# Multicriteria Approach to Determining the Optimal Composition of Technical Means in the Design of Sea Grain Terminals

Sergey Rudenko, Anatoliy Shakhov, Inna Lapkina, Oleksandr Shumylo, Mykola Malaksiano, Ihor Horchynskyi

The main aim of the article is to develop technique for determining the optimal equipment of a sea grain terminal with technical means at the stage of its design. In many works, in order to study the performance of transport systems operating under conditions when the loading level is subject to random fluctuations, the queuing theory methods and random processes are used. However, in a number of cases this approach does not allow to take into account all specifics of the processes that significantly affect sea terminals performance. Also, most of the available studies aim at enhancing a certain single key performance indicator (it can be total costs, performance, income, etc.) to its maximum, provided that the other indicators are within the permissible range of values. However, in many cases, there are more than one key performance indicator which need to be improved. Since the queuing theory and single criterion optimization methods did not allow to achieve the desired results, to study the problem, a technique was introduced based on the combination of simulation modelling and multicriteria optimization methods, which allows us to take into account all the main features of operations at grain terminals. To assess the terminal economic efficiency, the Equivalent Annual Cost indicator was used. The relationship between the cargo unit transshipment cost and the average processing time of consignments is analyzed, provided that the cargo flow intensity is subject to random fluctuations. Using this relationship, a technique for determining the optimal composition of grain terminal equipment was introduced, based upon the multicriteria optimization and simulation modelling methods. The developed technique makes it possible to determine the qualitative and quantitative choice of equipment for a sea grain terminal, taking into account both the cargo transshipment cost and the processing time of consignments. The studies have shown that, with an appropriate choice of the terminal equipment, it is possible to significantly reduce the time of cargo handling due to only a slight increase in the cargo unit transshipment cost.

**KEY WORDS**

~ Grain terminal
~ Optimization of the composition of technical means
~ Uneven loading
~ Simulation modelling
~ Multi-criteria assessment

Odessa National Maritime University, Odessa, Ukraine

e-mail: malax@ukr.net

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## 1. INTRODUCTION AND PROBLEM STATEMENT

Currently, there is a tendency towards an increase in world trade volumes and, accordingly, an increase in the volume of grain cargo transportation. The amount of international grain export increased by 7.1% in 2020 (512 million tons) compared to 2019 (478 million tons) and tends to grow (UNCTAD, 2021). A significant part of the international transportation of grain cargo is carried out by sea transport. The efficiency of grain storage and transportation technologies significantly affects its quality and cost for the end user. Therefore the development of technologies for grain cargo storage and transshipment at sea grain terminals is of great practical interest (Min et al., 2017).

There are a number of articles aimed at studying ways to improve the efficiency of sea terminals by means of the elaboration of new concepts for their development based on the analysis of accumulated experience. As a way to better utilise the existing terminal infrastructure and enhance terminal operating efficiencies, article (Min et al., 2017) proposes an integrated terminal operating system that can reduce duplicated investments in equipment, redundant workforce, and non-value-adding processes, while standardizing terminal services including loading/unloading and transferring cargo. The strategic pattern of 24 intermodal grain terminals spread throughout the five Brazilian regions was studied in (Santos et al., 2018) and groups of terminals from the perspective of their strategy and performance level are identified and analyzed. Article (Dafnomilis et al., 2018) investigates the optimization of biomass terminal equipment deployment. A mixed integer linear programming model was developed and applied to minimize the terminal's investment and operational costs related to partially used or shared equipment. A mixed integer linear program model for determining the capacity requirements, and the most cost-effective capacity improvement initiatives, to meet the demand while minimizing the total cost of infrastructure and demurrage was developed in (Singh et al., 2012) for the Hunter Valley Coal Chain. An automated traffic capacity calculation system for freight flows of bulk cargoes was proposed in (Panchenko et al., 2016). Paper (Lomotko et al., 2019) deals with the relationships between the participants of the grain transportation process and the balance between their interests based on the system of different criteria. Efficiency scores of world ports per cargo type (containers, oil, coal, iron ore, and grain) were calculated and analyzed in (Merk et al., 2012). These calculations were made using a database constructed for this purpose. Paper (Velury et al., 1992) concentrates on the selection of relevant factors that need to be considered in the design of a bulk material handling system and on the selection of equipment once these factors have been considered.

Effective use of equipment is one of the key factors for successful operation of sea port terminals. The methods for planning the optimum terms of replacement of sea port equipment with more advanced equipment of a new type, taking into account the degree of dispersion of possible values of equipment performance indicators were developed in (Lapkina et al., 2018). The study of dynamics of average indicators of equipment efficiency and fluctuations of these indicators over time, as well as development of a procedure for the substantiation of terms of replacement of sea port equipment, taking into account the instability of its loading intensity, was presented in (Malaksiano, 2012; Nemchuk et al., 2019; Lapkina et al., 2018).

When elaborating new strategies for the development of sea terminals, it is of great importance to build appropriate mathematical models that allow to take into account the main factors affecting terminal efficiency and provide the basis for making informed decisions regarding their design. The main approaches used in the construction of such models are based on the mathematical optimization methods, methods of probability theory, mathematical statistics, queuing theory, and simulation modelling. There are a number of works focused on the development of these approaches. Papers (Hyland et al., 2016; Reis et al., 2013; Marufuzzaman et al., 2017) introduce conceptual and mathematical models of the grain supply chains incorporating trucking, elevator storage, and rail transportation. Analysis of sea terminal performance based on multicriteria models was presented in (Da Cruz et al., 2013; Li et al., 2017). The problems associated with the optimization of maritime transport infrastructure were studied in (Melnyk et al., 2020; Zhykharieva et al., 2019), taking into account the specific characteristics of the cargo flow structure and protectionism. Article (Butko et al., 2019) proposes a mathematical model based on stochastic optimization for determining the rational motion intensity of traffic flows with account for balance of expenses on traction resources and cargo owners. Technological specifications and methodologies for evaluating the effectiveness of the bulk cargoes delivery process were studied in (Shramenko et al., 2019). Articles (Munisamy et al., 2010; Postan et al., 2016) develop a port planning and operations model for capacity planning, using stochastic processes and queuing theory. There are a number of works that use simulation modelling methods to evaluate and optimize sea transport infrastructure performance (Cimpeanu et al., 2017; Sislioglu et al., 2019; Tomashevskiy et al., 2008; Tomashevskyi et al., 2020; Lapkina et al., 2016a; Lapkina et al., 2016b; Bushuyev et al., 2021; Pavlenko et al., 2020; Turner et al., 2000). A discrete event simulation model for the analysis of bulk carrier unloading and storage of cargo at RUSAL Aughinish Alumina refinery was presented in (Cimpeanu et al., 2017). In (Sislioglu et al., 2019) a simulation model was designed to improve the productivity of sea terminal operations through investment alternatives. Analytical-simulation models for the decision making support systems, which take into account several criteria, were developed in (Tomashevskiy et al., 2008; Tomashevskyi et al., 2020). Simulation models were proposed in (Lapkina et al., 2016a; Lapkina et al., 2016b) for optimization of perishable cargo delivery system through the port of Odesa and optimization of the structure of sea port equipment fleet under unbalanced loading. The models based on the Monte-Carlo method and problems concerned with configuration of the project management were studied in (Teslia et al., 2018; Yehorchenkova et al., 2019). Optimization of logistics for the supply of agricultural products was performed in (Pavlenko et al., 2020) using Petri nets. A simulation study of terminal leasing policy and system performance was carried out in (Turner et al., 2000) for evaluating seaport policy alternatives.

Despite the fact that many articles have been focused on optimization of sea terminals infrastructure, a number of issues still require further study. In some papers (see, e.g., Dafnomilis et al., 2018; Singh et al., 2012; Marufuzzaman et al., 2017) mathematical models are proposed to optimize parameters of sea terminals, but not enough attention is paid to the study of the uncertainties involved. In other works (Munisamy et al., 2010; Postan et al., 2016; Lapkina et al., 2018), in order to take into account the uncertainties associated with the loading level of sea terminals, mathematical models based on the queuing theory and theory of stochastic processes were introduced. However, the use of these methods in a number of cases does not allow to fully take into account the specifics of various processes that have a significant impact on the performance of the terminals. Most of the available studies aim at improving a certain single performance indicator (it can be total costs, performance of the terminal, income, etc.) to its maximum, provided that the other indicators are within the permissible range of values (Hyland et al., 2016; Reis et al., 2013; Butko et al., 2019; Dafnomilis et al., 2018; Panchenko et al., 2016). However, in many cases, there are more than one performance indicator which need to be enhanced. Thus, in a number of cases, instead of single criterion methods, it becomes necessary to use multicriteria optimization methods. At the same time, the existing studies which deal with multicriteria approach (see, e.g., Da Cruz et al., 2013; Li et al., 2017; Melnyk et al., 2020; Lapkina et al., 2016a; Lapkina et al., 2016b) do not take into account peculiarities associated with cargo consignme,ts processing, neglect uncertainties involved, or omit some important features associated with the cargo operations at grain terminals. Many of the available techniques are mainly focused on the development and use of one of the known approaches (such as queuing theory, single criterion or multicriteria mathematical optimization methods, or simulation) and therefore these techniques at the same time have a number of advantages and disadvantages, determined by the choice of one of the approaches. In this regard, there is a need to develop new, more effective techniques based on a combination of different approaches. In this paper, we develop a technique based on a combination of simulation modelling and multicriteria optimization methods.

The main aim of this article is to develop a technique for determining the optimal composition of equipment for a sea grain terminal at the stage of its design. In this work, the construction project of an export terminal is considered, where it is planned to simultaneously accumulate and reload several consignments of different grain cargoes. It is assumed that the cargo can arrive at the terminal in different ways: by road, in specialized railway wagons, as well as in barges. The terminal is designed in such a way as to guarantee the expected annual cargo volume. At the same time, it is necessary to take into account a number of factors that are due to the peculiarities of technological processes, the specifics of commercial work, as well as the cargo flow seasonality.

Obviously, by restricting to the minimum set of equipment necessary to cope with the planned average annual cargo flow, it is possible to achieve the low cargo unit transshipment cost by minimizing capital costs. But at the same time, during peak loads, there can be a significant lack of carrying capacity. Because of this, at the peak of the season, the expected time for processing consignments can reach unacceptably high values. A significant reduction in the waiting time for processing consignments can be achieved by increasing the quality and quantity of the terminal handling equipment. However, this will increase capital expenditures on equipment, and, consequently, the cargo transshipment cost will also increase. Thus, the problem arises of choosing such a configuration for providing the terminal with equipment, which would achieve a balance between the cost of handling operations and the processing time of consignments at the terminal. This paper is focused on the study of this problem.

## 2. GENERAL WORKING PROCESS OF TERMINAL

### 2.1. Terminal performance

The investigated hypothetical terminal is planned to be built on the territory of the functioning Port of Odessa. The general scheme of organizing the work of the designed grain terminal is shown in Figure 1.

It is assumed that the total annual cargo flow passing through the terminal can be predicted with a certain degree of accuracy. Requests for transshipment of consignments are received from cargo owners to the terminal unevenly throughout the year. One request corresponds to one consignment arriving by different modes of transport. The incoming request specifies the volume of the consignment proposed for transshipment, the type of grain and what modes of transport are used for delivering this consignment to the terminal. It is assumed that one consignment can be delivered to the terminal in parallel by several modes of transport: by cars, by railway, and by barges. The request specifies the planned dates of the beginning of the arrival of the cargo at the terminal by each of the specified types of transport, the intensity of the arrival of the cargo, also indicating the date of arrival of the vessel for loading. When the request is accepted for processing, the terms specified in it are fixed by the contract, and, in accordance with these terms and rates, in the future, the cargo arrives at the terminal and the ship arrives for loading. If the terminal load does not allow servicing the incoming request immediately, then this request is placed in the queue (FIFO – first in first out). The terminal is designed in such a way as to handle full cargo volume planned for the year. It

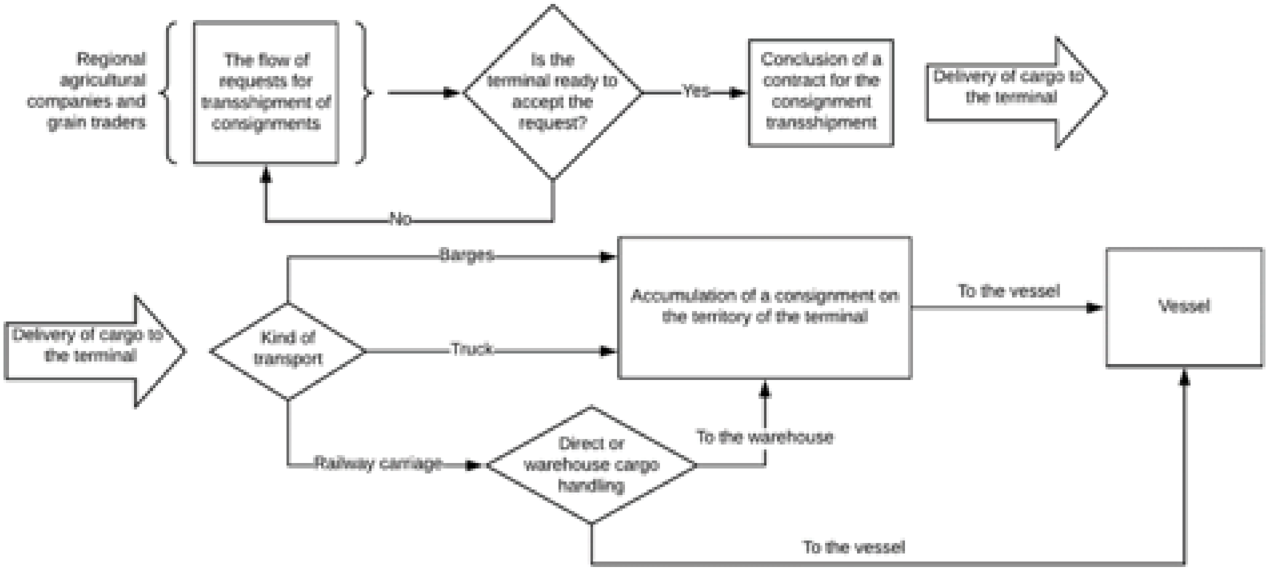


Figure 1.
General scheme of organization of the grain terminal operation.

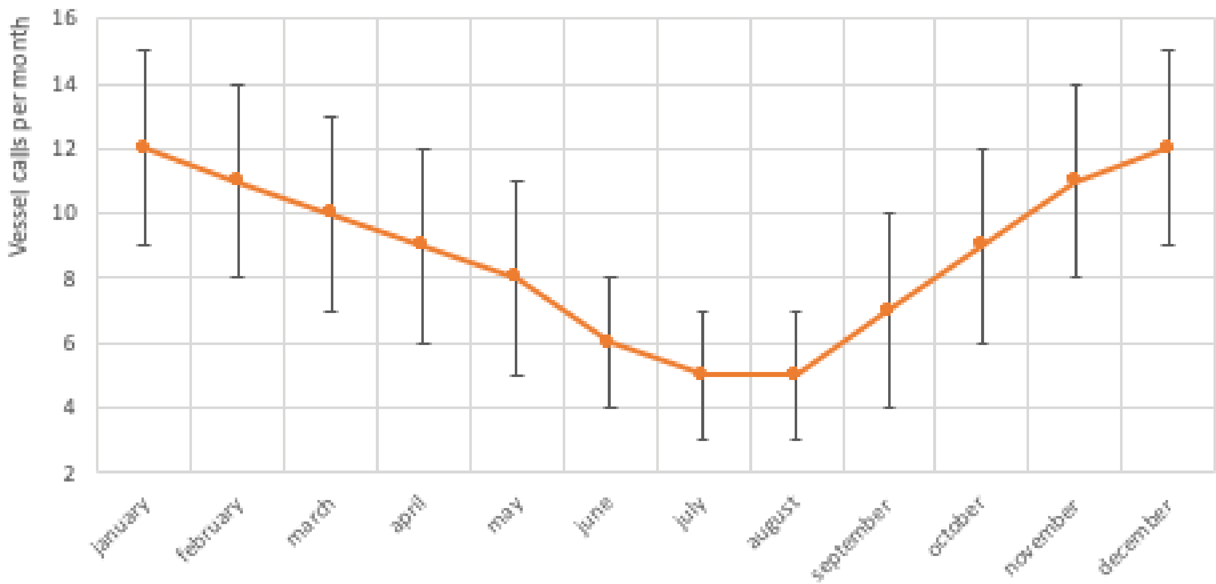


Figure 2.
Graph of change in the average expected level and the range of possible deviations in the cargo flow intensity during the year.

is assumed that some of the incoming requests will have to wait for a certain amount of time for their turn for service. Refusals to service requests are not allowed.

Seasonal fluctuations in the cargo flow intensity have a significant impact on the terminal operation. The graph of changes in the level of cargo flow intensity and the range of possible deviations in the cargo flow intensity, as well as the graph of changes in the expected structure of cargo flow during the year, are shown in Figure 2, 3.

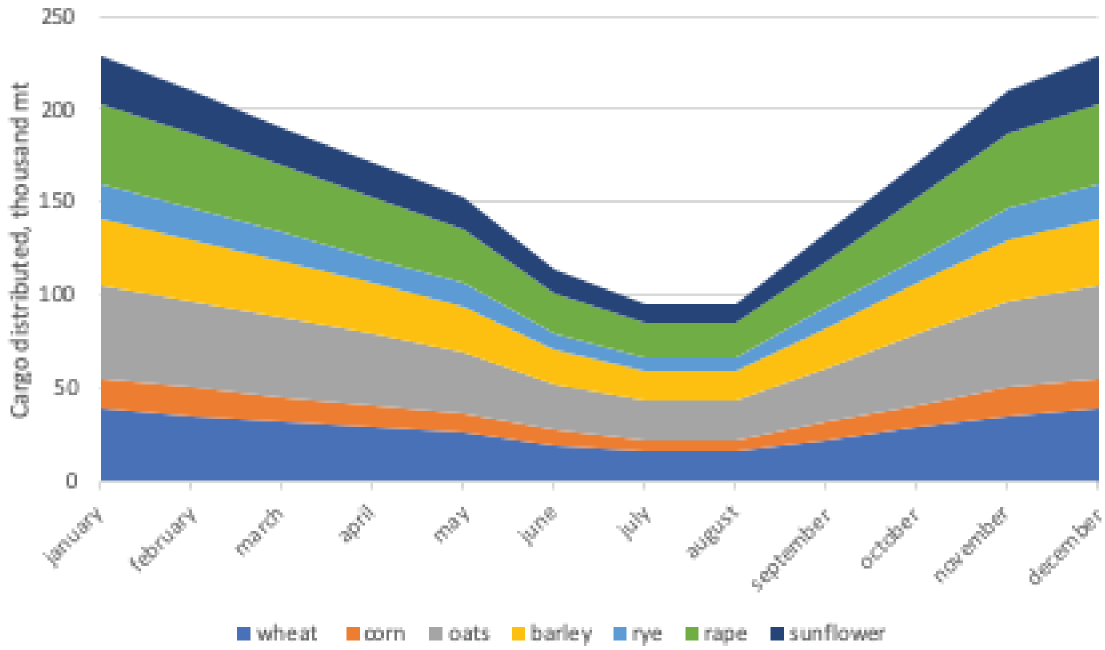


Figure 3.
Graph of change in the expected cargo flow structure during the year (on average 2 million tons/year).

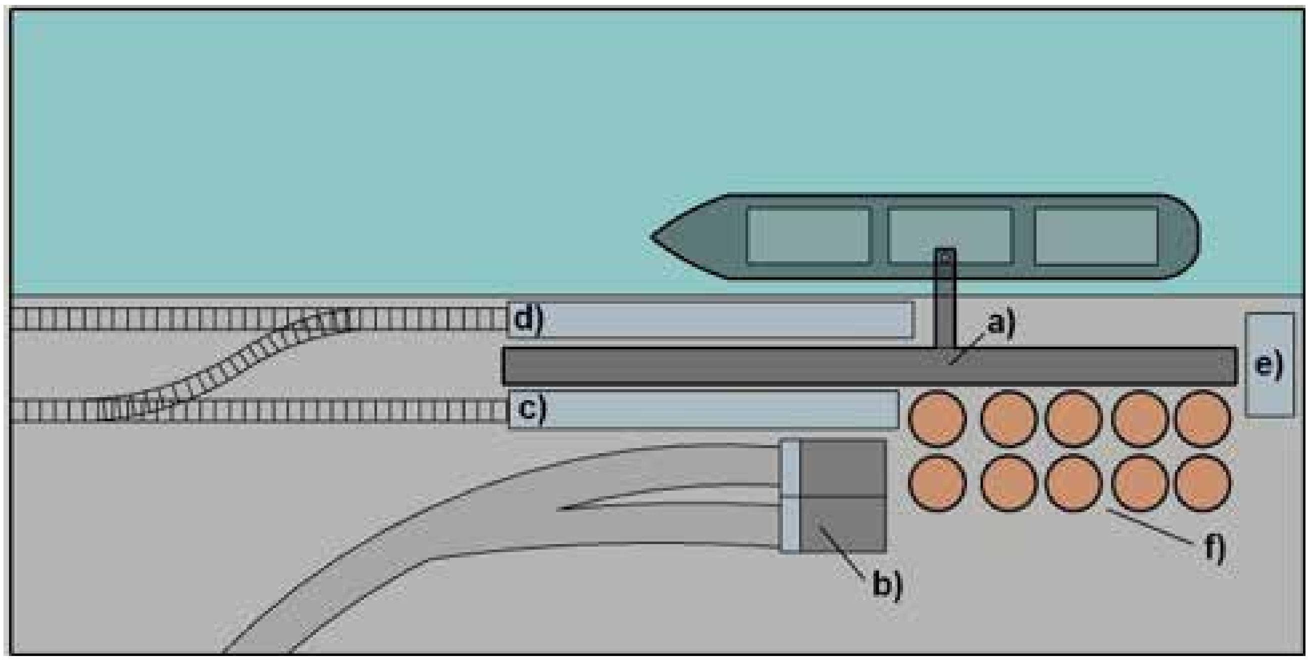


Figure 4.
Plan of one of the possible options for the grain terminal construction: a) conveyor gallery; b) car unloading station (CUS); c) wagon unloading station (WUS2); d) wagon unloading station (WUS1); e) barge unloading station (BUS); f) silo block.

Terminal performance indicators substantially depend on the qualitative and quantitative composition of the terminal equipment. There are a number of options for completing the grain terminal with equipment. The plan of one of the possible options for the construction of the grain terminal is shown in Figure 4.

Before turning to the discussion of the techniques for determining the optimal composition of equipment, some possible options for completing the terminal with equipment should be noted.

A conveyor system is planned to be used for grain transportation within the terminal and a ship-loading machine for the loading of vessels. The receiving points (Figure 4 - b, c, d) are used to receive incoming cargo from land transport. The possibility of direct loading onto a vessel, without intermediate storage in silages, is considered as a possible option that can improve the performance of the terminal. The low-capacity silages for intermediate storage are planned to be used to accumulate cargo before it enters the main silages. This is because the usage of low-capacity intermediate silages is especially effective when handling a large number of grain varieties and small transport units (trucks).

For this terminal, we have considered various equipment configurations based on the use of ship-loading machine capacity of 1,000, 1,100 or 1,200 t/h. The choice of the conveyor system capacity depends upon the ship-loading machine capacity (1,000, 1,100 or 1,200 t/h respectively) for the main conveyor belt and half the capacity for auxiliary conveyors (Table 1, items 1.2, 1.3)). On the main conveyor gallery (Figure 4, a; Table 1, item 1.1), it is advisable to use belt conveyors with side restraints. At the unloading wagon station (Figure 3, c; Table 1, item 1.3), scraper conveyors are planned to be used, since they allow unloading several cars, keeping high loading rates. At the car unloading station (Figure 3, b), as well as at the barge unloading station (Figure 3, e), conventional belt conveyors are used (Table 1, 1.2).

Within this study we have considered three options for organizing the main storages for grain: 93.5, 99.0, or 104.5 thousand tons (17, 18, or 19 metal round silages respectively, with corrugated panels with a capacity of 5,500 tons each). Such silages can be relatively easily erected at the considered terminal. Also, several options for intermediate silages are taken into consideration to accumulate the cargo arrived by trucks (2, 3, or 4 silages with a capacity of 800 – 1,000 tons each).

Also, for this terminal, it makes sense to consider three options for equipping a railway carriage unloading station (for 8, 9, or 10 simultaneously processed carriages), three options for building a truck unloading station (for 2, 3, or 4 trucks), and three options for building a station for unloading barges (500, 550 or 600 t/h).

It therefore becomes necessary to take into consideration 729 different alternative options for completing the terminal with equipment. All of the options considered for choosing each element of the terminal equipment are presented in Table. 1.

Table 1.
Terminal equipment options.

| Equipment | Item index | Type of equipment | Capacity (t/h) | Service life (years) |
|---|---|---|---|---|
| Conveyor transportation system | 1.1 | Main belt conveyor | 1,000-1,200 (t/h) | 20 |
| | 1.2 | Secondary belt conveyor | 500-600 (t/h) | 20 |
| | 1.3 | Scrapper conveyor | | |
| Silages | 2.1 | Main silages | 93,500-104,500 (t) | 30 |
| | 2.2 | Intermediary silages | 800-4,000 (t) | 25 |
| Reclaiming equipment | 3.1 | Underground hopper | 1,000-1,200 (t/h) | 30 |
| | 3.2 | Pneumatic unloader | 500-600 (t/h) | 7 |
| Ship loader | 4 | Loader | 1,000-1,200 (t/h) | 15 |

### 2.2. Calculation of terminal performance indicators

Among the important terminal performance indicators are the average cost of handling one ton of cargo, the average annual profit, and the average processing time of consignments. In some cases, when the planning horizon is certain, the Net Present Value (NPV) can be considered as the main criterion for the terminal efficiency. However, in the case under consideration, the designed terminal is planned to be used for a sufficiently long period of time, and it is impossible to determine this period in advance. At the same time, each piece of equipment located at the terminal has a well-defined service life, after which this equipment is replaced with new pieces of equipment of the same type. Therefore, it is advisable to consider the Equivalent Annual Cost (EAC) (see, e.g. (Jones et al., 1982) of the terminal profit or total expenses as the main economic indicator of the terminal performance.

To estimate the total average annual terminal costs, EAC value of the terminal total expenses will be used. This value is determined by the following formula:

$$EAC(C_{total}) = \sum_{k=1}^{m} (EAC(C_{capital\,k}) + EAC(C_{operational\,k})) + \\ + EAC(C_0) + EAC(C_{admin}) \quad (1)$$

where $EAC(C_{capital\ k})$ – equivalent annual cost of all capital expenses related to the k-th unit of equipment;

$EAC(C_{operational\ k})$ – equivalent annual cost of all operational expenses per k-th equipment unit;

$EAC(C_0)$ – equivalent annual cost of the expenses related to design and preparatory work associated with construction of the terminal;

$EAC(C_{admin})$ – equivalent annual cost of total fees and administrative expenses of the terminal.

The value of $EAC(C_{capital\ k})$ is calculated by the following formula:

$$EAC(C_{capital\,k}) = C_{acq\,k} \cdot \frac{e^r - 1}{1 - e^{-r \cdot T_k}} + C_{mount\,k} \cdot \frac{e^r - 1}{1 - e^{-r \cdot T_k}} + \\ + C_{unmount\,k} \cdot e^{-r \cdot T_k} \cdot \frac{e^r - 1}{1 - e^{-r \cdot T_k}} \quad (2)$$

where $C_{acq\ k}$ – acquiring cost of the equipment of the k-th type, USD;

$C_{mount\ k}$ – mounting cost of the equipment of the k-th type, USD;

$C_{unmount\ k}$ – unmounting cost of the equipment of the k-th type, USD;

$T_k$ – lifetime of the equipment of the k-th type, years;

r – continuous annual interest rate.

The value of $EAC(C_{capital\ k})$ is determined as follows

$$EAC(C_{operational\,k}) = \frac{e^r - 1}{1 - e^{-r \cdot T_k}} \cdot \int_0^{T_k} c_{maintanance\,k}(t) \cdot e^{-r \cdot T} dt + \\ + \frac{e^r - 1}{1 - e^{-r \cdot T_k}} \cdot \int_0^{T} (q_e \cdot 365 \cdot 24 \cdot r_{e\,k}(t)) \cdot e^{-r \cdot T} dt \quad (3)$$

where $C_{maintanance\ k}(t)$ – intensity of the costs associated with maintaining the equipment of the k-type ( k=1, ..., m ) in proper technical condition at time t, USD / year;

$q_e$ – electricity tariff, USD / kWh;

$r_{e\ k}(t)$ - electric power consumed by k-th equipment at time t, kW;

T – operation planning horizon, years.

The value of EAC ($C_0$ ) can be calculated using the formula below:

$$EAC(C_0) = C_0 \cdot (e^r - 1) \quad (4)$$

where $C_0$ – cost of design and preparatory work, USD.

Equivalent annual cost of total administrative expenses and fees of the terminal is calculated by the formula:

$$EAC(C_{admin}) = \frac{e^r - 1}{1 - e^{-r \cdot T_k}} \cdot \sum_{i=1}^{n} r_{berth\,i} \cdot A_i \cdot e^{-r \cdot t_i^{**}} + \\ + \frac{e^r - 1}{1 - e^{-r \cdot T}} \cdot \int_0^{T} (c_{wage} \cdot A_i \cdot e^{-r \cdot t} dt \quad (5)$$

where n – number of consignments served at the terminal for period of time T;

$A_i$ – amount of cargo in the i-th consignment, tons;

$T_i^{**}$ – actual time of completion of processing for the i-th consignment;

$r_{berth\ i}$ – tariff for services to provide access of the port operator to the berth per cargo unit of the i-th consignment, USD / ton (in accordance with (Law of Ukraine On Ukrainian Sea Ports, 2013))

$c_{wage}$ – wage costs for service and administrative personnel, USD / year.

Thus, the value of EAC ($C_{total}$ ) is:

$$EAC(C_{total}) = \frac{e^r - 1}{1 - e^{-r \cdot T}} \cdot \sum_{i=1}^{n} r_{berth\,i} \cdot A_i \cdot e^{-r \cdot t_i^{**}} + \\ + (e^r - 1) \cdot (C_0 + \sum_{k=1}^{m} \frac{C_{acq\,k} + C_{mount\,k}}{1 - e^{-r \cdot T_k}} + \sum_{k=1}^{m} \frac{C_{unmount\,k} \cdot e^{-r \cdot T_k}}{1 - e^{-r \cdot T_k}}) + \\ + (e^r - 1) \cdot \sum_{k=1}^{m} \frac{\int_0^{T_k} c_{maintanance\,k}(t) \cdot e^{-r \cdot t} dt}{1 - e^{-r \cdot T_k}} \\ + \frac{e^r - 1}{1 - e^{--r \cdot T}} \cdot \int_0^{T} (c_{wage} + q_e \cdot 365 \cdot 24 \cdot \sum_{k=1}^{m} r_{e\,k}(t)) \cdot e^{-r \cdot t} dt \quad (6)$$

To assess the terminal average annual profit (i.e., pure yields exceeding costs of the terminal), the value of the equivalent annual cost of profit EAC ( $P_{annual}$ ) will be considered, including all cash flows associated with the terminal expenses and incomes, which is calculated by the formula below:

$$EAC\,(P_{annual}) = \frac{e^{r}-1}{1-e^{-r \cdot T}} \cdot \sum_{i=1}^{n} r_{earn\,i} \cdot A_i \cdot e^{-r \cdot t_i^{**}} -$$
$$- (e^{r}-1) \cdot \left( C_0 + \sum_{k=1}^{m} \frac{C_{acq\,k} + C_{mount\,k}}{1-e^{-r \cdot T_k}} + \sum_{k=1}^{m} \frac{C_{unmount\,k} \cdot e^{-r \cdot T_k}}{1-e^{-r \cdot T_k}} \right) -$$
$$- (e^{r}-1) \cdot \sum_{k=1}^{m} \frac{\int_0^{T_k} c_{maintanance\,k}(t) \cdot e^{-r \cdot t}\,dt}{1-e^{-r \cdot T_k}}$$
$$- \frac{e^{r}-1}{1-e^{--r \cdot T}} \cdot \int_0^{T} \left(c_{wage} + q_e \cdot 365 \cdot 24 \cdot \sum_{k=1}^{m} r_{e\,k}(t)\right) \cdot e^{-r \cdot t}\,dt \tag{7}$$

where $r_{earn\,i}$ – rate for transshipment of a cargo unit of the i-th consignment, USD / ton.

To estimate the cargo unit transshipment cost $C_{unit}$, the EAC of all terminal costs divided by the average annual cargo flow is considered:

$$C_{unit} = \frac{EAC\,(C_{total}) \cdot T}{\sum_{i=1}^{n} A_i} \tag{8}$$

We denote $t_i$ – the readiness time for processing for the i-th consignment according to the request for cargo transshipment; $t_i^{*}$ - the actual start time of processing for the i-th consignment. Then the processing time of the i-th consignment is equal to $\Delta_{ac\,i} = t_i^{**} - t_i$. Thus, the average consignment processing time is as follows:

$$\bar{\Delta}_{ac\,i} = \frac{\sum_{i=1}^{n} \Delta_{ac\,i}}{n} \tag{9}$$

The waiting time for the i-th request is $\Delta_{w\,i} = t_i^{**} - t_i$. Thus, the average expected time for a request in the queue is:

$$\bar{\Delta}_{w\,i} = \frac{\sum_{i=1}^{n} \Delta_{w\,i}}{n} \tag{10}$$

It is also of interest to study the median values of the consignment processing time $\Delta_{mc}$. The values of $\Delta_{ac}$, $\Delta_{mc}$ and $\Delta_{w}$ can be minimized by installing the most efficient equipment at the terminal. However, in this case the cargo unit transshipment cost $C_{unit}$ would be too high, while the average annual profit EAC ($P_{annual}$ ) would be very small and may even be negative. On the other hand, if the terminal is equipped with the minimum amount of equipment that is necessary for the incoming cargo flow, it would be possible to reach the minimum value of $C_{unit}$ and, accordingly, the maximum value of EAC ($P_{annual}$ ); however, in this case, $\Delta_{ac}$, $\Delta_{mc}$ and $\Delta_{w}$ would assume quite large values. In this regard, it is clear that the structure of the terminal equipment should be chosen in such a way that a balance is achieved between the values of $\Delta_{ac}$, $\Delta_{mc}$ and $\Delta_{w}$ on the one hand, and the values of $C_{unit}$ and EAC ($P_{annual}$ ) on the other. It is therefore advisable to consider the following multicriteria optimization problems.

We denote ψ the set of all possible options for completing the terminal with equipment. Consider the problem of finding such a configuration of equipment ψϵψ, at which the maximum average annual profit of the terminal EAC ($P_{annual}$ ) is achieved and at the same time the minimum value of the average consignment processing time $\Delta_{ac}$ is achieved as well:

$$EAC\,(P_{annual}),\ \bar{\Delta}_{ac} \underset{\psi \epsilon \psi}{\rightarrow} (max,\ max) \tag{11}$$

Along with problem (11), another problem can be studied:

$$EAC\,(C_{unit}),\ \bar{\Delta}_{mc} \underset{\psi \epsilon \psi}{\rightarrow} (min,\ max) \tag{12}$$

in which the search for such a structure of equipment ψϵψ is carried out, at which the minimum value of the cargo unit transshipment cost $C_{unit}$ and the value of the median consignment processing time $\Delta_{mc}$ are to be simultaneously achieved.

Thus problems (11) and (12) cannot have a unique solution. To study these problems, the methods of multicriteria optimization should be used. The key information that allows to facilitate the reasonable choice of the optimal solution of the problems can be obtained based on the analysis of the set of all optimal in the Pareto sense structures of equipment. A structure of equipment $\psi_1 \epsilon \psi$ is called optimal in the Pareto sense if there does not exist any structure of equipment $\psi_2 \epsilon \psi$ such that $\psi_2$ dominates the $\psi_1$. We say that $\psi_1 \epsilon \psi$ dominates $\psi_2 \epsilon \psi$ if $\psi_1$ is at least as good as $\psi_2$ for all the objectives, and $\psi_1$ is strictly better than $\psi_2$ for at least one objective. Clearly, structures of equipment $\psi$ which are not optimal in the Pareto sense are of no practical interest. A more detailed discussion and analysis of solutions of the problems (11) and (12) are given in the second part of this article. The concepts and methods of the theory of multicriteria optimization and associated decision-making techniques are presented in more detail, for example, in (Ehrgott, 2005; Kaliszewski et al., 2016).

## 3. SIMULATION MODELLING OF TERMINAL FUNCTIONING

The study of multicriteria optimization problems (11) and (12) is associated with a number of difficulties. The first difficulty is that, even with a fixed structure of the terminal equipment, the estimation of indicators EAC ($P_{annual}$ ), $C_{unit}$, $\Delta_{ac}$, $\Delta_{mc}$ and $\Delta_w$ , using analytical mathematical methods, is not possible. This is due to the fact that the terminal is affected by random factors that have specific distribution laws, and the business logic of processes occurring at the terminal, without significant restrictions and assumptions, cannot be reduced to one of the schemes that can be effectively analyzed within the mathematical queuing theory. The second difficulty is related to the fact that, when studying problems (11) and (12), the set of all possible options for the terminal equipment can consist of hundreds and even thousands of different potentially acceptable options.

Since the analytical approach to solving problems (11) and (12) is associated with insurmountable difficulties, to tackle these problems, we have created a Java based computer simulation model of the terminal, which allows us to take into account all the main stages of processing for requests and consignments. The scheme of the simulation software module, which depicts the processing of the cargo handling requests at the terminal, is shown in Figure 5. In accordance with this scheme, cargo handling requests arrive at the terminal and accumulate in the requests pool, where they wait when the terminal is ready to start processing them. Requests in the pool are processed in the order in which they are received. Each request contains information regarding the ways and intensities of delivery for the grain consignment (within one consignment, the cargo can be delivered by trucks, carriages (direct / storage options), barges or combinations thereof), and also contains the vessel arrival time for loading. When the application is accepted, the corresponding processes of cargo arrival at the terminal are activated. When delivered within the direct option, the cargo is sent to the vessel bypassing the warehouse. When loading according to the storage option, the grain first goes to the warehouse, and then

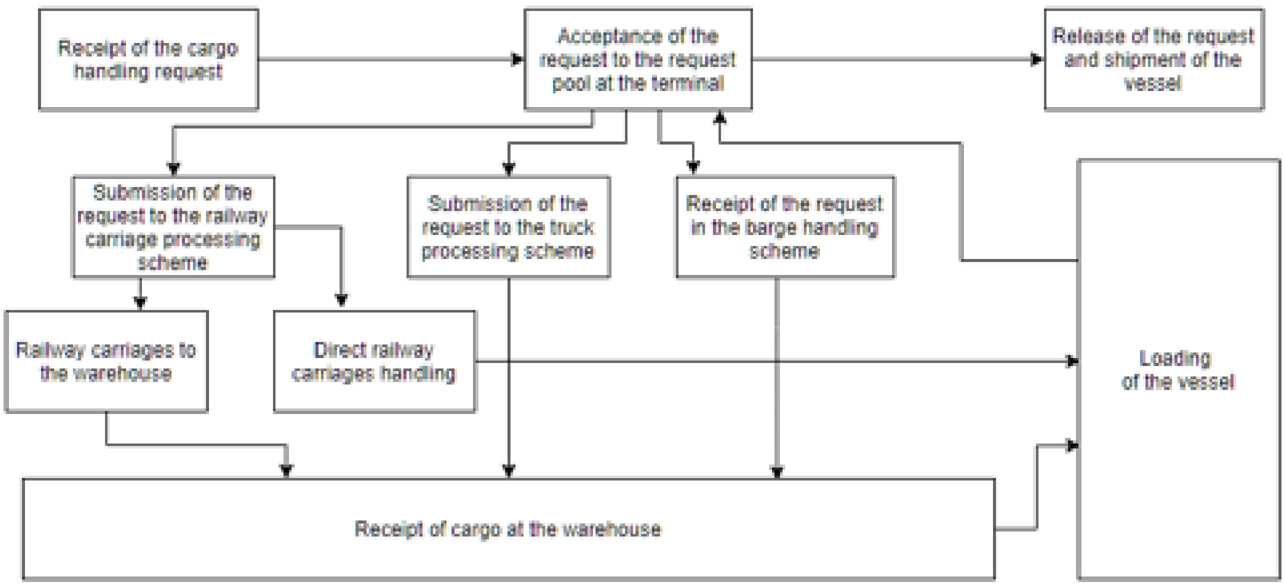


Figure 5.
Grain terminal simulation model module diagram.

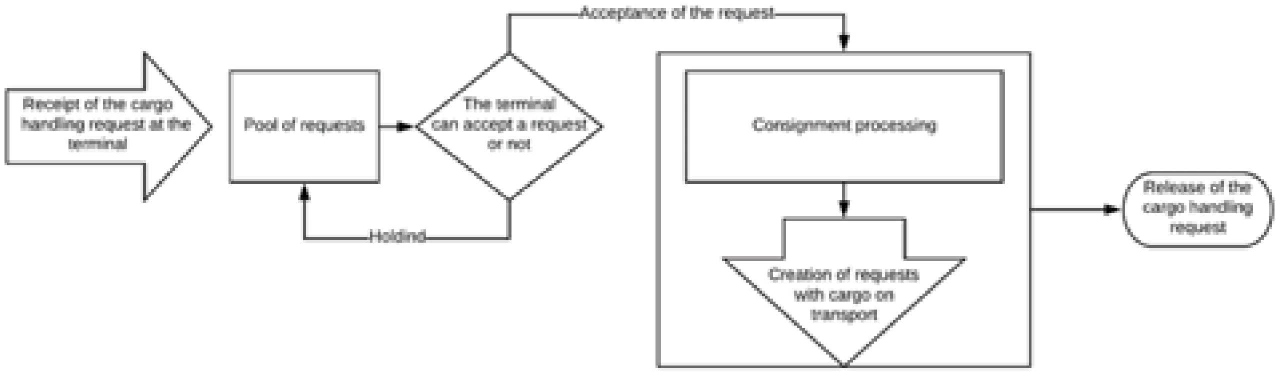


Figure 6.
Request processing module diagram.

to the vessel. At the end of the loading of the vessel, the request is considered closed and leaves the scheme. Figure 6. shows the procedure of processing a request in more detail.

When generating the flow of requests, the simulation model uses a number of random parameters, such as the consignment size, the cargo nomenclature, the cargo distribution by various ways of delivery to the terminal, etc. The model has no direct restrictions on the number of simultaneously processed consignments at the terminal. The processing of each consignment is modelled within specialized software modules.

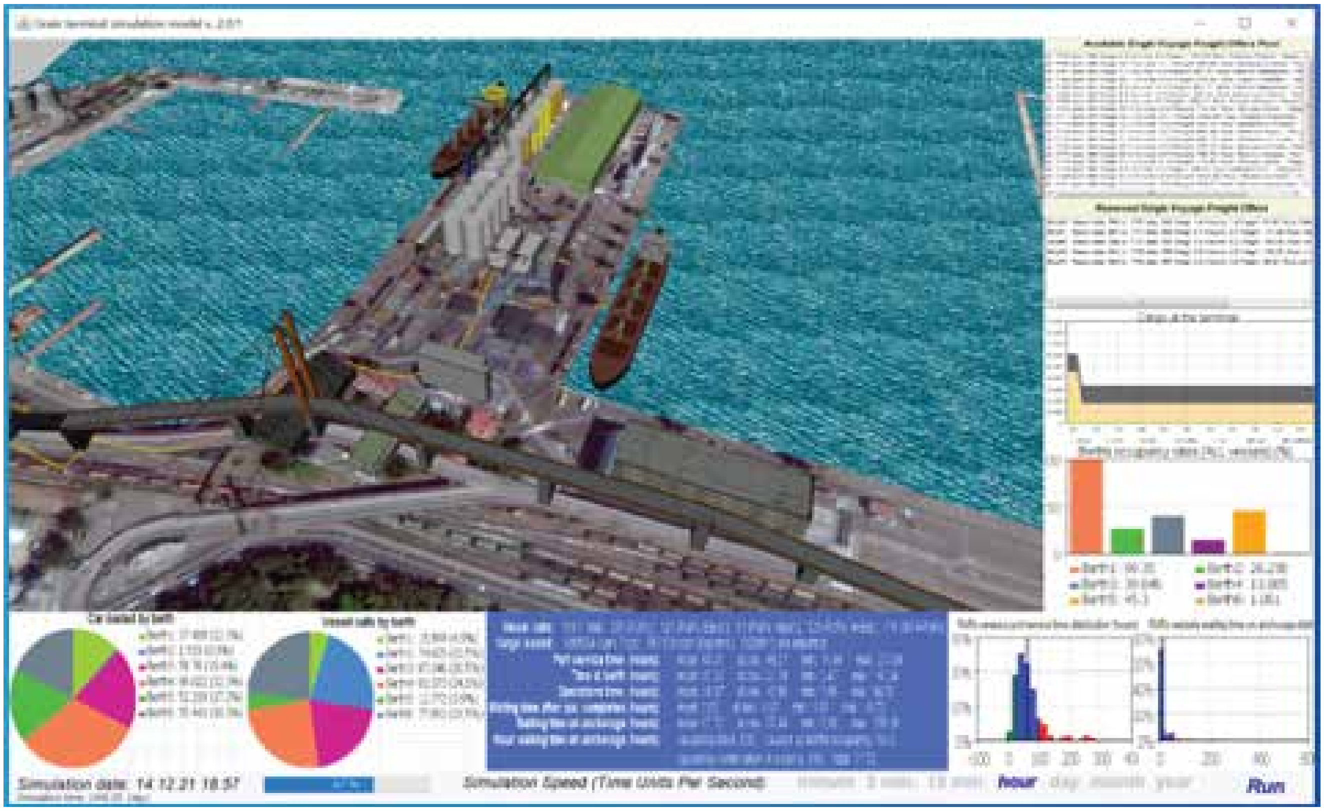


Figure 7.
Window of the simulation model in 3D.

Each module implements the business logic for managing technological processes associated with the processing of various types of transport. Cargo flows processed according to the direct option have priority over cargo flows reloaded through the warehouse.

The developed simulation model can work in real time with a demonstration of all the ongoing processes in 3D (Figure 7). After each run, the model generates massive database of statistical data that allows a comprehensive assessment of the terminal performance for different equipment options. Furthermore, this simulation model can run in an accelerated mode without animation. Simulation of one year of the terminal operation in this mode on a personal computer takes less than one second. Using the model in an accelerated mode allows a large number of runs to be carried out in a short time, which makes it possible to automate the variation of parameters in a series of runs.

As part of our research, the set ψ consisting of 729 equipment options (in accordance with Table 1) has been considered. To assess the performance indicators of the terminal for each of the equipment options, the series of runs has been performed with the planning horizon of T = 10 years. For each run, the time intervals between the cargo handling requests and the amounts of cargo in consignments have been generated as the gamma-distributed random values with cyclically changing parameters. Therefore, the time interval between the arrival of the request with cargo has been generated as a random variable, the probability density function of which is as follows:

$$f_t(x) = \begin{cases} x^{a^2(t)/s^2(t)-1} \cdot \dfrac{e^{\frac{-x}{s^2(t)/a(t)}}}{(s^2(t)/a(t))^{a^2(t)/s^2(t)} \cdot \Gamma(a^2(t)/s^2(t))}, & x \geq 0, \\ 0, & x<0 \end{cases} \tag{13}$$

where $\Gamma(y)$ – gamma function;

a(t) – average time interval between incoming cargo handling requests;

s(t) – standard deviation of the time between incoming cargo handling requests.

Functions a(t) and s(t), as well as the amounts of cargo in consignments, are taken based on the forecasts of monthly changes in the cargo flow structure provided by the experts (Figure 2, 3). The use of the gamma distribution allows to account for the specifics of changes in the cargo flow intensity, since with the appropriate combinations of parameters, this distribution can approximate both normal and exponential distribution.

For further calculations the annual interest rate has been assumed to be r = 0.8, the tariff for services to provide access of the port operator to the berth $r_{berth\ i}$ = 0.07 USD / t for all consignments. The electricity consumed by each piece of equipment is calculated by the simulation model at each moment in time, in accordance with the passport characteristics of the equipment and the current level of loading.

## 4. RESULTS

The terminal performance indicators are calculated based on the results of each run of the simulation model using formulas (1)–(10). Figure 8 shows a set of points, the coordinates of which are respectively equal to the average annual profit of the terminal and the average consignment processing time for different options of completing the terminal with equipment ψϵψ.

In Figure 8, unimprovable points lying on the Pareto frontier of the multicriteria optimization problem (11) are marked with blue circles. The options of completing the terminal with equipment $\psi_k$ corresponding to unimprovable solutions of the two-criterion optimization problem (11), are presented in Table 2.

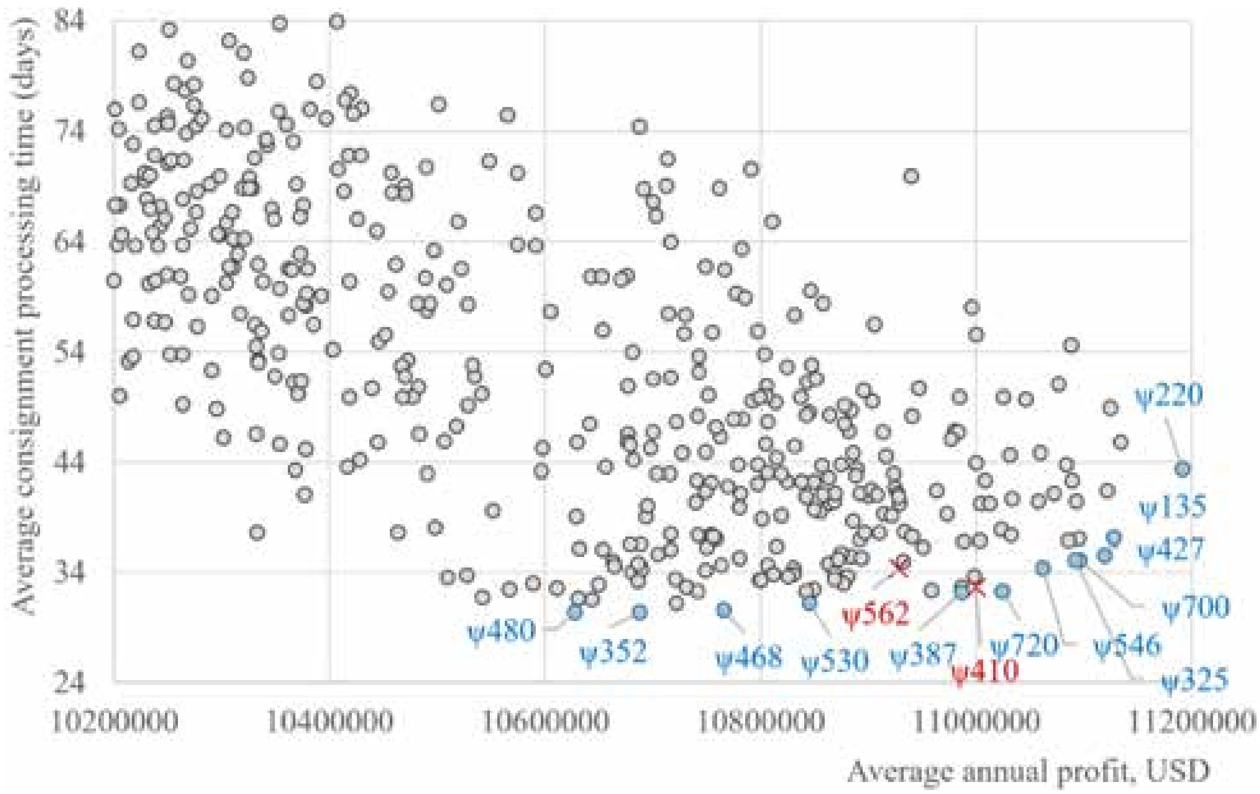


Figure 8.
The values of the terminal average annual profit and the average consignment processing time for different options of completing the terminal with equipment.

Table 2.
Unimprovable options for completing the terminal with equipment according to the multicriteria optimization problem (11).

| | Equipment | | | | | | | | | Simulation results | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Denotation for the terminal equipment options | Number of silages / capacity (tons) | Number of intermediate silages / capacity (tons) | Conveyor and shiploader capacity, tons/h | Truck unloading station capacity, tons/h | Number of truck unloading stations | Number of places for unloading railway carriages according to the direct option | Intensity of unloading railway carriages according to the direct option, tons/h | Number of places for unloading railway carriages to the warehouse | Intensity of unloading railway carriages to the warehouse, tons/h | Cargo unit transshipment cost, USD / ton | Average consignment processing time, days | Average expected time for a request in the queue, days | Terminal average annual profit, USD |
| ψ135 | 19/104500 | 3/3000 | 1100 | 550 | 3 | 10 | 550 | 8 | 550 | 5.55 | 37.15 | 23.37 | 11 127 978.13 |
| ψ220 | 19/104500 | 3/3000 | 1100 | 550 | 2 | 10 | 550 | 8 | 550 | 5.52 | 43.38 | 29.65 | 11 191 813.93 |
| ψ325 | 19/104500 | 4/4000 | 1100 | 550 | 2 | 10 | 550 | 9 | 550 | 5.57 | 35.09 | 22.08 | 11 092 121.00 |
| ψ352 | 19/104500 | 4/4000 | 1200 | 600 | 4 | 10 | 600 | 10 | 600 | 5.77 | 30.33 | 17.30 | 10 687 678.95 |
| ψ387 | 19/104500 | 3/3000 | 1200 | 600 | 3 | 10 | 600 | 8 | 600 | 5.62 | 32.10 | 17.50 | 10 986 767.79 |
| ψ427 | 19/104500 | 3/2700 | 1100 | 550 | 3 | 10 | 550 | 9 | 550 | 5.56 | 35.49 | 21.69 | 11 119 738.65 |
| ψ468 | 19/104500 | 4/3200 | 1200 | 600 | 4 | 10 | 600 | 10 | 600 | 5.73 | 30.54 | 16.70 | 10 766 017.38 |
| ψ480 | 19/104500 | 4/4600 | 1200 | 600 | 4 | 10 | 600 | 10 | 600 | 5.80 | 30.32 | 16.58 | 10 627 678.95 |
| ψ530 | 19/104500 | 4/3200 | 1200 | 600 | 3 | 10 | 600 | 9 | 600 | 5.69 | 31.20 | 17.50 | 10 845 612.00 |
| ψ546 | 19/104500 | 4/3200 | 1100 | 550 | 4 | 10 | 550 | 8 | 550 | 5.58 | 34.34 | 20.42 | 11 062 450.44 |
| ψ700 | 19/104500 | 4/3200 | 1100 | 550 | 3 | 10 | 550 | 8 | 550 | 5.57 | 35.11 | 21.34 | 11 096 816.87 |
| ψ720 | 19/104500 | 4/4000 | 1100 | 550 | 3 | 10 | 550 | 9 | 550 | 5.60 | 32.23 | 17.80 | 11 024 435.90 |

Figure 9 shows a set of points, the coordinates of which are respectively equal to the cargo unit transshipment cost and the median value of the consignment processing time for different options of completing the terminal with equipment (Table 3). The points of the Pareto frontier, which are unimprovable solutions of the multicriteria optimization problem (12), are marked with blue circles.

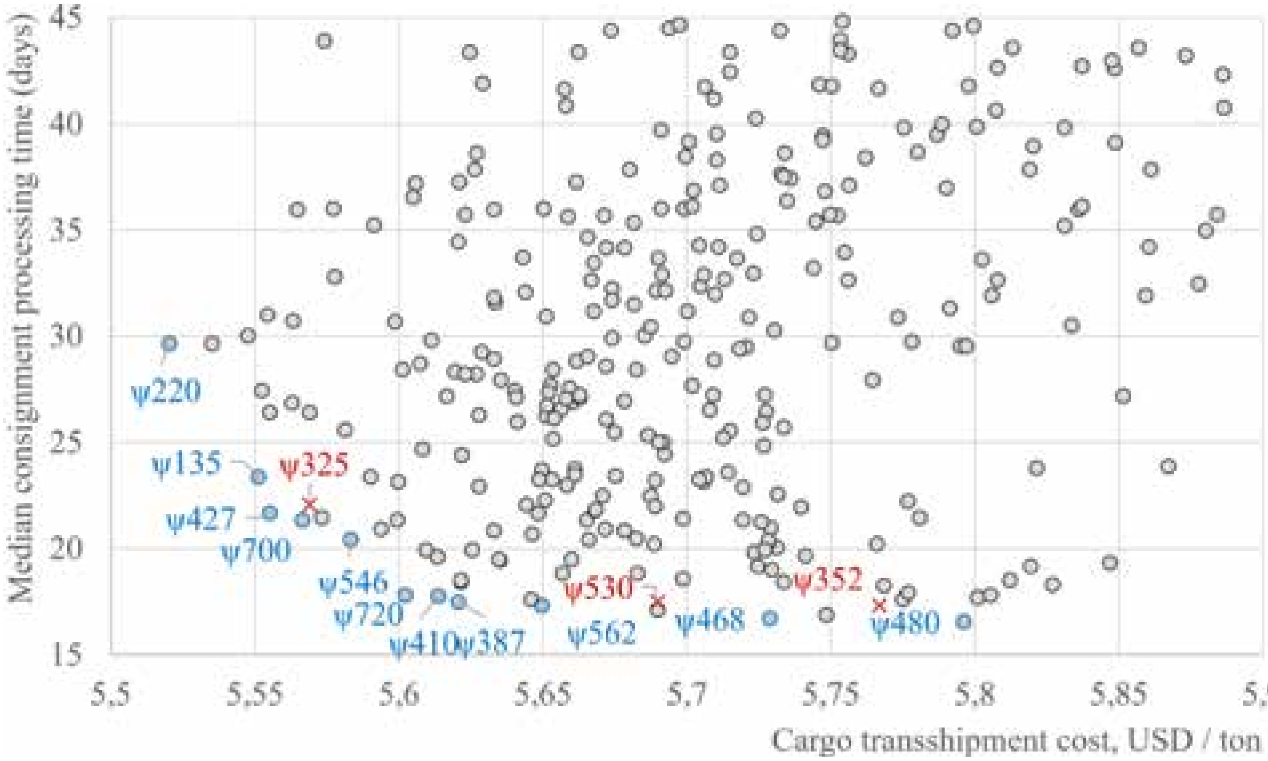


Figure 9.
Values of the unit cargo transshipment cost and median values of the consignment processing time for different options of completing the terminal with equipment.

In addition, in Figure 9, the points, corresponding to the Pareto optimal structures of equipment $\psi_k$ for the problem (11) are marked with crosses. Similarly, the Pareto optimal structures of equipment of the problem (11) are marked with crosses in Figure 8. As can be noted, from Figure 8 and Figure 9, that there are a number of structures of equipment $\psi_k$ that are Pareto optimal to both problems (11) and (12).

It is clear that the points that are not on the Pareto frontiers of problems (11) or (12) correspond to unbalanced equipment configurations. Such points are in the majority (Figure 8 and Figure 9), and their consideration is of no practical interest.

**Table 3.**
Unimprovable options for completing the terminal with equipment according to the multicriteria optimization problem (12).

| | Equipment | | | | | | | | | Simulation results | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Denotation for the terminal equipment options | Number of silages / capacity (tons) | Number of intermediate silages / capacity (tons) | Conveyor and shiploader capacity, tons/h | Truck unloading station capacity, tons/h | Number of truck unloading stations | Number of places for unloading railway carriages according to the direct option | Intensity of unloading railway carriages according to the direct option, tons/h | Number of places for unloading railway carriages to the warehouse | Intensity of unloading railway carriages to the warehouse, tons/h | Cargo unit transshipment cost, USD / ton | Median consignment processing time, days | Average expected time for a request in the queue, days | Terminal average annual profit, USD |
| ψ135 | 19/104500 | 3/3000 | 1100 | 550 | 3 | 10 | 550 | 8 | 550 | 5.55 | 37.15 | 23.37 | 11 127 978.13 |
| ψ220 | 19/104500 | 3/3000 | 1100 | 550 | 2 | 10 | 550 | 8 | 550 | 5.52 | 43.38 | 29.65 | 11 191 813.93 |
| ψ387 | 19/104500 | 3/3000 | 1200 | 600 | 3 | 10 | 600 | 8 | 600 | 5.62 | 32.10 | 17.50 | 10 986 767.79 |
| ψ410 | 19/104500 | 4/3200 | 1100 | 550 | 3 | 10 | 550 | 8 | 550 | 5.61 | 32.70 | 17.75 | 11 000 000.00 |
| ψ427 | 19/104500 | 3/2700 | 1100 | 550 | 3 | 10 | 550 | 9 | 550 | 5.56 | 35.49 | 21.69 | 11 119 738.65 |
| ψ468 | 19/104500 | 4/3200 | 1200 | 600 | 4 | 10 | 600 | 10 | 600 | 5.73 | 30.54 | 16.70 | 10 766 017.38 |
| ψ480 | 19/104500 | 4/4600 | 1200 | 600 | 4 | 10 | 600 | 10 | 600 | 5.80 | 30.32 | 16.58 | 10 627 678.95 |
| ψ546 | 19/104500 | 4/3200 | 1100 | 550 | 4 | 10 | 550 | 8 | 550 | 5.58 | 34.34 | 20.42 | 11 062 450.44 |
| ψ562 | 19/104500 | 4/3600 | 1200 | 600 | 2 | 10 | 600 | 9 | 600 | 5.65 | 34.32 | 17.30 | 10 927 678.95 |
| ψ700 | 19/104500 | 4/3200 | 1100 | 550 | 3 | 10 | 550 | 8 | 550 | 5.57 | 35.11 | 21.34 | 11 096 816.87 |
| ψ720 | 19/104500 | 4/4000 | 1100 | 550 | 3 | 10 | 550 | 9 | 550 | 5.60 | 32.23 | 17.80 | 11 024 435.90 |

The final choice of the structure of equipment that will eventually be implemented should be made by the decision-maker, based on the analysis of only unimprovable solutions that are on the Pareto frontiers of multicriteria optimization problems (11) and (12). Thus, having the Pareto frontier, the choice of the optimal structure of equipment becomes much easier. Since a huge number of options known to be ineffective can be excluded from consideration, the decision-maker's attention should be focused on only a very small number of Pareto optimal structures of equipment.

## 5. DISCUSSION AND CONCLUSION

Comparing the Pareto frontiers in Figure 8 and Figure 9, it should be noted that some options for completing the terminal with equipment ($\psi_{480}$, $\psi_{468}$, $\psi_{387}$, $\psi_{720}$, $\psi_{546}$, $\psi_{700}$, $\psi_{427}$, $\psi_{135}$ and $\psi_{220}$) have turned out to be Pareto optimal for both problems (11) and (12). In this case, the options for completing the terminal with equipment $\psi_{325}$, $\psi_{530}$, $\psi_{352}$ are optimal for problem (11), but they are not optimal for problem (12), and options of completing $\psi_{410}$ and $\psi_{562}$ are optimal for problem (12), but at the same time they are not optimal for problem (11). The research has shown (Figure 9, Table 3) that the minimum cost value is 5.52 USD / t and is achieved for the option of equipment $\psi_{220}$, that is the case when the terminal is equipped with 19 silages with a total capacity of 104.5 thousand tons, 2 car loading stations, the capacity of the main conveyor is 1100 t / h, and the capacity of bucket elevators, truck unloading stations and railway carriages unloading stations are 550 t / h each. At the same time, the average consignment processing time is 43.38 days, the average expected time for a request in the queue is 29.65 days, and the average annual profit is 11.19 million USD.

By increasing the amount of equipment, it is possible to achieve a reduction in the processing time of consignments, but at the same time the cargo unit transshipment cost increases. Let us compare the Pareto optimal options for completing the terminal with equipment $\psi_{220}$ and $\psi_{427}$. As shown in Figure 9 Table 2 and Table 3, with the same number of silages and truck unloading stations, due to a corresponding increase in the capacity of the handling equipment, it is possible to reduce the average expected time for a request in the queue from 29.6 to 21.6 days, with an increase in the cost of transshipment of a ton of cargo by only 0.04 USD.

The altering from the structure of equipment $\psi_{220}$ to $\psi_{427}$ or altering from $\psi_{427}$ to $\psi_{720}$ may be considered appropriate, since these changes entail a small increase in cost, while providing a noticeable reduction in the average expected time for requests in the queue (Figure 9). However, a further increase in equipment performance (for example, altering from option $\psi_{720}$ to option $\psi_{480}$) is not advisable because in this case the cargo unit transshipment cost noticeably increases, while the average expected time for the request in the queue hardly changes.

Thus the method for multicriteria assessment of the grain terminal functioning using simulation modelling is proposed in the paper. The relationship between the cargo unit transshipment cost and the average consignment processing time has been was analysed for the case when the cargo flow intensity is subject to random fluctuations. The study has shown that some Pareto optimal structures of equipment for the problem (11) are not optimal for the problem (12).

Based on the method for multicriteria assessment, a technique for determining the optimal structure of equipment has been proposed. This technique makes it possible to determine the qualitative and quantitative choice of the terminal equipment, taking into account both the cargo transshipment cost and the processing time of consignments. The research has shown that by choosing the terminal equipment structure, it is possible to significantly reduce the cargo processing time, slightly increasing the cargo unit transshipment cost. The developed simulation model has been built, taking into account the characteristics of the region considered; however, the general methodology for building a model and analyzing the results of modelling is universal and can be used for a wide range of sea terminals.

## CONFLICT OF INTEREST

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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