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IMPROVING THE EFFICIENCY OF MANAGEMENT OF TRANSPORT AND ENERGY RESOURCES OF THE LOGISTICS SYSTEM OF AN INDUSTRIAL ENTERPRISE

Purpose. To define peculiarities of the processes and indicators of the functioning of the transport and warehouse logistics system (TWLS) of industrial enterprises using a simulation model that takes into account the need to implement a cargo delivery plan to warehouses in conditions of restoring the flowability of cargo during unloading, in order to determine the optimal operating parameters based on the criterion of minimum costs.

Methodology. To build a model of the functioning of the transport-warehouse logistics system of unloading raw materials at the enterprise, the method of simulation modelling was used, statistical analysis was used to establish the laws of distribution of the input parameters of the model. The assessment of the use of energy resources was carried out using a regression analysis of the duration of heating of various types of cargo at industrial enterprises.

Findings. The conducted experiments on the developed simulation model made it possible to determine the rational number of used resources – locomotives and cargo heating chambers when they freeze. Due to the use of the proposed methods and model, the efficiency of the management of transport and energy resources of the logistics system of an industrial enterprise has been increased.

Originality. The developed simulation model of the functioning of the raw material and fuel unloading subsystem, unlike the existing ones, takes into account the peculiarities of the transport and storage process in the cold period of the year and allows determining the rational number of transport and auxiliary resources, taking into account the influence of external factors.

Practical value. The obtained results make it possible to increase the efficiency of the TWLS operation of industrial enterprises due to the development of methods based on the logistic approach to the management of transport-warehouse processes. The simulation model of the management of the heating and unloading process allows you to determine the most economical mode of operation of transport and warehouse logistics systems of industrial enterprises by determining the rational number of involved resources.

Keywords: *simulation modelling, railway freight transport, transport logistics; wagon, resource management, energy consumption*

Introduction. Some technological processes of modern industrial enterprises involve the use of loose components as raw materials for production. Provided that the delivery of loose components takes place in an open rolling stock of railway transport, such enterprises must have the infrastructure to restore the flowability of cargo [1] in the cold period of the year when they freeze. Despite the wide range of measures to restore the flowability of raw materials [2, 3] that freeze, the technology of using energy carriers for heating cargo in railway wagons remains the most effective.

Industrial enterprises of the metallurgical industry traditionally use energy sources that are a by-product of blast furnace production – blast furnace gas. Despite the relatively low cost of this energy source, under modern conditions it is a rather valuable fuel. In addition, the modern responsible global attitude to reducing carbon dioxide emissions determines the same attitude to the use of any energy sources [4, 5], including blast furnace gas. Therefore, the study of transport and logistics systems in the context of the effective use of technological infrastructure, which contains powerful objects in terms of energy consumption, which are devices for defrosting raw materials, is important.

Along with this, it is necessary to ensure the effective use of traction rolling stock – locomotives that service defrosting devices and wagons that transport raw materials. Considering the size and complexity of the transport and logistics system being studied and the presence of numerous stochastic processes in it [6], simulation modelling [7] is used as the main research method. In the context of the implementation of the logistic approach, such modelling is based on the use of modern software [8, 9].

Literature review. The implementation of lean production technologies [10] is a modern trend and is actively implemented at railway transport enterprises of Ukraine and the world. But for implementation in the conditions of industrial transport of metallurgical enterprises, they need to take into account the technological processes inherent in transport and production systems.

The efficiency of using infrastructure facilities depends on the location of equipment according to various dispatching rules and distribution strategies [11]. These approaches can also be used when planning cargo defrosting modes in railway wagons.

The principles of using discrete-event modelling [12, 13] make it possible to determine the optimal values of the number of resources, the capacity of transport infrastructure objects, including the parameters of track development of railway stations. However, these approaches require adaptation for use in the conditions of industrial transport of a metallurgical enterprise.

In transport systems, the need to coordinate modes and work schedules is a traditional task [14], these approaches are useful, but it is also necessary to take into account the fact that in the case of a delay in the process of unloading heated cargoes, it is possible for them to freeze, which requires reheating. This feature must be taken into account in the research being performed.

In [15], with the help of a simulation model, it was established that in transport systems, a significant amount of time in the process of cargo delivery is spent waiting for cargo operations, so in the course of the study, it is necessary to take into account this factor in the system of heating wagons with cargo.

When modelling the processes of mass cargo delivery, the peculiarities of their delivery by route trains are taken into account, while a systematic approach and principles of logistics are used, the interaction of production, transport and consumption is taken into account [16]. Therefore, in the conditions of a metallurgical enterprise, there is a need to take into account the loading of the nozzles of an industrial station for a higher level of adequacy of the model to real conditions.

In the study [17], based on the use of the RailNet simulation modelling platform, when modelling complex railway networks, it is proposed to carry out the feasibility of using infrastructural changes, in our case, the implemented approaches are useful in evaluating the effectiveness of the use of additional cargo defrosting chambers in railway wagons.

When establishing a rational option for the delivery of wagons, it is suggested to take into account the factor of unevenness or seasonality of transportation volumes [18]. Therefore, during the research, it will be worth performing a statistical analysis of the intervals of the arrival of railway trains and taking into account the production plans of the enterprise.

An important influencing factor on the transport and production system is the duration of work [19], which, in our case, in contrast to this study, significantly depends on the ambient temperature, which directly determines the duration of cargo heating.

The issue of improving the planning and time control system [20] in the management of cargo deliveries to unloading points in the conditions of a metallurgical enterprise is also relevant and needs to be taken into account when developing a simulation model.

To deal with systems that work with a large amount of data and processes that occur in parallel, various modeling platforms are used [21]; therefore, for the analysis of the transport and production system, the Anylogic program was chosen, which allows you to assess the objectivity of its work through animation of the presented processes.

It is important to assess the throughput capacity [22] of the cargo transportation system; in the case of this study, it is necessary to additionally consider the need to heat the cargo to restore its flowability.

In certain cases, it is necessary to take into account the different capacity of freight wagons and the productivity of loading and unloading means [23]. However, in the conditions of the transport and production system of industrial enterprises, the carrying capacity of wagons, taking into account the use of traditional powerful unloading means – ore grab loaders and wagon transferers – has an insignificant run-up, so this factor is not significantly influential under the conditions of this study. This factor has practically no effect on the cycle duration of the wagon tipper, when the carrying capacity of the wagons fluctuates, mainly in the range of 69–71 tons (within 1.4 % of the average weight of the cargo). In the same way, the productivity of ore grab loaders, depending on the amount of cargo in the wagons, can be levelled due to the experience of the crane operator and the distance of moving the cargo, due to the situation of the formation of the stack of the charge, which is rapidly changing.

In addition, cargo processing is limited by the number of resources, the capacity of infrastructure service facilities [24], the throughput capacity of the transport network [25]; these limitations must also be taken into account. Given that some enterprises located on the same industrial site may have similar means of defrosting cargo in wagons, it is expedient to take into account their use on mutually beneficial terms, this practice of using alternative transport facilities allows increasing work efficiency.

The results of this work can also be useful in the context of reducing the negative impact on the environment [26], so it is planned to form further research development taking into account this factor.

Earlier studies contain various approaches to the efficient organization of transport services, but none of them fully covers the issues of this article.

Unsolved aspects of the problem. During the literature review, it was established that simulation and mathematical modelling methods are widely used in the optimization of transport processes. It was noted that the proposed methods and approaches are not adapted to take into account in the transport and warehouse logistics systems (TWLS) of industrial enterprises the processes of restoring the flowability of cargo in the cold period of the year, namely:

- energy costs for heating cargo;
- shunting of locomotives for maintenance of defrosting devices;
- demurrage of freight wagons in the studied system.

Therefore, within the framework of this study, it is assumed that the above-mentioned features are taken into account in the proposed measures for the effective management of transport and energy resources of the logistics system of an industrial enterprise.

The purpose of the paper is to study the processes and indicators of the functioning of the transport and warehouse system of industrial enterprises using a simulation model that takes into account the need to implement a cargo delivery plan to warehouses in conditions of restoring the flowability of cargo during unloading, in order to determine the optimal operating parameters based on the criterion of minimum costs.

The object of the study was the transport and storage processes of the logistics systems of industrial enterprises. As a subject of research, the dependence of indicators of the efficiency of the functioning of these systems on the organization of delivery and cargo handling processes, taking into account the factor of cargo freezing, is considered.

To achieve the goal, the following tasks must be solved:

- to analyze the problem of organizing the operation of the transport-and-warehouse system at the production level of industrial enterprises;
- to develop a simulation model of transport and warehouse subsystems of industrial enterprises to establish rational parameters of their functioning;
- to determine the economic feasibility of implementing the proposed measures for effective management of transport and energy resources of the logistics system of an industrial enterprise.

Methods. The study is based on the use of a logistic approach, the method of simulation modelling and graphical analysis of its results.

The advantage of simulation modelling is the possibility of modelling complex systems in those cases when the use of analytical methods is complicated, it is necessary to take into account the stochastic nature of the processes, the components of the system change over time and interact with each other.

An important stage of modelling is the development of a conceptual model (analysis scheme). At this stage, the structuring of the model takes place, that is, the selection of individual subsystems of the definition of the elementary components of the model and their connections at each level of the hierarchy. The elements of the system, their connection, parameters and variables, as well as their relationship and the laws of their change must be expressed by means of the modelling environment, i.e. in this environment, the variables and parameters of the model must be defined, the procedures for calculating the change of variables and characteristics of the model in times.

The study is based on the processing of real data of the metallurgical enterprise "Zaporizhstal". The development of the simulation model is based on the structural diagram of transport flows and the system of analysing their parameters, which is presented in Fig. 1.

The scheme involves three stages: simulation of the arrival of wagons, simulation of wagon processing, and calculation of the obtained parameters (indicators).

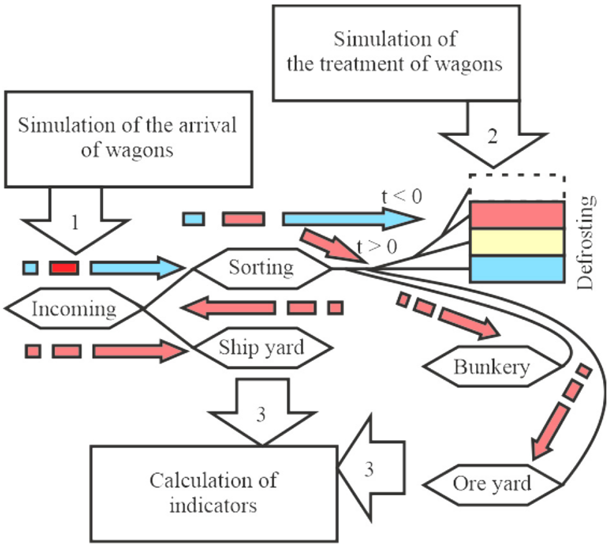

Fig. 1. Structural diagram of transport flows and system of analysis of their parameters

The last stage involves collecting information on the processed applications. The collected data is analysed using statistical tools, on the basis of which the modelling results are calculated.

On the basis of the structural diagram of transport flows, a simulation model is developed with a fixation of the level of abstraction and description of the control logic.

Modern means of simulation modelling also make it possible to implement an animated representation of the model. Animation allows you to avoid possible errors of the researcher and helps to check the correctness of the model, that is, to make sure that the processes of the real system are correctly reflected.

Determination of input parameters of the simulation model. The following are the main input parameters of the developed TWLS discharge simulation model:

- air temperature, *t,* ℃;
- cargo arrival intervals, I_{arr};
- duration of cargo heating, T_{heat};
- the duration of pulling the wagons out of the heating chamber, T_{pull};
- the duration of placing the wagons in the heating chambers, T_{plac};
- the duration of delivery of wagons from the heating chambers to the unloading fronts, T_{del};
- distribution of cargo to unloading fronts, Q_i;
- duration of unloading of wagons at cargo fronts, T_{unl}.

Since the cold period of the year is considered, the key input indicator of the TSLS discharge model is the air temperature. It is on this parameter that the further procedure of modelling the transport and storage processes of the metallurgical enterprise depends. According to meteorologists, the accuracy of the air temperature forecast is most accurate for 1–5 days (97 % for the first day, 95 % for the second day, 91 % for the third, 89 % for the fourth, 86 % for the fifth). Guided by these data, we set the duration of the experiment – 5 days.

In order to determine the intervals of the arrival of raw materials at the enterprise, a statistical analysis of the intervals was carried out and it was established that the intervals of arrival of the main types of goods at the enterprise are subject to the exponential (coal concentrate, coal and coke) and gamma distribution (iron ore concentrate, ore, limestone, pellets and others).

The duration of cargo heating depends on many factors: the average daily air temperature, the duration of transportation, the freezing strength of the cargo, the humidity of the cargo, etc. Ambient temperature is the main factor affecting the duration of defrosting of raw materials in heating chambers.

When determining the regression dependence of the duration of the heating of raw materials on the air temperature, temperature data were taken at the time of loading of raw materials, at the time of arrival of the cargo at the destination, and the temperature of the environment at the time of the start of heating. The following regression models were obtained:

$y = 1.38 - 0.23x$ – for iron ore concentrate;

$y = 1.79 - 0.23x$ – for ore;

$y = 2.17 - 0.26x$ – for limestone;

$y = 1.29 - 1.55x$ – for coal,

where *y* is duration of cargo heating, [h]; *x* is ambient temperature, [°C].

Models were developed similarly for other studied cargoes.

The duration of the delivery of wagons from the heating chambers to the unloading fronts is: Pivdenna station – Ore yard – 15 minutes; Pivdenna station – Sinter factory – 14 minutes; Pivdenna station – Ship yard – 5 min. The duration of placing the wagons in the warming chamber is 17.37 minutes, the duration of pulling out the wagons from the warming chamber is 16.34 minutes.

Distribution of cargo to unloading fronts. At large enterprises, continuous supply of raw materials is necessary for continuous production of products. They have more complex transport systems, so it is quite difficult to determine the optimal distribution of cargo in advance. For such cases, a trans-

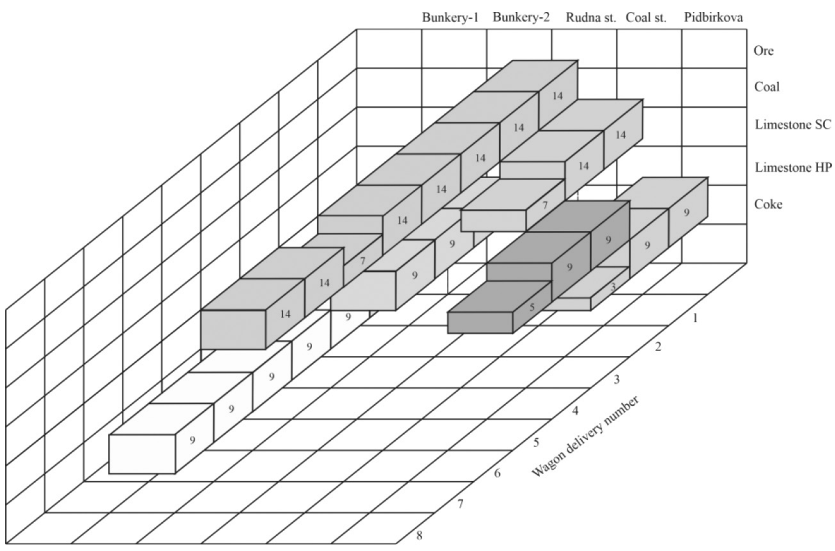

Fig. 2. Formation of deliveries according to optimal parameters

port problem consisting of *p*-number of blocks that depend on each other was proposed.

As a result of solving such a dynamic transport problem, the optimal distribution of cargo deliveries to the unloading fronts was obtained: *7* coke deliveries of *9* wagons each must be sent to the Aglofabryka station of Bunkery-1 park; *3* deliveries of limestone in hoppers of *9* wagons each arrive at the Aglofabryka station Bunkery-2 Park; to Rudna station – *8* deliveries of ore (*7* deliveries of *14* wagons and *1* delivery of *7* wagons); the Coal station will receive *3* deliveries of coal (*2* deliveries of *14* wagons and one for *7* wagons); to Pidbirkova station – *3* deliveries of limestone in semi-cars (*2* deliveries of *9* wagons and one for *5* wagons) and *3* deliveries of limestone in hoppers (*2* deliveries of *9* wagons and *1* for *3* wagons).

A statistical analysis of the company's data on the duration of the unloading of various types of cargo on certain fronts was carried out.

As a result of the statistical analysis, it was established that the duration of cargo unloading at the main cargo unloading fronts is subject to the normal law of distribution and gamma distribution. For "other" cargo arriving at the Ore Yard, the duration of unloading is taken to be equal to the average value, so the volumes of their arrival at this cargo front are insignificant.

Development of a simulation model of the process of heating and unloading of raw materials at a metallurgical enterprise. The basis of the discrete-event model is a process diagram – a set of interconnected blocks that specify the sequence of operations that will be performed on applications passing through the process diagram. The process diagram is created by adding library objects from the palette to the class diagram of the active object, connecting their ports and changing the properties according to the requirements of the model being developed. The process diagram begins with elements of type *source*, which generate streams of requests. Applications are objects that are created, processed, maintained, or otherwise exposed to the action of the simulated process. In this case, the applications are deliveries of wagons with raw materials arriving at the enterprise.

A separate java-class was created for each type of cargo, which allows you to set the appropriate duration of heating and unloading for each of them, as well as collect statistics at the output of the model. Each class of applications is generated in a separate *source* object, where cargo arrival intervals and the number of simultaneously arriving wagons are specified. The arrival intervals are established using distribution laws that were defined earlier for each type of cargo.

With the help of the *selectOutput5* object, the non-necessity of heating the load is determined. This object routes incoming requests to one of two outgoing ports depending on whether a condition is met. When the air temperature is negative, the cargo is sent to heating chambers, otherwise – to the unloading fronts.

The air temperature in this simulation model is set using *event* generation. For this, 8 events have been created, each of which corresponds to a certain moment in time. Events occur every three hours, at the time of the event the air temperature changes according to the initial data. The duration of the experiment will be 5 days, therefore, for convenience, the period of each event is set to 24 hours, and the day is changed using the program code written in the "action" field of each *event* object (Fig. 3).

It is necessary to take into account the fact that some time will pass from the moment of the arrival of loads and their distribution to the branches of the model until the moment of submission for heating and the air temperature may change; in this case the duration of the warm-up will be calculated incorrectly. To eliminate this error, when the event *event* occurs, the air temperature value is assigned to two variables at once. The first variable *temperature_arrival* is used to fix the value of the air temperature at the moment of the arrival of the delivery. The value of this variable is used in the *selectOutput5* object, which regulates the delivery of cargo to heating chambers. The second *temperature* variable sets the temperature value, which is used in the calculations of the duration of heating the cargo in the garage.

Fig. 4 shows the scheme of operation of the heating chambers. The applications sent to the boilers capture the free resource "locomotive" with the help of the service *object.* We set the resource delay time to be equal to the duration of placing the wagons in the chamber. During the heating of the cargo, the "locomotive" resource is released by an object of the *release* type, and it is captured again already when leaving the heating chamber. Now, the delay time of the "locomotive" resource is taken to be equal to the duration of pulling the wagons out of the defrosting chambers.

Since only one train can be located in the area before the entrance to the heating chambers, the static resource "bottleneck" has been introduced. This resource is grabbed by requests when approaching this area and released when the delivery hits the hotpot, so another request cannot grab the "bottleneck" resource before the previous request frees it.

The simulation of heating cameras is represented by blocks that include such objects as *delay, hold, release, and seize.* The *release seize* objects, as already mentioned, are responsible for releasing and seizing the "locomotive" resource for delivery manoeuvrers.

The delay of orders is implemented according to previously established regression dependencies on the state of the external environment in elements of the *delay* type. We set the capacity of this object equal to one, since there cannot be more than one supply in the heating chamber.

It is necessary to take into account the fact that for each type of cargo, the duration of heating takes different values. To do this, we set the delay time of the delay objects by the variables *heating_time_1...heating_time_3.* The initial value of the variables is not set, since it is initially unknown which cargo will arrive in which chamber. Assigning a new value to the hold time variable will occur in the *hold* objects using the program code. This code will check the class of the request received for service (the type of cargo that is served for heating) and, depending on the class, will set the value of the delay time variable of the *delay...delay2* objects according to the previously obtained regression dependencies.

With the help of *hold* objects, the filling of the heating chambers is regulated. These elements block or unblock the

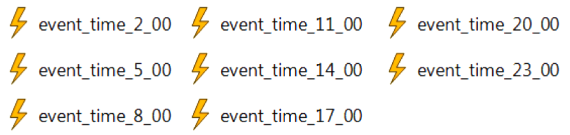

Fig. 3. Generation of events – changes in air temperature

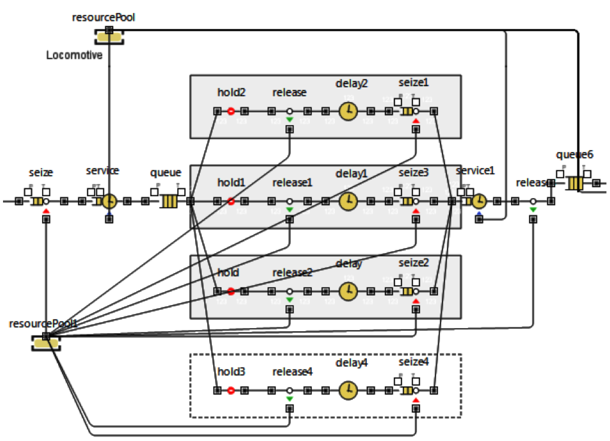

Fig. 4. Simulation of the process of restoring the flowability of cargo

flow of applications in a certain area of the process diagram, thereby providing an opportunity to avoid the delivery of wagons to a filled heating chamber.

In front of the blocks of heating chambers, a *queue* object is installed, in which applications are accumulated waiting to be accepted by the following objects. Enter the code in the "action on exit" field of the *queue* element: if (*delay.size*() = 1) *hold.setBlocked*(*true*). With the help of this code, the fullness of the *delay...delay4* objects will be checked, and in case of occupation of the specified heating chamber, the blockers *hold... hold2* will be activated. To further unlock the hold elements in the delay objects, in the "action on exit" field, specify the *hold.setBlocked*(*false*) code, which will allow the next delivery to enter this heating chamber after defrosting the cargo.

After heating, all deliveries fall into the general queue *queue6*, and deliveries that did not require heating are also received here. Here, with the help of *selectOutput* objects, they are sorted by type of cargo for further distribution to unloading fronts according to production needs (Fig. 5). To do this, a certain type of cargo is specified in the "condition" field of the *selectOutput* object, thus each of these objects selects exactly the specified cargo, and filters out others.

The unloading process is simulated using *delay* type elements (*Aglofabryka, Rudnyi_dvir, Park*). The duration of unloading is set by variables *unloading_time_1...unloading_time_3.* The values of these variables are generated in accordance with previously established distribution laws for each type of cargo. Queues *queue3...queue5* are set up for the accumulation of applications awaiting service. The general view of the process diagram of the simulation model is shown in Fig. 6.

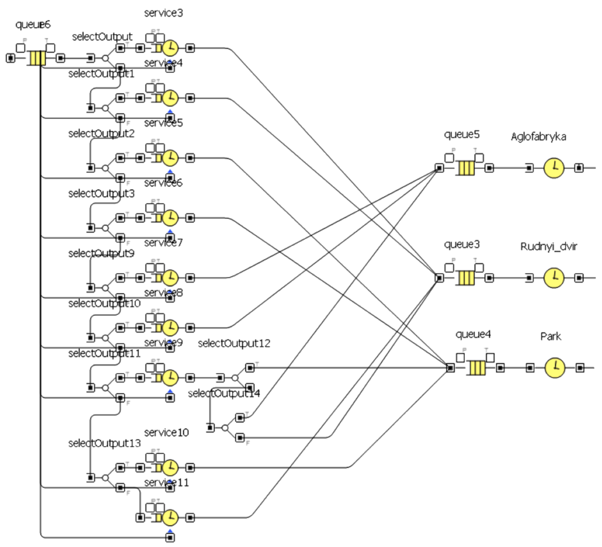

Fig. 5. Block diagram of the process of distributing raw materials to unloading fronts

Similarly, with the help of *selectOutput* objects, the sorting of applications by classes after unloading is implemented. This makes it possible to collect statistical data at the exit from the system for each type of cargo separately. In the *sink* objects, these data are recorded and added to statistical tools, and processed applications are destroyed. The collection of data on the duration of finding applications in the system is carried out using the *"Histogram data"* and *"Data set"* objects. Counting unprocessed deliveries is done by using variables. Also, with the help of variables, statistics on the use of resources – locomotives – are kept. The values of the statistical variables are assigned at the time of each request to the facility *sink*.

Results. To obtain more accurate simulation results, it is necessary to determine the required number of experiments. The basis of simulation modelling is the method of statistical tests (Monte Carlo method), which is based on the use of random numbers, that is, the possible values of some random variable with a given probability distribution. If the number of implementations is enough, then the obtained system modelling results acquire statistical stability and can be accepted with sufficient accuracy to evaluate the desired characteristics of the system functioning process.

In the case of estimation based on simulation results of the average value of some random variable *X*, the required number of implementations is determined by the formula

$$N_p = \frac{t_a^2 \cdot \sigma^2}{\delta^2 \cdot a^2}, \quad (1)$$

where *a* is the sample mean of the random variable; *σ* is the standard deviation of the random variable; δ is the specified accuracy of the parameter estimate (δ = 0.05); t_α is the quantile of the normal distribution for a given significance level α.

Since several random variables are modelled in the simulation model, the number of implementations is selected by condition

$$N_p = \max(N_{pi}),\ (i = \overline{i,k}), \quad (2)$$

where *k* is the number of model random variables.

As a result of calculations, the number of necessary realizations is $N_p = 262$ realizations. For the task of random variables with a normal distribution law, the model uses such parameters as the standard deviation and the average value, for

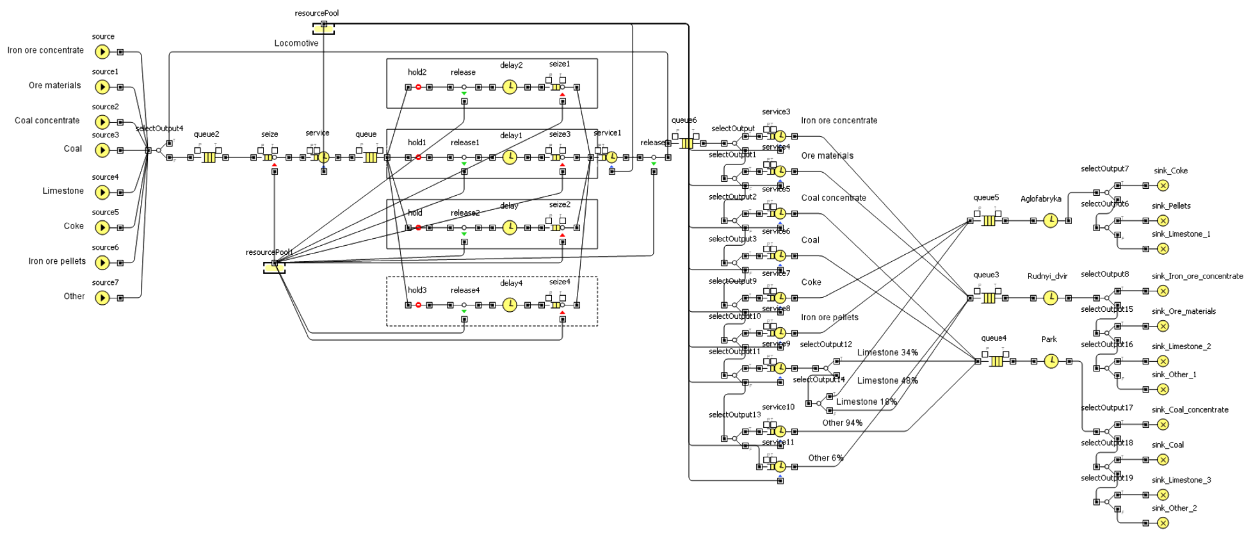

Fig. 6. General view of the simulation model process diagram

the exponential law – the average value. For random variables subject to the gamma distribution, the minimum value is used, and the distribution parameters α and β were also calculated.

Conducting experiments in the conditions of varying input parameters of the model. In order to establish the effective mode of operation of TWLS of industrial enterprises, the unloading simulation was carried out under the conditions of variation of the input parameters of the model. Variable parameters of the model are the number of used locomotives and the number of cargo heating chambers. At the time of the research, three heating chambers and four locomotives were used for shunting operations at the base enterprise during TWLS operation in the conditions of restoring the flowability of cargo. The model considers the possibility of using an additional fourth heating chamber.

When conducting an experiment, it is necessary to link the parameters placed on the root object of the process diagram with the parameters of nested objects. Linking parameters is necessary, since only the parameters of the root object can be changed during the experiment. As a result of binding, the value of the parameter of any level of the nested object will be equal to the value of the parameter of the upper level.

In order to observe the change in the duration of downtime of wagons in the system depending on the number of used resources, an experiment of the "Variation of parameters" type is created for the stochastic model. In the experiment, the following ranges of variation of the variable parameters are set: the number of locomotives – from 1 to 5, the number of warm-up chambers – from 1 to 4. The number of model runs according to preliminary calculations is set equal to 262 realizations.

To obtain the results of the model runs, the statistics collection elements "Data set" are used, which record the values of the duration of idle time of wagons, the percentage of locomotive use, the percentage of bottleneck use, as well as the number of wagons not serviced on time for each implementation. Graphical interpretation of modelling results is implemented using the "Graph" and "Histogram" tools (Fig. 7).

The "Schedule" element contains information about the duration of the application being found in the system at each implementation of the experiment and allows you to visually monitor the variation in the duration of the downtime of wagons. The "Histogram" element, in addition to data collection, provides basic statistical characteristics of a random variable and allows establishing their distribution laws. As can be seen from the histogram, the random value of the duration of finding the application (in our case, the submission of wagons) in the system is subject to the gamma distribution.

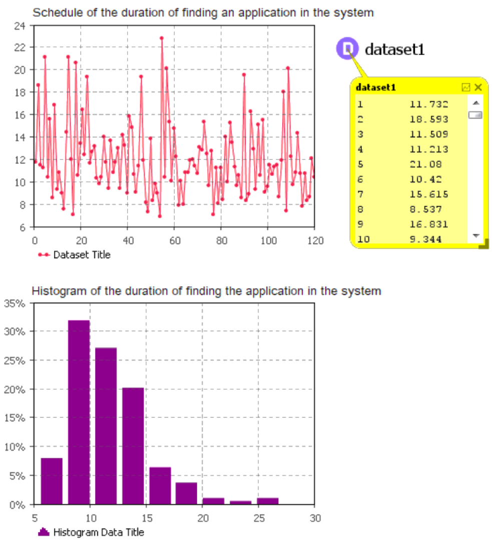

Fig. 7. Implementation of the collection of statistical data on the results of experiments

Table

Results of experiments in the conditions of variation of variable parameters of the model

No.	Number of locomotives, n_{loc}	Number of chambers N_{chamb}	Average downtime of wagons, t_{use}, hours	Use of bottleneck, $k_{b\text{-}neck}$	Use of locomotives, K_{loc}	Remains of unprocessed wagons, K_{unm}, %
1	1	1	27.12	0.96	0.42	52.24
2	2	1	25.93	0.95	0.22	51.22
3	3	1	26.31	0.95	0.15	51.65
4	4	1	26.18	0.96	0.11	51.18
5	5	1	26.59	0.96	0.09	51.74
6	1	2	24.43	0.95	0.62	38.51
7	2	2	20.82	0.93	0.35	31.38
8	3	2	20.41	0.93	0.24	31.17
9	4	2	20.39	0.93	0.18	32.15
10	5	2	19.85	0.93	0.15	31.75
11	1	3	20.72	0.94	0.74	29.91
12	2	3	15.37	0.87	0.44	20.18
13	3	3	14.55	0.86	0.29	18.85
14	4	3	14.29	0.85	0.22	18.84
15	5	3	13.65	0.84	0.18	18.47
16	1	4	19.15	0.92	0.79	26.64
17	2	4	12.41	0.81	0.49	14.19
18	3	4	11.71	0.77	0.33	12.74
19	4	4	11.44	0.76	0.25	12.86
20	5	4	11.58	0.76	0.19	12.45

For further analysis of the experimental results, the average values of the main parameters of the model were selected (Table).

As a result of the simulation, the lowest value of the duration of downtime of wagons was obtained when four locomotives and four heating chambers were used. However, under this mode of operation, the utilization rate of locomotives is low, which indicates an irrational use of resources. In addition, it is necessary to consider the costs when using an additional heating chamber. In order to choose the rational parameters of TWLS unloading, it is necessary to determine the costs for each option of system operation, taking into account all factors.

Discussion of results. The experiment was conducted with different values of such parameters as the number of heating chambers and the number of used locomotives. As a result of the simulation, the average duration of wagon downtime, the share of locomotive use, as well as the balance of unprocessed wagons under different modes of operation of the system were established. Taking into account these factors, it is necessary to determine the total costs of TWLS unloading operation at different values of variable parameters.

The total costs of the enterprise for the operation of TWLS unloading are determined by the formula

$$C_{unload}^{\text{TWLS}} = C_{\text{expens}} + C_{heat} + C_{loc}, \quad (3)$$

where C_{expens} is expenses for the fee for the use of wagons in TWLS unloading, UAH; C_{heat} is costs for heating frozen cargo, UAH; C_{loc} is expenses for the operation of locomotives in TWLS unloading, UAH.

Expenses for the payment for the use of wagons are determined by the formula

$$C_{\text{exp}} = n_{del} \cdot N_{wag} \cdot C_{wag} \cdot t_{use} \cdot \left(\frac{n_{unm}}{100} + 1 \right), \quad (4)$$

where n_{del} is the number of deliveries that arrived with cargo at the enterprise, units; N_{wag} is the number of wagons in supply, we accept 15 wagons; C_{wag} is cost per wagon hour, UAH; t_{use} is average time of wagon use, hours; n_{unm} is share of unmaintained wagons, %.

Cargo heating costs are determined by the formula

$$C_{heat} = q_{bl.gas} \cdot n_{chamb} \cdot C_{n.gas} \cdot t_{heat} \cdot k_{reduc}, \quad (5)$$

where $q_{bl.gas}$ is blast furnace gas consumption per 1 chamber per hour, m^3/hour; n_{chamb} is the number of operating heating chambers, units; $C_{n.gas}$ is the cost of natural gas for industrial enterprises, UAH; t_{heat} is duration of operation of heating chambers, h; k_{reduc} is the coefficient of reducing the calorific value of blast furnace gas to natural.

The costs of operating locomotives in TWLS unloading are determined by the formula

$$C_{loc} = n_{loc} \cdot c_{loc} \cdot t_{loc}, \quad (6)$$

where n_{loc} is the number of locomotives in operation, units; c_{loc} is the cost of a locomotive hour, UAH/hour. According to the company, at the time of the study, it was 582 UAH/hour; t_{loc} is duration of operation of locomotives hours. In our case, the experiment lasts 5 days, therefore $t_{loc} = 120$ hours.

The dependence of costs on the resources used is presented in the form of a surface in Fig. 8.

Conclusions. The study of the processes and indicators of functioning of the transport and warehouse system of industrial enterprises on the simulation model allowed determining the optimal parameters of operation according to the economic criterion. Using the real example of PJSC “Zaporizhstal”, the following values were determined: the number of locomotives – 4 units, the number of defrosting devices – 3 units, which ensure a minimum of total logistics costs.

The possibility of taking into account the forecast of air temperature in the developed model allows adjusting the operating mode of TWLS, due to which a more effective planning of the parameters of the system is achieved.

The proposed methodology, which is based on the logistic approach, the method of simulation modelling and graphical analysis of its results, allows establishing the optimal amount of resource support, namely the number of locomotives and heating chambers in conditions of changes in the ambient temperature. As a result of the use of the developed model, a more effective planning of the functioning parameters of the transport and logistics system has been achieved, which is confirmed at the real object due to the reduction of the number of locomotives.

Reducing the number of cargo heating chambers by improving the cargo delivery planning system also helps to reduce blast furnace gas consumption and, consequently, harmful emissions. This is an area that may be further explored in the future.

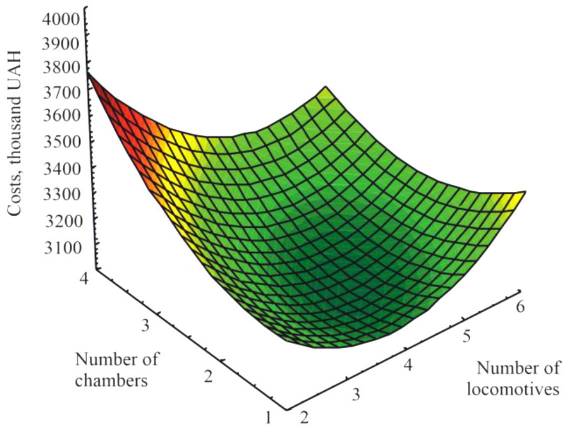

Fig. 8. Dependence of costs on used resources

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Підвищення ефективності управління транспортними та енергетичними ресурсами логістичної системи промислового підприємства

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Мета. Встановлення особливостей процесів і показників функціонування транспортно-складської логістичної системи (ТСЛС) промислових підприємств на імітаційній моделі, що враховує необхідність виконання плану доставки вантажів до складів в умовах відновлення сипкості вантажів при їх вивантаженні, для визначення оптимальних параметрів роботи за критерієм мінімальних витрат.

Методика. Для побудови моделі функціонування ТСЛС вивантаження сировини на підприємстві був використаний метод імітаційного моделювання, для встановлення законів розподілу вхідних параметрів моделі використано статистичний аналіз. Виконана оцінка використання енергетичних ресурсів за допомогою регресійного аналізу тривалості розігріву різних видів вантажу на промислових підприємствах.

Результати. Проведені експерименти на розробленій імітаційній моделі дозволили визначити раціональну кількість використовуваних ресурсів – локомотивів і камер розігріву вантажів при їх змерзанні. За рахунок використання запропонованих методів і моделі підвищена ефективність управління транспортними та енергетичними ресурсами логістичної системи промислового підприємства.

Наукова новизна. Розроблена імітаційна модель функціонування підсистеми вивантаження сировини й палива, на відміну від існуючих, ураховує особливості транспортно-складського процесу в холодний період року та дозволяє визначити раціональну кількість транспортних і допоміжних ресурсів з урахуванням впливу зовнішніх факторів.

Практична значимість. Отримані результати дозволяють підвищити ефективність роботи ТСЛС промислових підприємств за рахунок розробки методів, що базуються на логістичному підході до управління транспортно-складськими процесами. Імітаційна модель управління процесом розігріву й вивантаження дозволяє визначити найбільш економічний режим роботи транспортно-складських логістичних систем промислових підприємств шляхом визначення раціональної кількості залучених ресурсів.

Ключові слова: *імітаційне моделювання, вантажні залізничні перевезення, транспортна логістика, вагон, управління ресурсами, енерговитрати*

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