material flows within the system.

It should be noted that there are no available models for the considered transportation complex in open sources. The key features of the model presented below are BMMAP flow and its comprehensiveness.

3.1. Mathematical Description of the Incoming Car Traffic

The mines, the terminal, and the railway infrastructure are managed by different organizations, causing inconsistency in the operation of these systems. Additionally, train schedules are frequently disrupted due to the significant transportation distances and the impact of unforeseen factors [37,39]. The Poisson process is an effective tool for describing the arrival of trains at stations, taking into account possible deviations from the schedule [42].

The receiving yard receives trains of several categories that have different routes. The number of cars depends on the train category. At the same time, coal cars are unloaded at Daltransugol JSC separately. Therefore, the train should be considered as a group of service
requests. To describe such an incoming car flow, we apply a generalization of the Poisson process: batch marked Markovian arrival process (BMMAP). It allows one to describe several group flows within the same model. The flows can have different car types and distributions of request groups.

BMMAP is defined by a Markov chain with continuous time and state space \([1, \ldots, W]\) [43]. The intensity of arrival request groups \(\lambda_w, w = 1, W\) depends on the state number of the Markov chain. The residence time in each state is exponentially distributed. With probability \(p(r; w), r, w = 1, W\), the chain can go to state \(w\), while probability \(g_r(k)\) generates a group of random size \(k \geq 0\), and, with probability \(p^{(l)}_r\), the requests in the group have the type \(l \geq 1\). The normalization condition is satisfied: \(\sum_{l=1}^{\infty} \sum_{k=0}^{W} p(r; w) g_r(k) p^{(l)}_r = 1\).

It is convenient to collect all this information in matrices \(D_0, D^{(l)}_k\), which are set according to the formulas

\[
(D_0)_{r,r} = -\lambda_r, (D_0)_{r,w} = \lambda_r p(r; w) g_r(0),
\]

\[
(D^{(l)}_k)_{r,w} = \lambda_r p(r; w) g_r(k) p^{(l)}_r, r, w = 1, W, k \geq 1, l \geq 1.
\] (1)

Model of incoming car flow in the form of BMMAP. By request, we mean 70 tons of coal—the average car capacity—and the train is a group of requests. Freight trains leave the system immediately after stopping at Toki station. Therefore, the distribution of the car numbers does not affect the simulation results. This fact allows us to assume that it corresponds to the distribution of the length of coal trains (see Table 1).

Both coal (and freight) and passenger trains arrive at Toki station, so the control Markov chain has two states \([1, 2]\). The first state corresponds to the arrival of a freight train, and the second to a passenger train. After being serviced at the station, trains follow two routes: coal trains move further inside the system, and the rest leave it. To describe them, we use two types of requests: \(l = 1, 2\), respectively. The probability of arrival of either a coal or freight train is equal to \(p(2; 1) = 14/16 = 0.875\). For a passenger train, \(p(1; 2) = 2/16 = 0.125\). The probabilities of different types of requests are as follows: \(p_1^{(1)} = 13/14 = 0.929, p_1^{(2)} = 1/14 = 0.071, p_2^{(1)} = 0, p_2^{(2)} = 2/2 = 1\). The intensity of the train traffic is \(\lambda = 16/24 = 0.67\) per hour. The probabilities \(g_1(k)\) are taken from Table 1, and \(g_2(15) = 1, g_2(i) = 0, i \neq 15\). The maximum number of cars in a train is 71, so BMMAP includes 143 matrices \(D_0, D^{(1)}_k, D^{(2)}_k, k = 1, 71\), which are determined by Formula (1). Only 12 matrices are non-zero:

\[
D_0 = \begin{pmatrix}
-0.67 & 0 \\
0 & -0.67
\end{pmatrix};
D^{(1)}_{67} = \begin{pmatrix}
0.0270 & 0.0039 \\
0 & 0
\end{pmatrix};
D^{(1)}_{68} = \begin{pmatrix}
0.0436 & 0.0062 \\
0 & 0
\end{pmatrix};
\]

\[
D^{(2)}_{69} = \begin{pmatrix}
0.1470 & 0.0210 \\
0 & 0
\end{pmatrix};
D^{(1)}_{70} = \begin{pmatrix}
0.2505 & 0.0358 \\
0 & 0
\end{pmatrix};
D^{(1)}_{71} = \begin{pmatrix}
0.0762 & 0.0109 \\
0 & 0
\end{pmatrix};
\]

\[
D^{(2)}_{15} = \begin{pmatrix}
0 & 0.05826 \\
0 & 0.0838
\end{pmatrix};
D^{(2)}_{67} = \begin{pmatrix}
0.0021 & 0.0003 \\
0 & 0.0
\end{pmatrix};
D^{(2)}_{68} = \begin{pmatrix}
0.0033 & 0.0005 \\
0.0 & 0.0
\end{pmatrix};
\]

\[
D^{(2)}_{69} = \begin{pmatrix}
0.0112 & 0.0016 \\
0.0 & 0.0
\end{pmatrix};
D^{(2)}_{70} = \begin{pmatrix}
0.0191 & 0.0027 \\
0.0 & 0.0
\end{pmatrix};
D^{(2)}_{71} = \begin{pmatrix}
0.0058 & 0.0008 \\
0.0 & 0.0
\end{pmatrix};
\] (2)

### 3.2. Elements of the Coal Transshipment Complex

The mathematical model of the complex operation is constructed in the form of an open queuing network (QN), which is understood as a set of a finite number \(S\) of queuing systems (hereinafter referred to as nodes). Requests come to an open QN from the external environment. It is usually considered an additional (dummy) node having an index 0. The request route is given by the routing matrix \(P = (P_{ij})\), and the element \(P_{ij}\) is the probability of the request moving from Node \(i\) to Node \(j\) \((i, j = 0, S)\) [44].

The structural elements are described by QN nodes in different ways, depending on their type. The receiving yard (6 tracks) and terminal 1 (10 tracks) are modeled by BMMAP/G/6X/0 and *G/10/0 queues (Nodes 1 and 3, respectively), and the railway
track between them is the */GX/1/0 queue (Node 2). In these nodes, the channels are, in fact, the railway tracks, and requests are served in groups, the maximum size $X$ of which is equal to the largest length of the train (71).

Handling of the trains is lengthy and regulated but is affected by a large number of random factors. In this regard, according to the central limit theorem, their execution time can be taken as a random variable that obeys the normal distribution $N(\mu, \sigma)$ with the probability density function \[ f(x, \mu, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}. \]

Its mean value $\mu$ is determined by the average duration of the operations performed, and the standard deviation $\sigma$ is determined by the possible deviation from the average.

The model of the cargo yard is the */M2/2/200 queue with a finite queue (Node 4), where the channels are car dumpers, and the queue is the thrust paths, each accommodating 100 cars. The channels serve two requests at a time.

Two crushers are described separately in the form of two-channel QS with two places in a queue (two cars with coal), since they have different productivity (the */M2/2/2 queue (Node 5)). The queue servicing discipline in all nodes is FIFO. The service process for similar production lines is generally considered Markovian \[9,19\]. Therefore, we assume that the service time at Nodes 4 and 5 is described by an exponential distribution $\text{exp}(\lambda)$ with intensity $\lambda$ and the probability density function \[ f(x, \lambda) = \begin{cases} \lambda e^{-\lambda x}, & x \geq 0, \\ 0, & x < 0. \end{cases} \]

Two conveyor belts from the cargo yard to the warehouse and from the warehouse to the berth are described by */D/2/2 and */D/2/0 queues (Nodes 6 and 9, respectively). The operation of four SR is simulated by the */D/4/0 queue (Node 7). The warehouse is modeled by */D/2/m with a queue for $m=1,200,000/70 \approx 17,143$ places (Node 8). Its channels are fictitious and only necessary for transferring requests to Node 7. The nodes above handle requests one at a time, and their service time is deterministic and equal to 4200/70/60 = 1 min, since the speed of the belts is usually constant.

The berthing cargo yard is modeled by two QSs. The first two-channel QS describes the operation of two ship-loading machines—the */D/2/0 queue (loaders, Node 10). The second two-channel QS with group servicing of requests and a queue for 114,000/70 = 1623 places simulates the loading of carriers and their departure from two berths (the */GY/2/1623 queue (Node 11)). The queue size corresponds to the largest hold capacity of any vessel. The average service time for a group of requests in the channel is 58.27 h (3495 min) and obeys the normal distribution. Vessels have a significant variation in hold capacity (see Table 2); therefore, we use the discrete uniform distribution $U(a; b)$ to describe the size $Y$ of the service group. Its parameters—$a = 673$ and $b = 1623$—correspond to the smallest and largest hold capacity.

### 3.3. Material Flows within the System

Groups of requests of all types arrive at Node 1 and are serviced according to the complete rejection discipline \[43\]. Next, requests with type 1 move through the system. In this case, they can bypass Node 8 (warehouse), which means direct transshipment from train to carrier, or they can go to Node 8. Requests of type 2, after being serviced at Node 1, leave the QS. For each type of request, we have its own routing matrix $P_1$ and $P_2$. In this case, in $P_2$, there is only one non-zero element, $P_{10} = 1$. To prevent the loss of requests when moving between nodes, we add temporary blocking of the channels.

Tables 3 and 4 present formal descriptions of Node $N_i$ in terms of queuing theory, service time distribution ($T_i\mu$ parameters in minutes), and sizes of serviced groups of requests ($X_i$). Figure 4 shows the scheme of QN constructed (QN-1), where graph weights denote non-zero elements of the routing matrix $P_1$. 

1. In Node 3 (Terminal 1), the number of channels increases from 10 to 13. The weights of the graph indicate non-zero elements of the routing matrix with 11 nodes, an incoming BMMAP flow, and two types of requests with their own parameters in terms of queuing theory.

As a result, we obtain a model of the coal transshipment complex, including Daltransugol JSC and the Toki railway station (see Figure 2), which has the form of the QN with 11 nodes, an incoming BMMAP flow, and two types of requests with their own routing matrices \( P_1 \) and \( P_2 \). Matrices (2) are set BMMAP parameters. Nodes 1–5 and 11 are multi-channel QSSs with group request servicing and random service times. They describe the operation of the railway part of the complex and the departure of a carrier laden with coal. Nodes 6–10 are multi-channel QSSs with deterministic service time that simulate the operation of the conveyor system, stacker reclaimers, the coal warehouse, and ship-loading machines.

### Table 3. Parameters of QN-1 nodes in terms of queuing theory.

<table>
<thead>
<tr>
<th>No of Node</th>
<th>Node 1 Receiving Yard</th>
<th>Node 2 Track</th>
<th>Node 3 Terminal 1</th>
<th>Node 4 Cargo Yard</th>
<th>Node 5 Crushers</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_i )</td>
<td>BMMAP/( G^{X_l}/6/0 )</td>
<td>*/( G^{X_l}/1/0 )</td>
<td>*/( G^{X_l}/10/0 )</td>
<td>*/( M^{X_l}/2/200 )</td>
<td>*/( M/2/2 )</td>
</tr>
<tr>
<td>( T_i )</td>
<td>( N(75; 10) )</td>
<td>( N(10; 1) )</td>
<td>( N(20; 2) )</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>( X_i )</td>
<td>71</td>
<td>71</td>
<td>71</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No of Node</th>
<th>Node 6 Conveyor</th>
<th>Node 7 SR</th>
<th>Node 8 Warehouse</th>
<th>Node 9 Conveyor</th>
<th>Node 10 Loaders</th>
<th>Node 11 Carrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_i )</td>
<td>*/( D/2/2 )</td>
<td>*/( D/4/0 )</td>
<td>*/( D/2/17143 )</td>
<td>*/( D/2/0 )</td>
<td>*/( D/2/0 )</td>
<td>*/( G^{X_l}/2/1623 )</td>
</tr>
<tr>
<td>( T_i )</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>N( (3495; 700) )</td>
</tr>
<tr>
<td>( X_i )</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>U( (673; 623) )</td>
</tr>
</tbody>
</table>

**Figure 4.** Scheme of QN-1.

3.4. **Model Modification**

By 2030, Daltransugol JSC plans to build three new tracks in Terminal 1 and Terminal 2, a third unloading complex with a thrust path, and a second berthing cargo yard [45,46]. To take into account the planned changes, we modify QN-1 as follows.

1. In Node 3 (Terminal 1), the number of channels increases from 10 to 13.
2. In Nodes 4, 5, and 6, the number of channels increases from 2 to 3, and the queue length in Node 4 increases up to 300 places.
3. Nodes 12, 13, and 14 (new berthing cargo yard) are added, similar to Nodes 9, 10, and 11, respectively.
4. In Node 8 (warehouse), the number of channels increases from two to four, which corresponds to the new number of conveyor belts from the warehouse to two berths.

Table 4 presents a formal description of the changed and new nodes. Figure 5 shows the scheme of the new model (QN-2). The added elements are highlighted in gray, the weights of the graph indicate non-zero elements of the routing matrix \( P_1^* \). Matrix \( P_2 \) is the same.
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1. In Node 3 (Terminal 1), the number of channels increases from 10 to 13.
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Table 4. Parameters of new and changed QN nodes.

<table>
<thead>
<tr>
<th>No of Node</th>
<th>Node 3 Terminal 1</th>
<th>Node 4 Cargo Yard</th>
<th>Node 5 Crushers</th>
<th>Node 6 Conveyor</th>
<th>Node 8 Warehouse</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_i$</td>
<td>$*/G_{30}^N/13/0$</td>
<td>$*/M_{20}^N/3/300$</td>
<td>$*/M_{30}^N/3/4$</td>
<td>$*/D/3/4$</td>
<td>$*/D/4/17,143$</td>
</tr>
<tr>
<td>$T_i$</td>
<td>$N(20; 2)$</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$X_i$</td>
<td>71</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Thus, the modified model takes the form of the QN with incoming BMMAP, 14 nodes, and two types of requests that differ by route. Orders of the first type pass through the entire system and leave it through Nodes 11 or 14, while orders of the second type leave the system immediately after being serviced at Node 1. Matrices $P_1^*$ and $P_2$ define these three routes.

4. Computational Experiment

4.1. Simulation Model

In this section, we numerically study the QN obtained using a simulation model. It is based on the discrete-event modeling approach and Monte Carlo methods, and is implemented as software in Pascal object detection.

The software allows you to determine stationary performance indicators for a QN, which has up to 100 nodes and the same number of independent non-ordinary request flows, including BMAP and BMMAP flows. The route of the request between the nodes depends on its type and is kept in the corresponding route matrix, which is given by the user. For each node, the user sets the queue length, the number of channels, the distribution of the group size, and the distribution of service time.

Let us describe the algorithm of the simulation, the block diagram of which is presented in Figure 6. Before running the simulation, the user sets the QN parameters as follows:

- Number of nodes $S$;
- Number of channels $n_i$ and places in the queue $m_i$ at Node $i$;
- Distribution laws of service time and size of served groups for each channel;
- Routing matrix $P$;
Number of request flows $W$ in BMMAP, intensities $\lambda_w, w = 1, W$ and distribution laws of group size for each flow.

![Block diagram of the simulation model.](image)

**Figure 6.** Block diagram of the simulation model.

Block "Simulation of QN operation" executes the main loop of the simulation model. The unit of measurement of model time is one loop of execution of the main algorithm $T_c$ (see Figure 6). It is usually taken as equal to one minute. The program terminates after completing $T_m$ loops, which is specified by the user. The main loop consists of six blocks.

In the block "Generation of incoming groups of requests", $W$ independent random generators originate flows of requests by generating the group sizes and the time intervals between their arrivals according to the specified parameters. Block "Placement of requests to node" arranges incoming requests in free places in the queue (if available) or in the channels of the corresponding node. If there are not enough places, the group of requests is denied service.

Block "Operation of the channels" at each step of the main loop for all channels performs three functions as follows:

1. If channel $i$ is empty, then the size of the serviced group of requests $v_i$ and its service time $t_i$ are generated. Next, the corresponding group of requests is transferred from the queue (if any) or the incoming flow into this channel.
2. If channel $i$ is serving requests, then $t_i^* = t_i - 1$.
3. If $t_i = 0$ and $v_i > 0$ for channel $i$ of Node $j$ and the next node has $q < v_i$ free places, then the group cannot be accepted and the blocking time is counted as $h_j^* = h_j + 1$. 
Block “Transfer of serviced requests between nodes” transfers requests of serviced nodes in accordance with the routing matrix $P$.

Block “Calculating performance indicators” collects data for Node $j$ at the current step $z$ of the main loop as follows:
- $k_j(z)$ is the number of busy channels;
- $l_j(z)$ is the queue length;
- $g_j(z)$ is the number of received groups of requests;
- $r_j(z)$ is the number of singular requests.

Based on this, the following operation parameters are calculated:
1. $K_j = \sum_{z=0}^{T_c} k_j(z) / T_c$ and $L_j = \sum_{z=0}^{T_c} l_j(z) / T_c$ are an average number of busy channels and queue length at Node $j$, respectively;
2. $T_j = \sum_{z=0}^{T_c} [k_i(z) + l_i(z)] / r_i(z)$ is an average sojourn time for the request at Node $i$ (in minutes); $R_j = 1440 \sum_{z=0}^{T_c} r_i(z) / T_c$ is an average number of requests arrived at Node $i$ per day;
3. $b_i = h_i / n_i / 1440$ is duration (in day) of blocking of one channel in Node $i$ for the entire simulation time.

Next, in the block “Display of operation parameters”, the results are shown in tabular and graphical forms and can be exported to MS Excel 2010 and later versions.

The accuracy of the simulation model is tested on three types of problems with known characteristics—two- and three-phase QSs with blockings and BMAP [47], and an open exponential QN with six nodes [48]. As a result, the maximum relative error of the calculated performance indicators of the QSs differs from the known ones by no more than 4%. This accuracy is considered acceptable.

Further, Sections 4.2–4.4 present the results of three computational experiments. The first experiment focuses on the analysis of the complex’s loading with an expected coal transshipment volume of 23 million tons in 2024. The second concerns the maximum allowable throughput under current operating parameters. In the third experiment, the system performance is studied after the planned upgrade of Daltransugol.

Tables 5–7 show the average results of the numerical study. The virtual simulation time for each launch is 90 days. This is the minimum required time to reach the stationary mode and to calculate the performance indicators of the QN. At the initial moment of time, there are 4286 requests in the queue of Node 8, which corresponds to a 25% filling of the warehouse.

### 4.2. Experiment 1. Evaluation of the Current Performance of the Complex

Table 5 shows the results of simulating QN-1. The incoming flow, given by matrices (2), corresponds to a coal volume receipt of 23 million tons yearly.

<table>
<thead>
<tr>
<th>General Parameters</th>
<th>Received Groups</th>
<th>Received Requests</th>
<th>$P_L$</th>
<th>TH</th>
<th>TS</th>
<th>LC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node Parameters</td>
<td>1445.5</td>
<td>91,169.5</td>
<td>0</td>
<td>101.9</td>
<td>213.2</td>
<td>12,303.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Node</th>
<th>$K_i$</th>
<th>$L_i$</th>
<th>$T_i$</th>
<th>$R_i$</th>
<th>$b_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node 1</td>
<td>0.94</td>
<td>0.10</td>
<td>57.7</td>
<td>6807.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Node 2</td>
<td>0.42</td>
<td>1.31</td>
<td>1.2</td>
<td>1.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Node 3</td>
<td>1.02</td>
<td>1.00</td>
<td>0.5</td>
<td>1.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Node 4</td>
<td>0.73</td>
<td>0.73</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Node 5</td>
<td>0.73</td>
<td>0.73</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Node 6</td>
<td>2.43</td>
<td>2.43</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Node 7</td>
<td>2.00</td>
<td>2.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Node 8</td>
<td>1.30</td>
<td>1.30</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Node 9</td>
<td>1.30</td>
<td>1.30</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Node 10</td>
<td>1.98</td>
<td>1.98</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Node 11</td>
<td>1148.4</td>
<td>1148.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In Table 5 and further, $P_L$ is the loss probability for the group; $TH$ is an average total time (in hours) for the request to pass through Nodes 1–7 and Nodes 9–11; $TS$ is an average sojourn time for the request into the QN (in hours); $LC$ is a queue length of Node 8 (warehouse) at the end of the simulation.
Let us interpret the modeling results (Table 5) in terms of the object considered and analyze them.

1. All requests enter the system freely, so the loss probability $P_L = 0$. At the same time, the channel blocking duration ($b_1 = 0.1$) at Node 1 is one of the smallest among all nodes. Consequently, trains arrive and depart from the receiving yard without any hindrance. The situation is similar at Terminal 1 (Node 3).

2. For Node 4 (cargo yard), the channel load factor $K_4 = \overline{K}_4/n_4 = 0.66$ ($n_4$ is the number of channels) and $K_6 = 0.37$, $K_9 = 0.65$, and $K_{10} = 0.65$ for Nodes 6, 9, and 10, respectively. It means that the subsystems for unloading coal from cars and transporting it to Daltransugol JSC are loaded at no more than 66%.

3. The longest blocking duration among Nodes 6, 9, and 10 is $b_{10} = 32.5$ days. This means that the conveyor system is idle $32.5/90 \times 100 = 36\%$ of the time due to the lack of vessels.

4. At the initial time moment, the queue length at Node 8 (warehouse) is 4286 requests, and at the end of the simulation, $LC = 12303$. Consequently, 11.5 vessels per month are not enough to depart the incoming volume of coal, and the warehouse will be overfilled within six months.

Thus, the current complex load does not exceed 66% and the volume of coal transshipment can be significantly increased. The limiting factor is the size of the bulk carrier fleet. Thus, during the observation period, the average number of dispatches is 11.5 per month. Perhaps, in the future, their number will be increased, which is indirectly confirmed by the following.

One loader fills the hold of a vessel with the largest capacity (114 thousand tons) at an average of 114,000/4200 = 27.1 h. If we take into account the duration of other operations that are performed before departure (replenishment of supplies, preparation of documents, technical breaks) [2], then the average time for loading vessels can be estimated at 1.5–1.6 days. This value is close to the average time the request spends in the queue at Node 11 (5850.6/60 – 58.27 = 39.24 h), which can be interpreted as the average time the vessel spends at the berth. If we consider this value as the service time, then the throughput of the berthing cargo yard will increase by 32.7%. Next, let us assume the average carrier loading time is 39.24 h and evaluate the maximum performance of the complex.

4.3. Experiment 2. Estimation of Maximum System Performance

We modify QN-1 as follows. The service time at Node 4 is reduced to 4 min ($T_4 = 4$ min), which corresponds to the maximum design capacity of the cargo yard. The average service time at Node 11 is 39.24 h or $T_{11} = N (2354; 500)$ minutes. The remaining parameters of the model are the same (see Table 3). Table 6 presents the simulation results with an increase in the values of all elements in matrices (2) by 12.5%, 20%, 30%, and 40%, which corresponds to an average overload of 25.7, 27.4, 29.9, and 32.2 million tons of coal per year, respectively.

<table>
<thead>
<tr>
<th>No</th>
<th>$\lambda$</th>
<th>$V$</th>
<th>Input Groups</th>
<th>Input Requests</th>
<th>$PL$</th>
<th>$TH$</th>
<th>$TS$</th>
<th>$LC$</th>
<th>Max bi</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.75</td>
<td>25.7</td>
<td>1619.2</td>
<td>102,262.5</td>
<td>0.0002</td>
<td>69.2</td>
<td>87.9</td>
<td>41.4</td>
<td>15.9</td>
</tr>
<tr>
<td>2</td>
<td>0.80</td>
<td>27.4</td>
<td>1725.3</td>
<td>109,080.0</td>
<td>0.0004</td>
<td>70.1</td>
<td>116.1</td>
<td>3217.5</td>
<td>17.3</td>
</tr>
<tr>
<td>3</td>
<td>0.87</td>
<td>29.9</td>
<td>1881.6</td>
<td>118,624.5</td>
<td>0.0013</td>
<td>72.2</td>
<td>168.6</td>
<td>10,428.2</td>
<td>18.8</td>
</tr>
<tr>
<td>4</td>
<td>0.94</td>
<td>32.2</td>
<td>2032.6</td>
<td>128,169.0</td>
<td>0.0173</td>
<td>75.3</td>
<td>242.0</td>
<td>16,411.0</td>
<td>27.4</td>
</tr>
</tbody>
</table>

In Table 6 and further, $V$ is volume (in million tons) of coal that is expected to be transshipped per year at the current intensity $\lambda$ of train arrivals; $b_{\text{max}} = \max b_i, i = 6, 7, 9–11$, where the nodes listed describe the conveyor system and the berthing cargo yard.

Let us interpret the results of Experiment 2. We call “decline of service” of the request group a situation when trains are not accepted at Toki station because its tracks are busy. In this case, their schedule is disrupted, and the trains stop at neighboring railway stations to wait for a free space in Toki and a new schedule.
Let us analyze the data in Table 6. With an increase in the intensity of receipt of the request groups by 30% (row 3), you can see that, over 90 days, on average, 1881.6 × 0.0013 = 2.5 trains are not accepted. This number of unserviced trains does not significantly affect the operation of the system as a whole. Parameter $b_{max}$ is less than the same parameter in Experiment 1. Therefore, the system can handle the load. However, the large value $LC = 10,428.2 > 4286$ indicates that the vessels do not manage to export all the incoming coal and the warehouse will be completely full in six months.

Rows 1 and 2 show that with the transshipment of up to 25–26 million tons of coal per year, all trains will be accepted. The value $PL = 0.0002$ (0.33 trains per year) is insignificant since dispatch control can vanish it. At the same time, the resulting estimate (25 million tons of coal per year) corresponds to the recommended loading of Daltransugol JSC, which is 24.98 million tons of coal per year [49]. Moreover, Daltransugol JSC is capable of processing up to 28–29 million tons of coal per year in normal mode.

Figure 7 shows the values of $b_i$ for all nodes for each option.

![Figure 7. Experiment 2. Total blocking duration ($b_i$) of one channel in Node $i$.](image)

If $\lambda = 0.94$, there is a dramatic increase in blocking duration in Nodes 1–3 due to the insufficient capacity of Node 4 (cargo yard). We also see a significant increase in the blocking duration in Nodes 6–8. The largest increase in $b_i$ occurs in Node 7 (SR) due to a queue overflow in Node 8 (warehouse), and blocking Nodes 9 and 10. Thus, an increase in transshipment volumes over 30 million tons is hard to carry out since warehouse capacity and the capacity of the berthing cargo yard (Node 11) is not enough. Nevertheless, the conveyor system (Nodes 6, 9, and 10), even with an overload of 32.2 million tons per year, has a margin of productivity.

4.4. Experiment 3. Evaluation of Complex Performance after the Planned Upgrade of Daltransugol JSC

Table 7 shows the results of a numerical study of QN-2 with an increase in the values of all elements in matrices (2) firstly by 73%, which corresponds to an average overload of 40 million tons of coal per year, and then consistently by 83%, 93%, and 103%.

<table>
<thead>
<tr>
<th>No</th>
<th>$\lambda$</th>
<th>$V$</th>
<th>Input Groups</th>
<th>Input Requests</th>
<th>$PL$</th>
<th>$TH$</th>
<th>$TS$</th>
<th>$LC$</th>
<th>$b_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.16</td>
<td>40.1</td>
<td>2505.8</td>
<td>158,166.0</td>
<td>0.0057</td>
<td>62.5</td>
<td>71.1</td>
<td>0.0</td>
<td>7.3</td>
</tr>
<tr>
<td>2</td>
<td>1.23</td>
<td>42.1</td>
<td>2658.2</td>
<td>167,710.5</td>
<td>0.0056</td>
<td>63.2</td>
<td>75.7</td>
<td>0.0</td>
<td>8.5</td>
</tr>
<tr>
<td>3</td>
<td>1.30</td>
<td>46.7</td>
<td>2804.4</td>
<td>177,255.0</td>
<td>0.0086</td>
<td>64.8</td>
<td>77.9</td>
<td>0.0</td>
<td>10.4</td>
</tr>
<tr>
<td>4</td>
<td>1.36</td>
<td>50.9</td>
<td>2939.2</td>
<td>185,436.0</td>
<td>0.0162</td>
<td>67.8</td>
<td>82.2</td>
<td>0.0</td>
<td>11.3</td>
</tr>
</tbody>
</table>
Based on Table 7, we can conclude the following. With the transshipment of 46.7 million tons of coal per year, an average of 1.9 trains per week will not be accepted at Toki station. This value is approaching the critical one, which is three trains per week for Toki’s railway segment, according to expert assessment. Therefore, the maximum capacity of the system can be estimated at 46–47 million tons of coal yearly with timely loading and dispatch of a total of two carriers daily from both berths. In this case, coal will mainly be reloaded immediately from trains to vessels, and the warehouse will be empty ($LC = 0$). Daltransugol JSC retains a capacity margin of about 10–15%, which is confirmed by lower values of $TH$, $LC$, and $b_{\text{max}}$ compared with similar parameters in Table 6 for all $\lambda$.

Figure 8 shows the values of $b_i$ for all nodes for each option.

![Figure 8. Experiment 3. Total blocking duration ($b_i$) of one channel in Node $i$.](image)

After the modernization of Daltransugol JSC, we can point out two bottlenecks in the system that prevent an increase in transshipment volumes over 47–48 million tons of coal per year. The first is the receiving yard (Node 1), since, at $\lambda = 1.36$, there is a relatively small increase in $b_1$ with a sharp increase in the loss probability (from 0.0086 to 0.0162). The second bottleneck is the cargo yard (Node 4). It causes a significant increase in the blocking duration of Node 3 for $\lambda = 1.36$. The throughput capacity of the conveyor system and two berths is enough to transship 50.9 million tons of coal yearly. In particular, $b_i$ at Nodes 5, 6, 9, 10, 12, and 13 remain relatively small and stay equal for $\lambda = 1.30$ and $\lambda = 1.36$. Therefore, with an increase in the capacity of the receiving yard and the productivity of the cargo yard, a further increase in transshipment volumes is possible. In particular, the receiving yard at Toki station needs to have four or five additional tracks, along with the capability to unload three cars at a time using the new car dumper. In this case, we estimate it at 52–54 million tons of coal per year, since the conveyor system’s capacity reserve is about 10–15%.

5. Discussion of the Simulation Results

This study addresses modeling the operation of the coal transshipment complex, which includes Toki marshaling station and Daltransugol JSC. Therefore, in addition to the arrival of coal trains, we consider the arrival of passenger and freight trains. The operation of the complex is studied in the summer, as train traffic decreases in winter conditions to reduce the wear of infrastructure, particularly rails and coal-loaded wagons.

To create the model, we use part of the statistical data on the movement of trains and vessels obtained from field observation, technical parameters of the loading and unloading equipment, and the performance of the conveyor system presented in publicly available sources [40,41,49]. The verification of the simulation results is performed as follows. First, we compare three samples—the number of arriving trains per day, the number of departing vessels per day, and the size of the transported shipment on vessels—with the corresponding samples obtained from the remaining statistical data. To achieve this, we apply the Wilcoxon signed-rank test. Ten experiments are conducted with each pair of samples, from
which it follows that, in 95% of cases, with a significance level of 0.05, there is no reason to reject the hypothesis of sample correspondence. Second, the estimates of the throughput of individual subsystems presented in Tables 5 and 6 are compared with those obtained by other researchers from field observations. Thus, when the system load is 25–26 million tons per year, the cargo yard and berths effectively cope with the load, which corresponds to the recommended loading of the cargo yard (24.5–25 million tons) and berthing cargo yard (25.2 million tons) [49,50]. Thus, we can claim that the presented model adequately describes the system and can be used to predict its operation.

Based on the simulation results, we conclude the following. All trains arrive and depart from the receiving yard at Toki station unhindered. The conveyor system is idle 36% of the time due to the lack of vessels. The complex is currently at about 66% capacity. Its throughput can be increased to 28–29 million tons of coal yearly, 25% more than expected in 2024. Such an increase requires expanding the bulk carrier fleet to ensure the departure of an average of 16 carriers per month.

After the planned modernization, the complex will be able to handle up to 46–47 million tons of coal yearly, almost two times more than the current capacity. In this case, the most significant bottleneck will be the receiving yard, which receives and processes coal trains before transferring them to Terminal 1. For efficient operation, it seems advisable to increase the number of tracks in it or build a new specialized yard at Toki station to service coal trains.

The model presented has some limitations. It is not suitable for modeling individual events or solving optimization problems specifically related to planning the supply of goods and the distribution of berths. However, the obtained results make it possible to conduct scenario analysis, estimate the maximum permissible volumes of incoming material flows, the risk of the system switching to an irregular operating mode, and to assess the required fleet of transshipment equipment.

The models of individual subsystems of the marine transshipment complex are relatively simple since they consider only the capacity, number of service devices, and their throughput. Equipment failures and technical interruptions are omitted. However, this makes it possible to describe essential operating parameters and functions of subsystems, discarding minor ones, such as planned maintenance breaks and dust suppression systems on coal handling equipment.

This study does not address the issue of the receipt of cars with frozen coal, which need to be loosened before transferring to the railway cargo yard for unloading. For instance, only in January 2022, in the ports of the Russian Far East, the actual unloading was 40% lower than the standard. According to the management of Russian Railways (Maritime news of Russia, frozen cargo will impact the finances of shipper and port workers. https://morvesti.ru/analitika/1687/95252/ (in Russian), accessed on 3 June 2024), the reason is poor-quality preparation of bulk cargoes during shipment and lengthy unloading at marine terminals. At the same time, according to the statements of the management of Daltransugol JSC, the unloading of coal cars in winter was carried out without delay, and its volume decreased due to problems with the movement of trains across Russia. Thus, this issue requires a profound study, which can be a direction for further research.

6. Conclusions

Currently, the Asia–Pacific region is witnessing the construction of new coal-fired thermal power plants in response to the rising need for electricity. Such a situation will require an increase in the volume of coal transportation, particularly by sea, and, consequently, the establishment of new terminals and the upgrade of existing marine ones. Therefore, the development of tools that allow analyzing the port infrastructure and related land transport systems as a single complex is significant.

The results obtained in this study contribute to the solution to the described problem. We have presented a model algorithmic toolkit for studying the operation of a marine transshipment complex, which includes a coal terminal and an associated railway station.
Our approach is based on queuing networks with batch incoming flows and several types of requests. As a result, the model considers the influence of random factors on the running and maintaining of trains and vessels, the different number of cars in trains, vessel capacity, the hierarchical structure of the system, and the operating features of its elements.

The simulation of the resulting QN allows one to determine the bottlenecks and pre-evaluate the effectiveness of various measures to eliminate them. Moreover, the proposed model is highly adaptive and can be applied to terminals with different structures in a relatively short time. Another advantage of the presented tools is that high-performance equipment is not required to conduct computational experiments and personal computers can be used.

Using the presented model, we simulate the joint operation of the Toki railway station and the Daltransugol JSC export coal terminal, one of the largest and most modern terminals in Russia. The operation of the system is studied during the summer period, which is the most critical, since the volume of incoming trains with coal is maximum. Based on the results of numerical experiments, we have estimated the current and maximum throughput of the transshipment complex and forecast its capacity after the planned modernization.

Further research can concentrate on the following points. The first is to develop the proposed approach by applying a non-stationary process for servicing requests, which allows for the consideration of breaks for personnel and equipment shutdown for maintenance. The second is to apply the presented tools to describe other types of marine terminals, in particular container and oil terminals. The operation of the system in winter is also worth studying, since the volume of train traffic decreases but additional time is required to crush frozen coal from incoming trains.

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