Keywords: warehouses; numerical modeling; internal transport; performance analysis

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SUBSTANTIATION OF A REASONABLE NUMBER OF FORKLIFTS FOR A WAREHOUSE COMPLEX WITH FRONTAL RACKS IN AN ANYLOGIC ENVIRONMENT

Summary. This paper is devoted to the study of the impact of volumetric planning solutions and the main production and technological parameters of a modern warehouse on the effectiveness of its functioning. The object of analysis is a class A warehouse complex located in Almaty. Simulation modeling was utilized to find and substantiate management decisions. The software product AnyLogic was used as the environment for the simulation. This paper develops a generalized algorithm for creating simulation models of warehouse complexes and a simulation model consisting of 114 blocks. The model is presented in the form of a black box, which made it possible to identify and establish correlations and relations between the input and output parameters of the warehouse, as well as its resources. A simulation experiment was conducted consisting of 63 model calculations. Variation parameters were the number of loading and unloading docks, as well as the number of forklifts in the storage area. As a result of the simulation, four options for the operation of the warehouse were established to ensure the unloading and loading of the required number of cars during the day. The optimal variant of the functioning of the warehouse complex was chosen on the basis of the proposed comprehensive criterion.

1. INTRODUCTION

The Republic of Kazakhstan, as is known [1], is the ninth-largest state in the world. Located in the heart of the Eurasian continent and having a complex of road and railway networks and air routes, as well as a strategically important port on the Caspian Sea, the country is able to realize the existing high national transit potential to ensure uninterrupted Eurasian transport communication. Taking into account the growth in the volume of cargo flows between a major producer (China) and a significant consumer (Europe), the main goal of the state's transport policy remains the further creation of the Eurasian transcontinental bridge. Given the limited capacity of the railway, special attention is paid to transit transportation by road. Thus, according to the results pertaining to the first half of 2022, the

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transportation of goods by all means of transport (freight traffic) in Kazakhstan amounted to 1,710,014.6 thousand tons, which is 0.18% more than in the same period of 2021. Freight traffic amounted to 202,958.6 million t-km, which is 5.6% more than in 2021. At the same time, the freight traffic of road transport is 1,362,501.1 thousand tons, and that of rail transport is 206,172.2 thousand tons. Thus, road transport accounts for 79.6% of cargo transportation in Kazakhstan, while rail transport accounts for 12%. At the end of 2018, the freight traffic of these modes of transport amounted to 82% and 9.7%, respectively. The average annual increase in cargo transportation over the past four years was 3% [2].

One of the most important factors in developing the potential of the transit corridor is warehouse logistics. Between production, transport, and consumers, there are storage facilities designed to transform the shape and parameters of material flows and smooth out uneven cycles of freight traffic during the operation of various means of transport. Thus, the provision of the country with high-quality 3PL and 4PL operators can provide a full range of services that meet all international standards, which indicates its transit potential. In Kazakhstan, the construction of warehouses is taking place as a part of the implementation of the 65th step of the "Plan of the Nation – 100 Concrete Steps," which is the "Integration of Kazakhstan into international transport and communication flows" [3].

According to [4], 70% of the warehouse logistics market is located in the city of Almaty and the Almaty region. However, even these volumes of warehouses are not enough compared to the European level. Thus, all storage needs are not met. Although the market as a whole shows an increase in demand for warehouses, there is still a clear lag between supply and demand. At present, the market of warehouses in Almaty is slightly more than 1 million m^2. The bulk of the warehouse market in Almaty comprises class A and B warehouses (according to the Swiss Realty Group classification), which account for 80% of all warehouse space [5].

The current paper is devoted to the analysis of the impact of volumetric planning decisions and the main production and technological parameters of the current warehouse on the efficiency of its functioning.

2. PURPOSE OF THE STUDY

The purpose of this paper is to increase the reliability of the work of modern warehouse complexes and change the capital and flow rates for the hours of their operation to develop simulation models at the AnyLogic core. AnyLogic (the AnyLogic Company retailer) is a single platform for the simulation modeling of any business system [6]. It is a corporate standard for business modeling in many multinational companies (including CATERPILLAR, Mitsubishi Motors, INTEL, Xerox, AstraZeneca, HP, Boeing, IBM, NASA, MacDonald, and Pfizer), and today is widely recognized in 63 countries.

3. METHODS

The modern warehouse complex belongs to complex systems [7, 8] since it includes many technological processes that differ significantly from each other. In complex systems, the possibility of applying traditional methods of finding the optimal solution is limited since loosely structured tasks combine both quantitative and qualitative dependencies. Therefore, it is necessary to use modern research methods to find and substantiate management solutions during the development or modernization of warehouse operations. One such method is simulation modeling.

The software product AnyLogic was chosen as the environment for modeling because it supports the design, development, and documentation of the model, which allows computer experiments to be performed with the model, including various types of analysis, from sensitivity analyses of model parameters to their optimization according to a selected criterion. This software has the ability to create models using all three modern approaches: discrete-event, agent, and system dynamics.

According to the organization and optimization of warehouse complexes, AnyLogic is used to solve the following problems [9]: calculation of the number, type, and characteristics of transport and cargo equipment; determination of the required number of personnel serving posts and forklifts; calculation of the areas for the reception, shipment, assembly, sorting, and storage of goods (initial data that must be adjusted in case of solving problem No. 1); calculation of the number of gates for loading and unloading; and calculation of warehouse performance indicators, including operation time, resource utilization rates, and dynamics of inventory level changes.

4. LITERATURE REVIEW

A criterion for the effective operation of any warehouse is ensuring the necessary freight circulation of goods at optimal costs for processing and storing goods. It should be remembered that the warehouse of each company is designed to solve different problems: In one case, it is placing the maximum amount of cargo in a specific room [10]; in the second case, it is ensuring the maximum cargo circulation [11]; in the third, it is optimizing the structure of warehouses [12]; and in the fourth, it is reducing operating expenses [13]. Therefore, an important aspect of research on warehouse management systems is the development of decision support systems for the design and management of warehouse systems [14]. Material flows enter storage and processing systems with one parameter and leave with others. The parameters should be understood as the intensity, power, rhythmicity, and structure of these flows, as well as the type and method of product packaging, time of arrival and departure of transport lots, etc. If the parameters of material flows in some sections of transport networks do not require changes, then there is no need to create warehouses or transformation centers (which include several warehouse complexes). In fact, both transformation centers and individual warehouses form peculiar storage and processing systems of varying degrees of complexity. Misunderstanding their role and importance in the management of flow processes leads to the inefficient organization of transport networks [15] and, in turn, to deficiencies in the general system of production, distribution, physical movement, and consumption of products [16]. The evolution of logistics has also led to the fact that, in addition to the traditional functions of storing goods and materials, warehouses are used as cross-docking points [17]. One of the main tasks during the design of a warehouse complex is the organization of an optimal storage system. Authors [18] have claimed that despite the importance of warehousing for customer service and maintaining the required level of costs, there is no comprehensive universal warehouse design methodology.

At the stage of the literature analysis, it was found that warehouse and logistics processes are continuously developing and that the robotization of warehouse complexes is already being carried out by many successful enterprises. The leaders in warehouse robotization are Amazon, IKEA, and Tesla. Among other well-known corporations that actively use robots for warehousing and moving goods, one can single out the logistics company DHL, the Meijer supermarket chain, the manufacturer of LEGO constructors, and Coca-Cola, the largest player in the soft drinks market [19]. One of the main problems of a robotic warehouse is ensuring the efficient navigation of autonomous equipment inside the premises. There are several ways to solve this problem. Some devices require special markings on the floor to work, and more advanced models recognize objects in real time due to infrared radiation and built-in sensors [20]. In recent years, warehouse management systems have gained popularity. Connecting robots to such software allows one to fully automate the operation of the equipment [21]. At the same time, data protection is ensured by integrating the blockchain into warehouse systems.

The launch of 5G has led to the possibility of creating the Internet of Things. A continuous stream of information allows people to track pallets, analyze data, and make forecasts. Warehouse automation has recently become one of the most relevant topics in the field of cargo transportation and logistics. Smart technologies for warehousing and logistics can solve problems associated with a lack of operators [22], human error [23], the need to transport heavy loads [24], the quality of inventory management [25], the productivity and minimization of the risk of unforeseen situations [26], and the number of forklifts and the size of the fleet of vehicles [27, 28] for servicing warehouse operations. Making the final decision during the conversion of existing premises or the design of a new one requires one to consider the features of the product range and the scope of application, as well as the advantages and disadvantages of the existing storage area organization schemes. An example of such an approach is found in [29], in which a comparative analysis of warehouse processes was conducted in selected cases of three companies. It is based on the following algorithm: the current state of the warehouse system is analyzed, optimization proposals are made in accordance with the identified bottlenecks, and finally, a comparative analysis of the suggested optimization proposals is made.

Our paper considers a warehouse complex equipped with front racks in the storage area. Front racks (RapidBlock) are metal structures that are used to store pallets. Such racking systems are loaded and unloaded from the front side. This loading method is very convenient for storing a wide range of products with a limited shelf life. Front racks provide quick and easy access to any product unit.

5. RESEARCH MATERIALS

5.1. Source data and problem statement

A class A warehouse complex located in Almaty was chosen as the research object. The warehouse is equipped with front racks in the storage area. It has three loading and unloading docks. During the day (from 8^{00} to 18^{00}), 24 euro trucks with a capacity of 33 pallets are loaded at the warehouse, and 48 cars with a capacity of 16 pallets are loaded, with average intensities of arrival and departure of three and six cars per hour, respectively. The main parameters of the research object are given in Table 1.

Table 1

Main parameters of the research object

Indicator	Value
Average daily external freight traffic on arrival and departure, tons	273.44
The average daily amount of cargo processing per warehouse, tons	1421.88
Hourly intensity of internal freight traffic, tons per hour.	66.65
Area of the warehouse, m^2	6 927.06
Number of pallets with cargo stored in the warehouse, units	11 020.00
Number of forklifts / unloading docks / loading docks, units	20 / 3 / 3
Average number of cars unloaded during the day	24
Average number of cars loaded during the day	48

According to the results of the technological audit of the warehouse, which was carried out by the LLP Research and Technology and Innovation Corporation "Aul Nur," the coefficients of the use of forklifts for the respective zones were determined through time-keeping observations (Fig. 1).

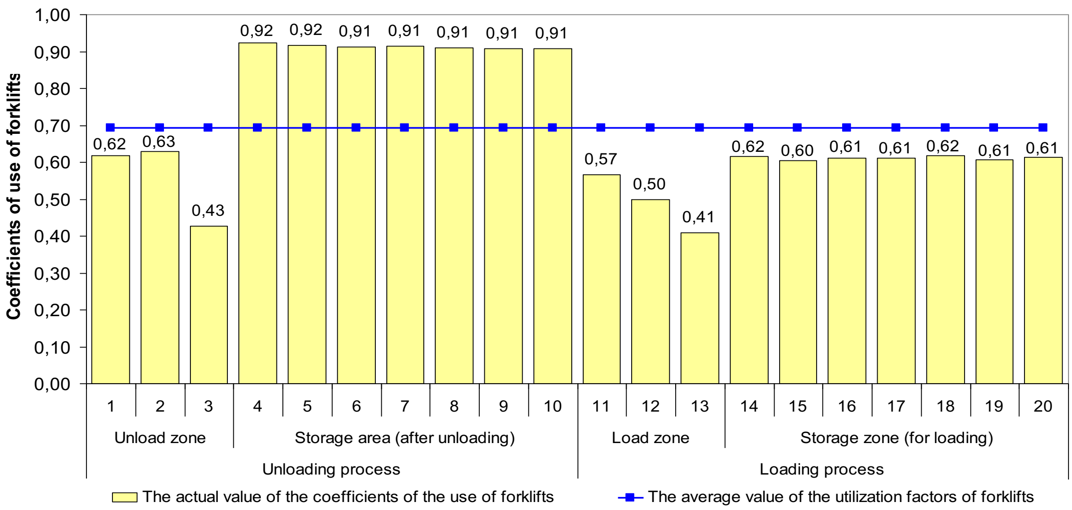


Fig. 1. The value of the coefficients of the use of forklifts for the corresponding areas of the warehouse

The analysis of Fig. 1 allows us to draw the following conclusions: The coefficient values of the use of forklifts are distributed in the range of 0.41...0.92. The average coefficient values of the use of forklifts are 0.76 (in the storage area), 0.49 (in the unloading zone), and 0.56 (in the loading zone). Finally, the weighted average value of the coefficients of the use of forklifts in general in the warehouse is 0.69.

Thus, an underutilization of 31% of the main production facilities was observed at the research facility, which leads to an increase in the costs of their operation and maintenance and an increase in the required number of warehouse service personnel. Given the stochastic nature of the main technological operations that take place in the warehouse, including the arrival of cars and their loading (unloading), the location of pallets with goods in the storage area, and order picking, the terminal management decided to develop a simulation model of the warehouse complex in the AnyLogic environment, which allows, in both present and future conditions, the identification of bottlenecks in the operation of the warehouse and solutions for their elimination; the evaluation of the effectiveness of various warehousing and storage policies, the determination of the optimal number of forklifts and other warehouse resources for the effective functioning of the warehouse in the conditions of an uneven schedule of arrival (departure) of vehicles, and the risk-free testing of any hypothesis planned for implementation.

5.2. Development of a simulation model of a warehouse complex equipped with front racks in the AnyLogic environment

The authors have developed a generalized algorithm for creating simulation models of warehouse complexes equipped with front racks in the AnyLogic environment (Fig. 2).

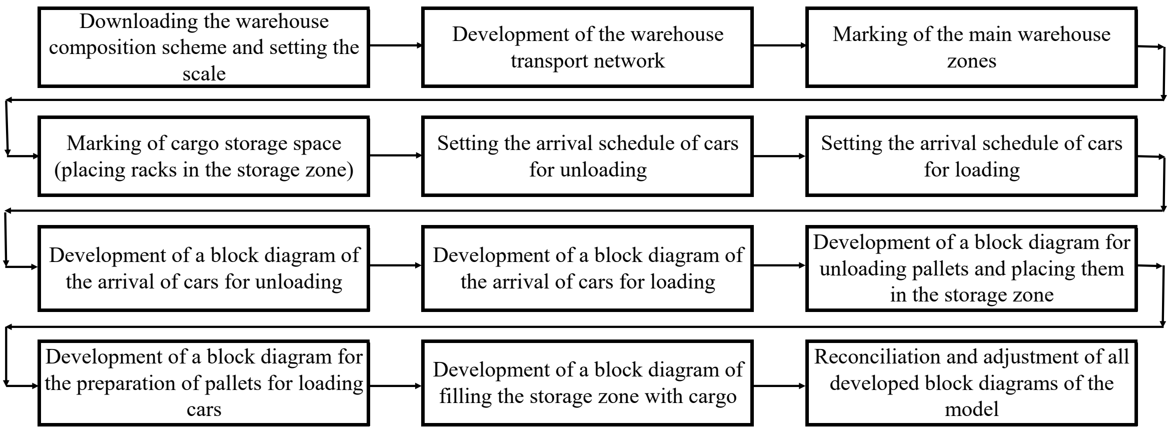


Fig. 2. Algorithm for creating simulation models of warehouse complexes equipped with front racks in the AnyLogic environment

In general, the development of a warehouse simulation model in the AnyLogic environment can be divided into two stages: First, with the help of *Space Markup* elements, such as *Path, Point Node* and *Rectangular Node*, a transport network is created for the movement of cars and forklifts and the placement of racks in warehouse zones in accordance with its layout scheme using the *Pallet Rock* element (Fig. 3). Second, model operation logic is assigned using a sequence of blocks included in the *Process Modeling Library* and their settings.

The analysis of the structure of technological processes that occur in warehouses as a result of the processing of external and internal freight traffic allows us to conclude that the process being modeled can be represented as a stochastic multiphase multichannel system for mass service of a closed type with a limited input capacity. The logic underlying the model in the *AnyLogic* environment is set graphically in the form of a sequence of blocks (forming a certain technological process), each of which represents a separate operation performed by the corresponding agents. The blocks of the *Process Modeling Library*, which were used for the assignment of the logic of the simulation model of the warehouse, are listed in Table 2. The model itself, consisting of 114 blocks, is presented in Fig. 4.

The abbreviations “U” and “L” have been used for the names of the blocks, which correspond to the steps associated with the *Unloading* and *Loading* processes. The combination of the description of the functionality of the corresponding block (Table 2) and its name (identifier) provides a visual opportunity to present the structure of the technological process being modeled. The distinguishing feature of the developed simulation model is that it implements all technological operations that take place in modern warehouses. Specifically, Module No. 1 describes the process of unloading cars; Module No. 2 describes their loading; Module No. 3 describes the process of unloading pallets and moving them to the storage area; Module No. 4 describes the process of moving pallets from the storage area to the loading area; Module No. 5 is responsible for creating pallets that form the insurance stock; and Module No. 6 forms the main resources of the warehouse (forklifts and the storage area).

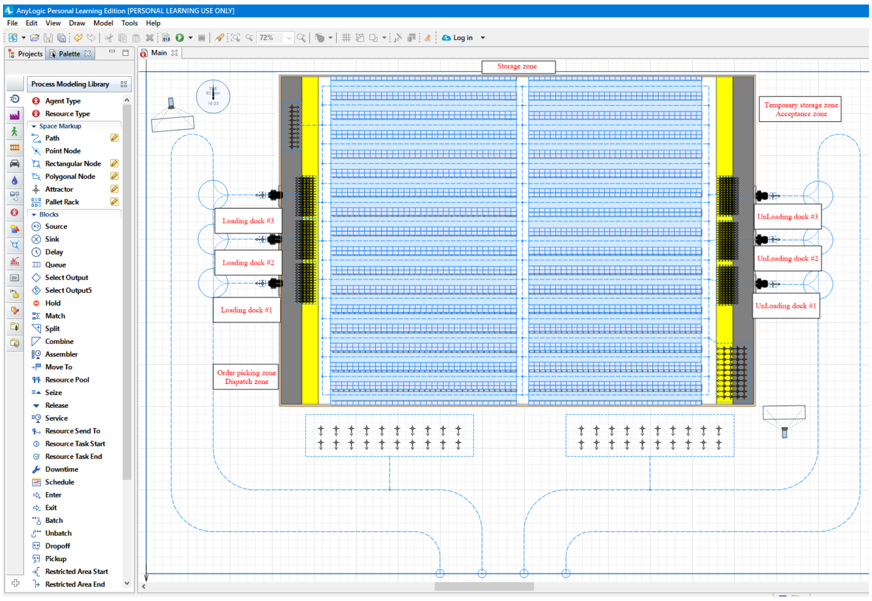


Fig. 3. The development transport network for the movement of cars and forklifts and the placement of racks in warehouse zones in the AnyLogic environment

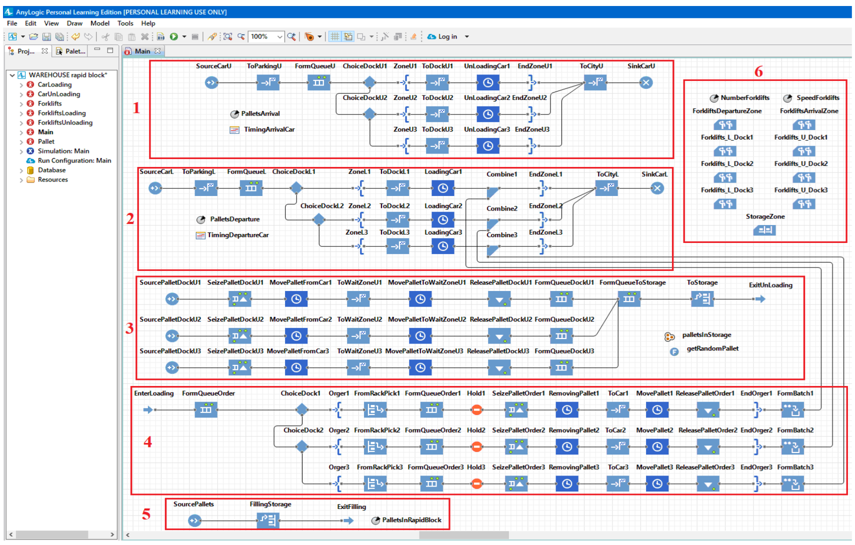


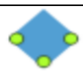
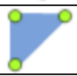
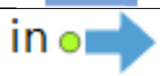
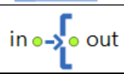
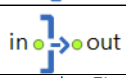
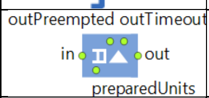
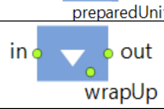
Fig. 4. The developed model of warehouse operation with front racks in the *AnyLogic* environment

The following objects act as agents in the developed model (Fig. 4): *CarLoading* represents the cars arriving under loading, *CarUnLoading* represents the cars arriving under unloading, *Forklifts* represents the forklifts serving the storage area, *ForkliftsLoading* represents the forklifts serving the loading area, *ForkliftsUnloading* represents the forklifts serving the unloading area, and *Pallet* represents pallets with cargo.

Most modern forklift models are capable of reaching a maximum speed of 14 to 19 km/h. Efforts to reduce the cycle time during forklift movement (with or without a load) involve attempting to realize the maximum design speed. In the developed simulation model, the speed of the loaders was set according to a triangular distribution (which is often used as a functional form of representing areas with fuzzy logic) with the following *triangular* parameters: 14, 17, and 19. Parameter 17 is the median of the distribution, which corresponds to the most frequent value of the maximum design speed.

Table 2

Blocks of the *Process Modeling Library* used to assign the logics model of the warehouse

Block name	Conventional designation	Description of the functionality of the block
Source		Generates agents. This block is usually a starting point of a process flowchart.
Sink		Disposes of incoming agents. This block is usually a final point of a process flowchart.
Queue		A queue (a buffer) of agents waiting to be accepted by the next block in the flowchart.
Delay		Delays agents for a given amount of time.
Hold		Temporarily blocks the agent flow for the following branch of the process flowchart.
SelectOutput		Routes the incoming agents to one of the two output ports depending on (probabilistic or deterministic) condition.
Combine		Waits for the two agents to arrive (in arbitrary order) at ports in1 and in2 and produces and outputs a new agent.
Batch		Converts a number of agents into one agent (batch) by either discarding the original agents or creating a new one (permanent batch).
Exit		Takes the incoming agents out of the process flow and lets the user specify what to do with them.
Enter		Inserts the (already existing) agents into a particular point of the process flowchart.
Move To		Moves the agent to a new location.
Restricted Area Start		Marks the entry into the section (area) of the process where the user wishes to limit the maximum number of agents.
Restricted Area End		Marks an exit from the section (area) of the process where the user wishes to limit the maximum number of agents.
Seize		Seizes a given number of resource units from the given ResourcePool block(s).
Release		Releases a given number of resource units previously seized by the Seize object.
Rack Store		RackStore puts an agent into a cell of a given pallet rack or RackSystem.
Rack Pick		RackPick removes an agent from a cell in the specified pallet rack or RackSystem and moves it to the specified destination location.
Resource Pool		Defines a set of resource units. Resources are objects required by agents to perform certain tasks.
Rack System		RackSystem is used to represent a number of storages as a single block with multiple rows and aisles.

The accepted values of other parameters of the model are as follows: the speed of vehicles on the territory of the warehouse = 10 km/h, lifting (lowering) the forks of the forklift = 5 s per tier of the rack, marking and registration of an unloaded pallet = 120 s, and preparing a pallet for loading = 150 s.

5.3. Setting up a simulation experiment and analyzing the results

The developed simulation model allows the user to identify and establish correlations and relations between the input and output parameters of the warehouse, as well as its resources – for example, between the number of forklifts (or docks) and the duration of unloading (loading) of vehicles, their waiting time, and the coefficients of the use of forklifts. With this in mind, the developed simulation model of the warehouse with front racks (Fig. 4) can be presented in the form of the model of a black box as presented in Fig. 5.

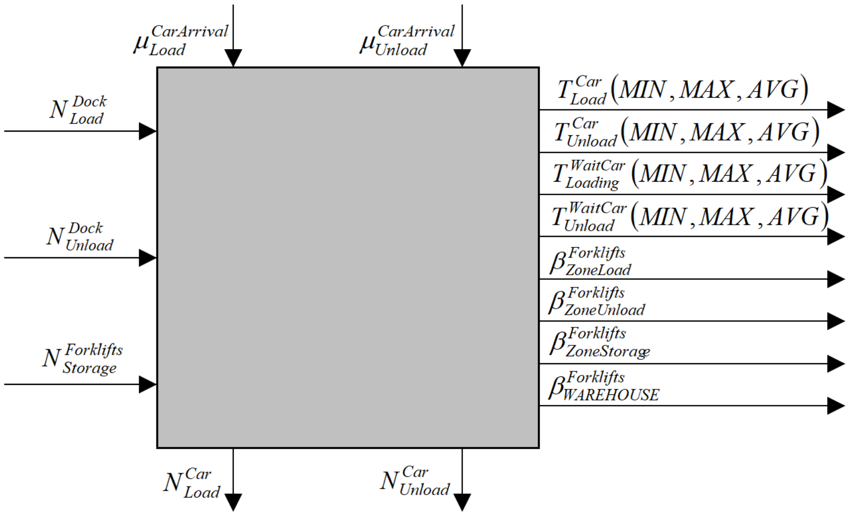


Fig. 5. Black box model of warehouse complex functioning

The conventional designations shown in Fig. 5 are as follows: N_{Load}^{Dock} is the number of loading docks in the warehouse, in units; N_{Unload}^{Dock} is the number of unloading docks in the warehouse, in units; $N_{Storage}^{Forklifts}$ is the number of forklifts in the storage area, in units; $\mu_{Load}^{CarArrival}$ is the daily intensity of the arrival of cars under loading, in units; $\mu_{Unload}^{CarArrival}$ is the daily intensity of the arrival of cars for unloading, in units; N_{Load}^{Car} is the number of loaded cars during the day, in units; N_{Unload}^{Car} is the number of unloaded cars during the day, in units; $T_{Load}^{Car}(MIN, MAX, AVG)$ is the duration of car loading (minimum, maximum, and average values), in min.; $T_{Unload}^{Car}(MIN, MAX, AVG)$ is the duration of car unloading (minimum, maximum, and average value), in min.; $T_{Load}^{WaitCar}(MIN, MAX, AVG)$ is the waiting time for car loading (minimum, maximumm and average value), in min.; $T_{Unload}^{WaitCar}(MIN, MAX, AVG)$ is the waiting time for unloading cars (minimum, maximum, and average values), in min.; $\beta_{ZoneLoad}^{Forklifts}$, $\beta_{ZoneUnload}^{Forklifts}$, $\beta_{ZoneStorage}^{Forklifts}$, and $\beta_{WAREHOUSE}^{Forklifts}$ are the coefficients of the use of forklifts in the loading, unloading, storage areas, and in the warehouse on average, respectively.

The analysis of the black box model allows us to draw the following conclusions: $\mu_{Load}^{CarArrival}$ and $\mu_{Unload}^{CarArrival}$ are the input parameters of the model; N_{Load}^{Car} and N_{Unload}^{Car} are the output parameters of the model; N_{Load}^{Dock}, N_{Unload}^{Dock} and $N_{Storage}^{Forklifts}$ are parameters that vary; $T_{Load}^{Car}(MIN, MAX, AVG)$, $T_{Unload}^{Car}(MIN, MAX, AVG)$, $T_{Loading}^{WaitCar}(MIN, MAX, AVG)$, $T_{Unload}^{WaitCar}(MIN, MAX, AVG)$, $\beta_{ZoneLoad}^{Forklifts}$,

$\beta^{Forklifts}_{ZoneUnload}$, $\beta^{Forklifts}_{ZoneStorage}$, and $\beta^{Forklifts}_{WAREHOUSE}$ are parameters that allow us to evaluate the efficiency of the system.

Taking into account the peculiarities of the implementation of the logic of the model in *AnyLogic*, during the preparation for the simulation experiment, the following assumptions were made (and then implemented programmatically in the model): The number of forklifts in the unloading (loading) zone depends on the number of docks in the zone (one forklift for each dock). When the number of docks is reduced, the forklifts associated with the dock are removed from the system. The number of forklifts in the storage area is divided into two groups, which are assigned to the unloading and loading areas, respectively. The number of forklifts in the storage area changes in pairs. Finally, the intensity of the arrival of cars for loading and unloading is six and three cars per hour, respectively. The numerical parameters of the developed simulation experiment are given in Table 3, and the algorithm of its implementation is depicted in Fig. 6. Taking into account the structure of the proposed algorithm, which consists of a triple nested cycle (Fig. 6) and the numerical parameters of the simulation experiment (Table. 3), the number of model calculations is 63 variants. Some results of the performed modeling process are presented in Figs. 7 and 8. Thus, as a result of the simulation, the warehouse capacity was estimated from the point of view of the possibility of "mastering" the daily incoming and outgoing cargo flows not by one variable but by varying three parameters at once: the number of docks for loading, the number of docks for unloading, and the number of forklifts in the storage area (Fig. 5). During the modeling process (for each of the 63 variants of the model run), 18 technical and operational parameters of warehouse functioning were determined, which, according to the authors, is sufficient for making further management decisions by the warehouse designers and managers.

Table 3

Numerical parameters of the simulation experiment

INPUT PARAMETERS OF THE MODEL			
Indicator	Designation	Value	
Daily intensity of the arrival of cars for unloading	$\mu^{CarArrival}_{Unload}$	24	
Daily intensity of the arrival of cars for loading	$\mu^{CarArrival}_{Load}$	48	
PARAMETERS THAT VARY			
Indicator	Designation	Value	
		MIN	MAX
Number of unloading docks	N^{Dock}_{Unload}	1	3
Number of loading docks	N^{Dock}_{Load}	1	3
Number of forklifts in the storage area (two groups)	$N^{Forklifts}_{Storage}$	2(1+1)	14(7+7)

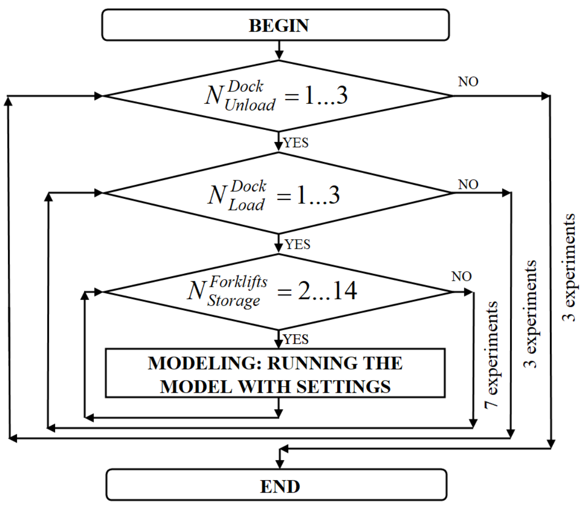


Fig. 6. Algorithm for setting up a simulation experiment

Additionally, Figs. 7 and 8 show the results of the calculations of the total number of forklifts operated in the warehouse during the corresponding calculation of the model:

$$N_{WAREHOUSE}^{Forklifts} = N_{Storage}^{Forklifts} + N_{Unload}^{Dock} + N_{Load}^{Dock}. \quad (1)$$

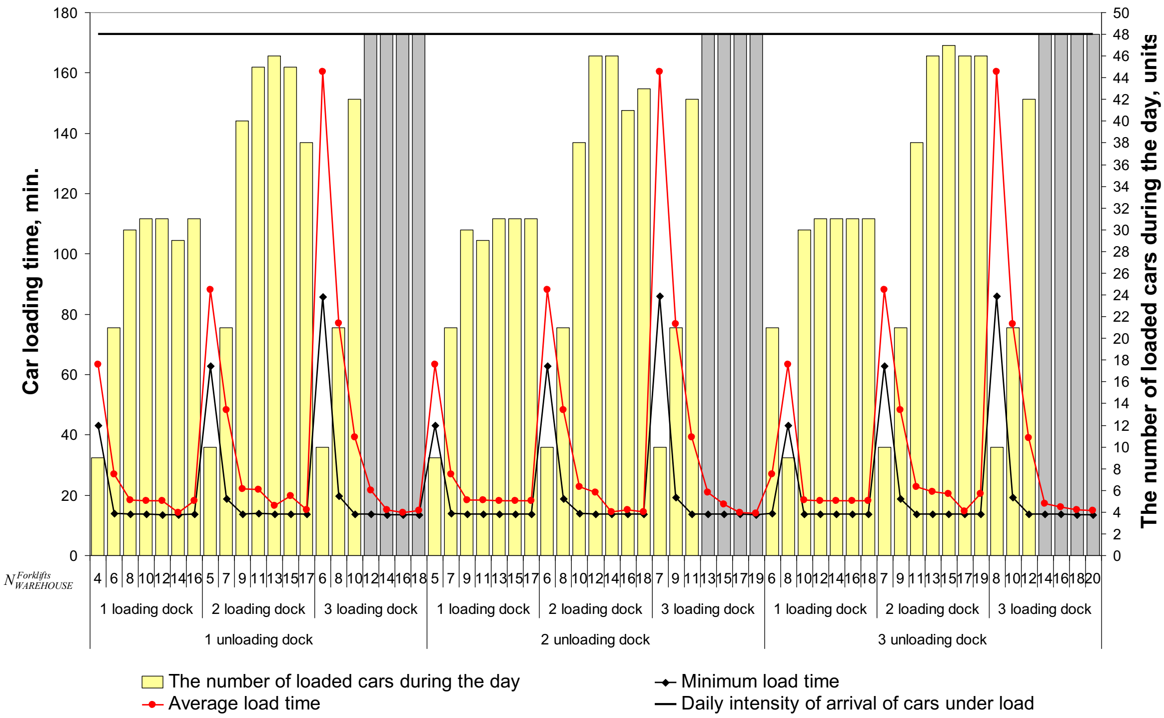


Fig. 7. Joint analysis of the distribution of the number of loaded cars and loading duration

An analysis of the information presented in Fig. 7 allows us to conclude that at least three loading stations with at least 12 forklifts in the warehouse in total should be operated in order to control the daily cargo turnover by dispatch. At the same time, the value of the coefficient of their use will be 0.65-0.80 (Fig. 8).

The overall analysis of the modeling results allows us to draw the following conclusions: 19 variants of calculations allowed the daily freight traffic upon arrival to be mastered; 12 variants of calculations allowed the daily freight traffic to be mastered; the combination of these received options shows that there are only four options for the state of the investigated system, which ensure the functioning of the warehouse complex in accordance with the input parameters of $\mu_{Unload}^{CarArrival} = 24$ cars and $\mu_{Load}^{CarArrival} = 48$ cars (these are model runs No. 60, No. 61, No. 62, and No. 63).

5.4. Integral evaluation of experimental results: Choosing the best option

The following performance indicators of the system were chosen to determine the optimal option for the operation of the warehouse complex: the total number of forklifts operated in the warehouse $N_{WAREHOUSE}^{Forklifts}$, the coefficients of the average use of forklifts in the warehouse $\beta_{WAREHOUSE}^{Forklifts}$, the average duration of loading and unloading cars $T_{Load}^{Car}(AVG)$ and $T_{Unload}^{Car}(AVG)$, and the average waiting time for cars for loading and unloading $T_{Load}^{WaitCar}(AVG)$ and $T_{Unload}^{WaitCar}(AVG)$.

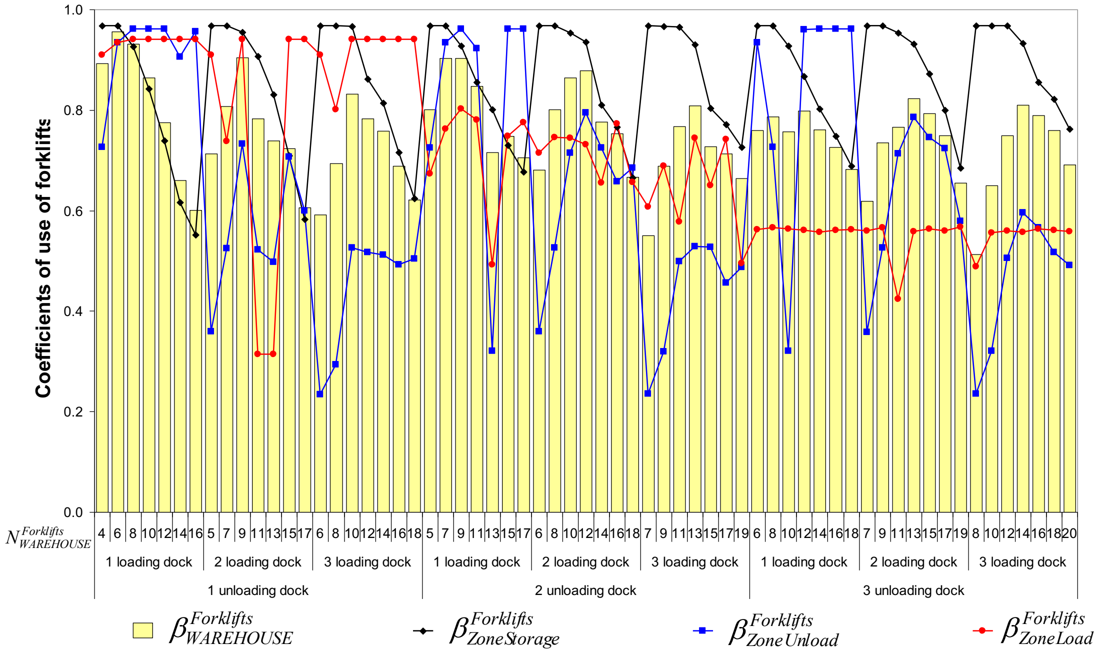


Fig. 8. Analysis of the distribution of forklift utilization factors in the respective zones

The numerical values of the indicators that were chosen to determine the optimal version of the warehouse complex are given in Table 4.

Calculation cipher coding: "3DU3DL14F": three unloading docks, three loading docks, and 14 forklifts are operated in the warehouse.

Regarding the evaluation of the efficiency of the warehouse, the authors propose a structure of a complex indicator in the form of a functional of the following type:

$$K_i = \sum_{j=1}^{n} \omega^j \cdot k_i^j \rightarrow \max, \quad (2)$$

where k_i^j is the relative value of the j-th indicator on the i-th run,

n is the number of indicators taken into account, and

ω^j is the specific weight of the j-th indicator.

Table 4

Numerical values of the indicators that were chosen to determine the optimal variant of the warehouse

Indicator	Indicator value				Best indicator	
Run number	60	61	62	63		
Run cipher	3DU3DL14F	3DU3DL16F	3DU3DL18F	3DU3DL20F	Direction	Value
$N_{WAREHOUSE}^{Forklifts}$	14	16	18	20	MIN	14
$\beta_{WAREHOUSE}^{Forklifts}$	0.81	0.79	0.76	0.69	MAX	0.81
$T_{Load}^{Car}(AVG)$	17.14	16.03	15.14	14.82	MIN	14.82
$T_{Unload}^{Car}(AVG)$	36.18	34.87	34.86	34.08	MIN	34.08
$T_{Unload}^{WaitCar}(AVG)$	11.24	10.67	9.08	8.80	MIN	8.80
$T_{Load}^{WaitCar}(AVG)$	15.49	14.38	12.78	12.06	MIN	12.06

Relative values k_i^j reflect the degree of deterioration of the value of each indicator that is considered in comparison with the best value in the group under study:

$$k_i^j = \begin{Bmatrix} \dfrac{X_i^{j(best)}}{X_i^j}, \ if \ X_i^{j(best)} = \min\left(X_i^j\right) \\ \dfrac{X_i^j}{X_i^{j(best)}}, \ if \ X_i^{j(best)} = \max\left(X_i^j\right) \end{Bmatrix}, \tag{3}$$

where X_i^j is the absolute value of the j-th indicator for the i-th run (Table. 4) and $X_i^{j(best)}$ is the best value of the j-th indicator for the i-th run (Table 4).

Due to the fact that the indicators can have a different direction of influence on the efficiency of the warehouse, the minimum or maximum value of the indicator from all considered options for each run can be accepted as the best:

$$X_i^{j(best)} = \min\left(X_i^j\right) \ OR \ \max\left(X_i^j\right), \tag{4}$$

where $X_i^{j(\max)}$ and $X_i^{j(\min)}$ are the maximum and minimum values of the j-th indicator for the i-th run (Table 4).

The results of calculations of relative values k_i^j according to (3) are given in Table 5. Meanwhile, Table 6 shows the results of the survey (which was conducted by the LLP Research and Technology and Innovation Corporation "Aul Nur," Republic of Kazakhstan) regarding the determination of the specific weight of the j-th indicator ω^j. The survey was conducted among leading specialists in Almaty specializing in warehouse logistics issues. On the basis of the performed calculations according to (2), the values of the K_i complex indicator were determined, which are presented in Table 5. An analysis of the table allows us to conclude that the operation of the warehouse in the "*3DU3DL14F"* variant will allow six forklifts to be released from work and increase the efficiency of its work by 8% according to the proposed comprehensive criterion while ensuring mastery of daily freight traffic without a critical increase in time spent on loading, unloading, and waiting for means of transport.

Table 5

Results of calculations of relative values k_i^j and a complex indicator K_i

Indicator	Indicator value				ω^j
Run number	60	61	62	63	
Run cipher	3DU3DL14F	3DU3DL16F	3DU3DL18F	3DU3DL20F	
$k(N_{WAREHOUSE}^{Forklifts})$	1.00	0.88	0.78	0.70	0.30
$k(\beta_{WAREHOUSE}^{Forklifts})$	1.00	0.98	0.94	0.85	0.30
$k(T_{Load}^{Car})$	0.86	0.92	0.98	1.00	0.15
$k(T_{Unload}^{Car})$	0.94	0.98	0.98	1.00	0.15
$k(T_{Unload}^{WaitCar})$	0.78	0.82	0.97	1.00	0.05
$k(T_{Load}^{WaitCar})$	0.78	0.75	0.37	1.00	0.05
K_i	0.95	0.92	0.88	0.87	

6. CONCLUSIONS

The insufficient number of modern warehouse complexes, as well as the suboptimal organization of their functioning, significantly limits the development potential of the transit corridor of the Republic of Kazakhstan despite the constant growth in freight traffic. Thus, according to the results of the technological audit of a class A warehouse complex located in Almaty that is equipped with front racks in the storage area, it was established that there is a 31% underutilization of the main production capacities, which leads to an increase in the costs of their operation and maintenance and an increase of the necessary number of service personnel of the warehouse.

Considering the stochastic nature of the main technological operations that take place in the warehouse, the management of the terminal decided to develop a simulation model of the warehouse complex. The software product AnyLogic (developed by the AnyLogic Company) was chosen as the environment for modeling, which is a corporate standard in business modeling in many multinational companies and is currently widely used in 63 countries. The authors developed a generalized algorithm for creating simulation models of warehouse complexes in the AnyLogic environment. It consists of creating a transport network for the movement of cars, forklifts, and placing racks in warehouse areas using *Space Markup* elements. It also includes the tasks of the model operation logic using a sequence of blocks included in the *Process Modeling Library*.

The developed simulation model (consisting of 114 blocks) was presented in the form of a black box model, which made it possible to identify and establish correlations and relations between the input and output parameters of the warehouse, as well as its resources. A simulation experiment was set up, which consisted of 63 model calculations. The number of unloading docks, the number of loading docks, and the number of forklifts in the storage area were chosen as variable parameters. The results of the performed simulation are presented, and the results show that four variants of warehouse operation were established, which ensure the unloading and loading of the required number of cars during the day.

The following performance indicators of the system were selected for choosing the optimal option for the operation of the warehouse complex: the total number of forklifts in the warehouse, the coefficients of the use of forklifts in the warehouse on average, the average duration of loading and unloading cars, the average waiting time for cars under loading and unloading, and the structure of the complex indicator. The results of the performed calculations confirmed that the operation of the warehouse, which is equipped with three docks for loading and unloading and in which 14 loaders are operated, will allow six forklifts to be released from work to increase the efficiency of its work by 8% according to the proposed complex criterion while ensuring the mastery of daily freight traffic without a critical increase in time spent on loading, unloading, and waiting for transport means.

References

1. *Official website of the President of the Republic of Kazakhstan.* Available at: https://www.akorda.kz/ru/republic_of_kazakhstan/kazakhstan.
2. *Kazlogistics. Statistics I half year 2022.* Available at: https://www.kazlogistics.kz/ru/library/statistics/20.
3. *Warehouse logistics on the verge of change.* Available at: https://forbes.kz/stats/3pl_drayver_razvitiya_riteyla/
4. Imanbekova, M.A. & Abzal, S. Development of innovative warehouse system of Kazakhstan. *The Bulletin of KazATC*. 2022. Vol. 1(120). P. 62-69.
5. *Almaty's logistics potential. The role of Kazakhstan's megacity in the Nurly Zhol and China's One Belt, One Road strategy.* Available at: https://trans.info/ru/logisticheskiy-potentsial-almatyi-rol-kazahstanskogo-megapolisa-v-strategii-nurlyi-zhol-i-kitaya-odin-poyas-odin-put-260667.
6. Zhang, Y. & Wang, Y. & Wu, L. Research on demand-driven leagile supply chain operation model: a simulation based on AnyLogic in system engineering. *Systems Engineering Procedia.* 2012. Vol. 3. P. 249-258.
7. Eller, B. & Movahedi Rad, M. & Fekete, I. & Szalai, S. & Harrach, D. & Baranyai, G. & Kurhan, D. & Sysyn, M. & Fischer, S. Examination of concrete canvas under quasi-realistic loading by computed tomography. *Infrastructures*. 2023. Vol. 8(2). P. 23.
8. *Fischer*, S. Investigation of the horizontal track geometry regarding geogrid reinforcement under ballast. *Acta Polytechnica Hungarica*. 2022. Vol. 19(3). P. 89-101.
9. *AnyLogic: simulation modelling for business*. Available at: https://www.anylogic.com/.
10. Silva, A. & Roodbergen, K.J. & Coelho, L.C. & Darvish, Maryam. Estimating optimal ABC zone sizes in manual warehouses. *International Journal of Production Economics*. 2022. Vol. 252. No. 108579.

11. Celik, M. & Archetti, C & Süral, H. Inventory routing in a warehouse: The storage replenishment routing problem. *European Journal of Operational Research*. 2022. Vol. 301(3). P.1117-1132.
12. Oliveira, R.L.M.De. & Dablanc, L. & Schorung, M. Changes in warehouse spatial patterns and rental prices: Are they related? Exploring the case of US metropolitan areas. *Journal of Transport Geography*. 2022. Vol. 104. No. 103450.
13. de Jesus Pacheco, D.A. & Møller Clausen, D. & Bumann, J. A multi-method approach for reducing operational wastes in distribution warehouses. *International Journal of Production Economics*. 2023. Vol. 256. No. 108705.
14. Accorsi, R. & Manzini, R. & Maranesi, F. A decision-support system for the design and management of warehousing systems. *Computers in Industry*. 2014. Vol. 65(1). P. 175-186.
15. Nugymanova, G. & Nurgaliyeva, M. & Zhanbirov, Zh. & Naumov, V., & Taran, I. Choosing a servicing company's strategy while interacting with freight owners at the road transport market. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*. 2021. Vol. 1. P. 204-210.
16. Ramazan, B. & Mussaliyeva, R. & Bitileuova, Z. & Naumov, V. & Taran, I. Choosing the logistics chain structure for deliveries of bulk loads: Case study of the Republic Kazakhstan. *Naukovyi Visnyk Natsionalnoho HirnychohoUniversytetu*. 2021. Vol. 3. P. 142-147.
17. Fabry, Q. & Agnetis, A. & Berghman, L & Briand, C. Complexity of flow time minimization in a crossdock truck scheduling problem with asymmetric handover relations. *Operations Research Letters*. 2022. Vol. 50(1). P. 50-56.
18. Baker, P. & Canessa, M. Warehouse design: A structured approach. *European Journal of Operational Research.* 2009. Vol. 193(2). P. 425-436.
19. *Warehouse and logistics automation and robotisation.* Available at: https://sunone.com.ua/ru/articles-ru/avtomatizaciya-i-robotizaciya-sklada-i-logisticheskih-predpriyatij/
20. Vale, A. & Ventura, R. & Lopes, P. & Ribeiro, I. Assessment of navigation technologies for automated guided vehicle in nuclear fusion facilities. *Robotics and Autonomous Systems.* 2017. Vol. 97. P. 153-170.
21. Cao, W. & Zhang, M. The optimization and scheduling research of shuttle combined vehicles in automatic three-dimensional warehouse. *Procedia Engineering*. 2017. Vol. 174. P. 579-587.
22. Zhang, J. & Wang, X. & Huang, K. Integrated on-line scheduling of order batching and delivery under B2C e-commerce. *Computers & Industrial Engineering*. 2016. Vol. 94. P. 280-289.
23. Bolu, A. & Korcak, O. Path Planning for Multiple Mobile Robots in Smart Warehouse. *IEEE 7th International Conference on Control, Mechatronics and Automation*, *ICCMA*. 2019. No. 8988635. P. 144-150.
24. Friswell, R. & Williamson, A. Management of heavy truck driver queuing and waiting for loading and unloading at road transport customers' depots. *Safety Science*. 2019. Vol. 120. P. 194-205.
25. Onal, S. & Zhu, W. & Das, S.K. Order picking heuristics for online order fulfillment warehouses with explosive storage. *International Journal of Production Economics*. 2023. Vol. 256. No. 108747.
26. Dotoli, M. & Epicoco, N. Falagario, M. & Costantino, N. & Turchiano, B. An integrated approach for warehouse analysis and optimization: A case study. *Computers in Industry*. 2015. Vol. 70. P. 56-69.
27. Ferrara, A. & Gebennini, E. & Grassi, A. Fleet sizing of laser guided vehicles and pallet shuttles in automated warehouses. *International Journal of Production Economics*. 2014. Vol. 157. P. 7-14.
28. Cheberiachko, S.I. & Koriashkina, L.S. & Deryugin, O.V. & Odnovol, M.M. Rational organization of the work of an electric vehicle maintenance station. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*. 2020. Vol. 5. P. 136-142.
29. Žilina, M. & Rogić, K. & Bajor, I. Case-study analysis of warehouse process optimization. *Transportation Research Procedia*. 2022. Vol. 64. P. 215-223.

Received 12.08.2021; accepted in revised form 03.06.2023