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REVEALING THE CAUSES OF DELAYS AT TRANSIT POINTS ALONG AN INTERMODAL GRAIN SUPPLY CHAIN

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This study's object is the transport and technological system of grain supply along international routes. The issue considered is the emergence of excess cargo weight at the junctions of various types of transport.

The study was conducted on the basis of a constructed simulation model built according to the agent and discrete-event principles. It covers both the maximum transportation volumes in one of the Ukraine's oblasts in 2021 (880 thousand tons) and the forecasted indicators (1–1.5 million tons per year).

The application of the model has made it possible to determine the optimal parameters for the fleet of vehicles in a supply chain, guided by the system criterion – minimization of the average delivery time of one ton of grain. It was established that for transporting 1 million tons of grain per year, the optimal composition of the transport fleet should include 92 trucks and four railroad routes.

Patterns in the formation of excess cargo weight depending on the estimated composition of vehicles were also determined. With a planned transportation intensity of 1 million tons per year, reducing the number of trucks by 12 units could lead to the accumulation of 237 thousand tons of cargo mass at transit points. Reducing the number of railroad routes by one unit would lead to the accumulation of 544 thousand tons of cargo mass, which corresponds to USD 106 million.

The proposed model makes it possible to assess the consequences of delays in delivery, as well as the formation of excess cargo mass at transit logistics terminals and grain elevators

Keywords: agent simulation, intermodal transportation, excess cargo mass, optimal working fleet

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1. Introduction

Grain production is a key factor in the national and global food security. The process of production and supply of grain commodities to global supply chains is a complex multi-phase intermodal transport and technological system. It is a process of interaction between a set of carriers and points of interaction between them, which function as transit grain elevators. Such elevators are designed for temporary storage of grain and its accumulation until the loading rate for the next stage of transportation is reached.

In the case of organizing transportation in an intermodal road-rail-water connection, which is the most effective way for transporting grains, each subsequent phase involves the use of vehicles with a higher loading rate. In particular, trucks provide transportation of 20–30 tons, railroad freight trains – 3,500–4,000 tons, and sea vessels (bulk carriers) – from 25–50 thousand tons of deadweight [1]. This approach requires additional time to accumulate the cargo to the required volume, which leads to the formation of excess grain mass at transit points.

The volume of this technical excess mass directly depends on the delays in the technological cycle of the circulation of transport units at each of the intermodal stages of transportation. Therefore, optimization of parameters for transport and technological subsystems of intermodal transportation is an urgent scientific and applied task, especially in the context of the effective organization of global grain supply chains.

The growth of production in the agricultural and food sectors in Ukraine is accompanied by an increase in the volume of export-oriented shipments, in particular within global supply chains. According to the results of 2021, and despite the large-scale military aggression by the russian federation after 2022, the export of Ukrainian wheat and pasta products reached a record level, exceeding 20 million tons.

At the same time, the transport system of Ukraine turned out to be insufficiently prepared to service such volumes of transportation, especially taking into account the artificial blockade of the Black Sea by the russian federation, which limited the possibilities of sea shipping. Ukrainian land transport, primarily rail, has traditionally focused on other types of transportation and groups of goods, which caused an excessive load on road and rail transport of port infrastructure [1]. The imbalance between grain cargo flows and the parameters of the existing road and rail transport system has led to significant delays in the delivery of grain by land. This has led to a significant accumulation of excess cargo mass at the junctions of various types of transport, and, as a result, an increase in logistics costs.

Thus, one of the priority tasks for ensuring stable production and export of grain is the optimization of transport system parameters. Thus, the scientific task of improving transport and technological systems, which are part of the chain of transportation of grain cargo for export, is relevant. Both the stable functioning of the agricultural sector of the Ukrainian economy and global food security depend on its rational solution.

2. Literature review and problem statement

In [2], various methods and results of risk assessment in grain supply chains were investigated for their further optimization. The proposed alternative methodology is based on the selection of indices for assessing the ideal delivery system. According to the conclusions in the work, the grain supply chain within China is the most stable in terms of these indicators, which proves their stability and resistance to risks. However, the study does not reveal the essence and methods of calculating significant indices, which leaves room for further research. In a similar study [3], the entire supply chain is considered as a single logistics system, which makes it possible to optimize technological parameters according to a single criterion – cargo delivery time. However, the authors focus only on domestic transportation, while the relevance of global grain supply is growing in the world. This makes it impossible to use the proposed methodology for global supply chains, therefore, conducting research in this area is advisable.

Additional evidence of the relevance of the problem of assessing logistics risks is found in publications in various areas of transport activity. Thus, the authors of study [4] assessed typical parameters of railroad transport systems using agent modeling methods to analyze the predicted and unforeseen risks of failure to meet cargo delivery deadlines. However, the authors focused exclusively on centralized management of the locomotive fleet and did not determine the impact of such technology on transportation time. In work [5], the same issue is considered from the perspective of the impact of the human factor and the organizational structure of railroad safety management. Despite the use of powerful agent modeling methods, the authors offer generalized approaches to the functioning of such systems without reference to specific production situations. This also indicates the need for further research into the impact of various parameters of railroad operation on supply chain indicators, in particular the volume of inventories.

The authors of [6] note that as a result of the russian military aggression, grain supply chains from Ukraine are disrupted, which leads to a decrease in the efficiency of existing transport routes. They propose using wave models to assess the demand and supply of grain on the world market and provide the results of long-term forecasts for strategic planning of food security. However, the reliability of the proposed forecasts is not properly substantiated. A similar study [7] also examines the consequences of the war between the Russian Federation and Ukraine for global supply chains, in particular the blocking of free shipping in the Black Sea. The work forecasts the rates of grain exports from key producing countries and draws attention to the risks of worsening food security in Asian and African countries. However, the work considers only the supply of grain from seaports while not considering the process of consolidation and supply of grain from producers to port elevators.

Study [8] substantiates the efficiency of multimodal transportation. The authors concluded that multimodal transportation is key to organizing global supply chains, in particular when transporting perishable and urgent goods, including pharmaceutical products. At the same time, the paper does not present research tools to confirm these conclusions. Similar results were obtained in [9] when optimizing the parameters of global iron ore concentrate supply chains in rail-water transport. However, this task cannot be considered typical since the model does not take into account the supply network structure. The study data prove that for grain transportation it is advisable to consider multimodal transportation options as the most effective.

Study [10] examines the process of consolidation and cargo operations in organizing container transportation along multimodal routes. The authors emphasize that the docking of different modes of transport with cargo consolidation is a key element of multimodal transportation. To increase the efficiency of transit consolidation, a genetic algorithm is used. However, the work does not take into account the principle of a systems approach and the features of different modes of transport in organizing container transportation. The authors of [11] define the time and cost of delivery as key criteria for choosing a method of transporting goods, in particular in global supply chains. A mechanical method for determining variable railroad costs on a selected route in Texas is proposed. However, this method does not take into account time delays and possible emergency situations.

In study [12], the principles of multimodal transportation are used to ensure the delivery of drugs during their therapeutic action. The authors understand multimodality as a set of stages of the promotion of active substances in the body's systems. In the course of the work, a series of experiments were conducted, demonstrating the significant variability of the drug delivery time and a wide range of factors affecting this process.

In work [13], the conditions for the emergence of delays during the movement of trains on the railroad network and in mixed traffic are considered. A modeling method is proposed in which the objective function takes into account the cyclic schedule of train movements. As a result, the dependences between the number and duration of delays for the railroads of Ukraine were obtained. However, the method does not take into account the stochasticity of the execution of the main technological operations when processing trains at railroad stations. Also, the study is aimed at the averaged cargo transported and does not take into account the specificity of grain cargo transportation.

Simulation modeling remains one of the few tools that make it possible to take into account the maximum number of input parameters, enable a systematic approach, and take into account the stochasticity of technological operations. Thus, in study [14], a simulation model of intermodal export supply chains of grains is presented. Experimental studies were conducted to estimate the volume of CO_2 emissions and other key indicators of the efficiency of supply chains. However, the work did not take into account the specificity of different types of transport when organizing such transportation.

In [15], the logistics flows of metallurgical enterprises are considered as a micro-logistics process. A mathematical model is proposed that models the interaction of transport flows of rolling stock and infrastructure facilities, allowing for the detailed development of the production transport process. At the same time, the authors do not specify their approach to scientific tools but present a general methodology for assessing the efficiency of transport and technological processes at the micro-level.

In study [16], Petri net tools were used to analyze information systems in digital logistics. The authors argue that the proposed approach makes it possible to predict the activities of the main participants in the transportation process and increase the efficiency of their interaction. However, this apparatus is difficult to use for large systems, which include global grain supply chains. In work [17], the feasibility of choosing a rational option for reverse transport using an integrated selection criterion is considered. According to the authors, the proposed approach could help increase the efficiency of transport companies.

Our review of related literature showed that, in relation to transportation using different types of transport, there is a complexity in organizing the interaction of different types at interaction points, which affects the performance of the supply chain. Another problem is associated with the formation of stocks at the junctions of different types of transport, which is a source of risks, especially during martial law. Both of these issues are closely related and should be studied in an integrated manner, using appropriate tools.

3. The aim and objectives of the study

The purpose of our study is to determine the conditions for the formation of delays at transit points along the intermodal grain supply chain. This will make it possible to define optimal parameters for the transport and technological system based on the criterion of minimizing the volume of excess cargo mass.

To achieve this aim, the following objectives were accomplished:

– to construct a mathematical simulation model of the transport process of the intermodal grain supply chain based on agent and discrete-event approaches, which integrates automobile, railroad, and maritime transport and technological subsystems into a single technological system;

– within the framework of a single technological system, to investigate the features of vehicle turnover on automobile, railroad, and maritime lines and experimentally determine the degree of influence of the size of operational fleets of automobile and railroad transport on the average cargo delivery time and the volume of cargo accumulation at loading points.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the transport and technological system of grain supply along international routes.

The hypothesis of the study assumes that the size of the fleet of transport vehicles in each individual transport and technological subsystem inversely affects the size of the excess cargo mass in all other subsystems of the multi-phase transportation process.

During the study and the construction of a simulation mathematical model, the following assumptions were adopted:

– the technological process is rational and complies with the typical norms and provisions of the theory of transport processes and systems;

– the throughput capacity of transport and technological lines and communication routes is sufficient to ensure the planned volume of cargo transportation – 1 million tons per year, and even under conditions of changing the installation mass and varying the size of the fleet of vehicles, the throughput capacity is not a limiting factor;

– the processing capacity of cargo devices and the capacity of terminals are sufficient and do not affect the results of the study;

– the incoming flow of cargo into the first link of the multi-phase transport process is supplied in the form of the simplest cargo module – 1 t of grain;

– the reliability of the transport and technological process is guaranteed by technical equipment and rolling stock, which provide the appropriate level of operational reliability, and the influence of the human factor on the efficiency of transportation is not taken into account.

The main simplification of our study is that the multi-phase process of grain supply is considered as a process of mixed (intermodal) transportation, in which legal, legislative, and regulatory formalities do not affect the quality of the organization of cargo transportation.

4. 2. Construction of a mathematical (simulation) model

The considered problem is optimization and multi-criteria problem; however, the main optimization criterion is the minimum possible cargo delivery time. The choice of this criterion is the most appropriate from the point of view of logistics principles, in particular:

1. Ensuring consistency: the average cargo delivery time is an integral indicator of the efficiency of the entire transport and technological system of grain supply since it characterizes the average time the cargo stays in the system.

2. Minimizing the time of asset turnover and reducing the cost of transportation: the shorter the time the cargo stays in the transport and technological system, the smaller the losses associated with the "freezing" of current assets.

Thus, the statement of our problem is reduced to a classical optimization problem with an objective function and corresponding constraints.

Since the minimum delivery time can be achieved only under conditions of unlimited resources, the main constraints to the objective function are:

– rational use of the capacity of transport lines;

– optimal use of the working fleet of vehicles in all subsystems of the transport and technological complex.

To increase the adequacy of the model to the real process, the stochastic nature of the duration of technological operations is taken into account. Therefore, the implementation of this model on the example of real supply chains with numerical parameters is possible only within the framework of simulation modeling.

Numerical studies were conducted on the basis of the constructed simulation model in the AnyLogic University Researcher environment, which is based on the agent and discrete-event principle, which is a relevant tool for conducting scientific research. Such an apparatus is flexible and makes it possible to study various aspects of technological processes that are performed during transportation [18–20]. This has made it possible to cover the entire transport and technological system of grain delivery from the point of its origin to the final destination in one experimental model. In addition, the model simulates the discrete-event technological cycles of cargo turnover of road, rail, and water transport vehicles, as well as the processes of their interaction in transit grain terminals.

5. Results of investigating the conditions for the formation of excess cargo mass

5. 1. Results of the construction of a mathematical (simulation) optimization model of the transport process of the intermodal grain supply chain

The average cargo delivery time under the conditions of a complex, mixed, and multi-component route is defined as the sum of the transportation time costs within each individual transport subsystem. However, taking into account the synergistic effect – characteristic of complex transport and technological systems – the total average cargo delivery time along the entire route cannot be determined by simply adding the average values of the transportation time in each subsystem. In other words, formally the total average cargo delivery time within the entire transport and technological system takes the following form

$$\overline{T_{syst}} = \sum_{i=1}^{I} \overline{t_i}, i \in I, \tag{1}$$

where t_i – estimated cargo stay time in the i-th subsystem; I – total number of transport and technological subsystems.

For the grain transportation route within the global supply chain, the total number of transport and technological subsystems is three. These include road and rail (land) subsystems, as well as water – from Ukrainian sea trade ports to ports of destination countries or transit countries.

The only and, at the same time, most important parameter that determines the structure and configuration of the entire supply chain within the transport and technological system is the average intensity of cargo arrival for transportation. It is this intensity that forms the total load on both individual subsystem and the system as a whole. It will retain its absolute value, changing only in the form of transformation in accordance with the transportation conditions within each transport and technological subsystem.

In the context of the conditions considered in our study, the intensity of cargo arrival will correspond to the planned volume of transportation of grains, legumes, and oilseeds transported in bulk: first by trucks; then by grain dispatch railroad routes; and, finally, by sea vessels (bulk carriers).

The primary process of collecting and transporting grains from the network of elevators by road transport is a network-type problem, characterized by the presence of a set of departure points and one or more destinations. In this regard, the estimated delivery time of a consignment of cargo by road transport is formalized as:

$$t_{auto} = f\left(\lambda_i, \left\{M_j; M_J\right\}, \left\{Q_r; Q_R\right\}\right), \tag{2}$$

$$j \in J,$$

$$r \in R,$$

$$\Lambda = \sum_{j=1}^{J} \lambda_j,$$

where λ_i – intensity of cargo arrival to the j-th departure point; $\{M_j; M_J\}$ – set of technological and technical characteristics and parameters of road transport routes on the calculation network: length, average technical speed, etc.; $\{Q_r; Q_R\}$ – set of technical and operational characteristics of the truck fleet: technical loading rate, number, etc.

In the railroad transport subsystem, there is also a branching of routes, but it is not as critical as in the automobile one. The key limiting factor in determining the transportation time in this case is the limited throughput capacity of the railroad, as well as a much higher loading rate into the train. These are the features that determine the additional time required to accumulate cargo when loading railroad cars and forming a freight train:

$$t_{rail} = f\left(f\left(\Lambda\right)_a, \left\{MZ_z : MZ_Z\right\}, \left\{QZ_h : QZ_H\right\}\right), \tag{3}$$

$$z \in Z,$$

$$h \in H,$$

where $f(\Lambda)_a$ is a function that determines the transformed freight flow after road transport at the entrance to the railroad subsystem; $\{MZ_z; MZ_Z\}$ is a set of technological and technical characteristics and parameters of the railroad network routes: available capacity, route speed, loading rates, useful track length, etc.; $\{QZ_h; QZ_H\}$ is a set of technical and operational characteristics of the railroad rolling stock fleet: technical loading rate of railroad cars, fleet of railroad cars and locomotives.

For the water transport and technological system, the key characteristics are the relatively larger carrying capacity of vessels and the significantly longer length of transportation routes. Formally, these features can be represented as:

$$t_{sea} = f\left(f\left(\Lambda\right)_r, \left\{MS_s : MS_S\right\}, \left\{QS_b : QS_B\right\}\right), \tag{4}$$

$$s \in S,$$

$$b \in B,$$

where $f(\Lambda)_r$ is the function that determines the transformed after railroad transport cargo flow at the entrance to the maritime transport and technological subsystem; $\{MS_s; MS_S\}$ – set of technological and technical characteristics and parameters of cargo delivery routes by maritime transport: route speed, loading rates, useful track length, etc.

Then, according to expression (1), the objective function takes the following form

$$\overline{\left\{\begin{array}{l} \left(\lambda_i, \left\{M_j; M_J\right\}, \left\{Q_r; Q_R\right\}\right) + \\ \left(f\left(\Lambda\right)_a, \left\{MZ_z : MZ_Z\right\}, \left\{QZ_h : QZ_H\right\}\right) + \\ \left(f\left(\Lambda\right)_r, \left\{MS_s : MS_S\right\}, \left\{QS_b : QS_B\right\}\right) \end{array}\right\}} \rightarrow \min. \tag{5}$$

Since any production process must ensure the rational use of available resources, when organizing multi-stage transportation of grain, the main limitations are:

– efficient and reliable use of the existing fleet of vehicles;

– minimization of the volume of transit mass at transshipment points and reduction of cargo accumulation before its loading into the appropriate vehicles

$$\begin{cases} \xi_{rt} \le \psi\left(Q_r : Q_R\right) \le \xi_{rl}, \\ \xi_{rt} \le \psi\left(QZ_h : QZ_H\right) \le \xi_{rl}, \\ \xi_{rt} \le \psi\left(QS_b : QS_B\right) \le \xi_{rl}, \\ \overline{\sum Q_{auto}} \to \min, \\ \overline{\sum Q_{rail}} \to \min, \\ \overline{\sum Q_{sea}} \to \min, \\ \left\{RO, RR, SS\right\} - \text{const}, \end{cases} \quad (6)$$

where ξ_{rt}, ξ_{rl} is the limit of rational and reliable use of the fleet of vehicles; $\psi(Q_r:Q_R)$, $\psi(QZ_h:QZ_H)$, $\psi(QS_b:QS_B)$ – coefficients of utilization of the working fleets of transport units of the road, rail, and water transport systems, respectively. Since in this study a transport unit is understood as a means of transporting one consignment of cargo, then:

– for road transport, this is one truck (or road train);

– for rail transport, this is one freight train;

– for water transport, this is one bulk carrier;

$\overline{\sum Q_{auto}}$, $\overline{\sum Q_{rail}}$, $\overline{\sum Q_{sea}}$ – average level of the volume of cargo mass located at the loading points within the relevant transport subsystem; $\{RO, RR, SS\}$ – estimated working fleet of transport units, respectively, for the road, rail, and water transport subsystems.

When constructing the agent model, the following agents were built:

1. Agent 1 – simulation of the functioning of the road transport system.

2. Agent 2 – simulation of the functioning of the railroad transport system.

3. Agent 3 – simulation of the functioning of the railroad transport system.

4. Population of agents 4 – simulation of the process of primary accumulation of grain at the points of departure.

5. Population of agents 5 – simulation of the formation and movement of the cargo module (one ton of grain is taken as the cargo module).

6. Populations 6–8 – simulation of the functioning of the fleet of transport units of road, rail, and water transport, respectively.

The key element of the model is the simulation of the technological turnover of transport units in three transport systems (agents 1–3). These modules are designed on the basis of a discrete-event principle. It is this principle of simulation modeling that makes it possible to detail complex and multi-element technological processes in transport at the lowest level of abstraction (Fig. 1).

Through the *enter* module, a group of agents 5 arrives in the amount that forms a batch of cargo, in accordance with the loading rate into the transport unit (agent 6). In the *seize* module, the presence of a free agent 6 (truck module) is checked, and, if there is one, the full technological turnover of the truck is simulated:

– *moveTo* – movement of the truck in an empty state for loading at the grain elevator;

– *delay* – loading the vehicle;

– *moveTo*1 – movement of the truck in a loaded state to the railroad station of departure;

– *unloading* – unloading the vehicle at a railroad station;

– *release* – release of the vehicle and transfer to agent 6 to the *truck* module.

Upon completion of unloading (discrete transition between the *unloading* and *waitForConsol* modules), the algorithm for forming the cargo mass to the loading rate into the vehicle of the next transport subsystem, railroad (Fig. 2), is implemented.

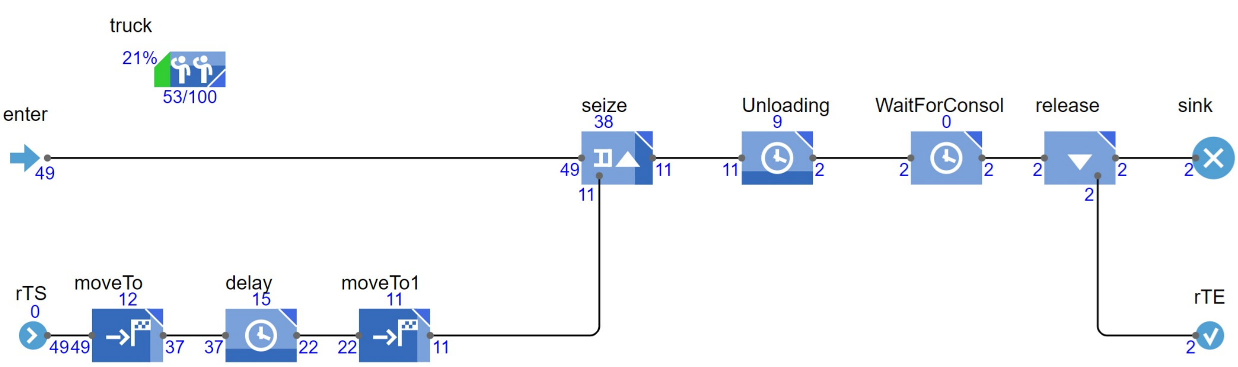

Fig. 1. Representation of a discrete-event simulation of the technological turnover of a transport unit in agent 1 (automobile transport subsystem) in the AnyLogic University Researcher environment

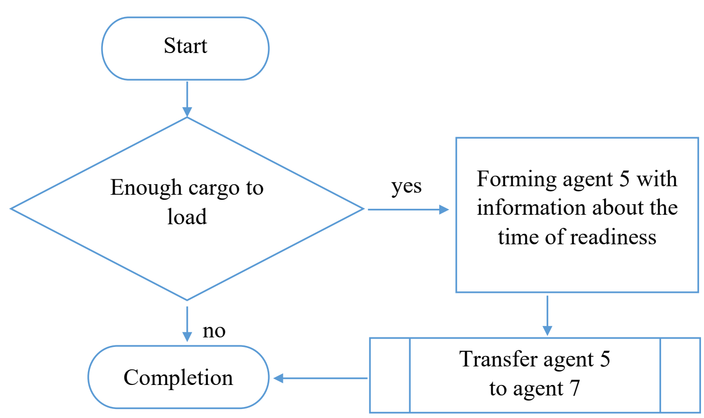

Fig. 2. Algorithm for forming the required volume of cargo mass for loading

Similar processes are implemented in agents 2 and 3, thereby simulating the entire technological process of functioning and interaction of the road, rail, and water transport subsystems.

The structural-logical model of interaction of agents in the simulation model is a reflection of the real multi-factor process of grain transportation in the global supply chain and the interaction of three transport subsystems: road, rail, and water (7). From the model of agent interaction, it is clear that the population of agents 5 (cargo module) interacts with all other agents over the entire stage of modeling (Fig. 3)

$$\{agents4, agents5\} \rightarrow agent1\{agents6, agents5\} \rightarrow agents2\{agents7, agents5\} \rightarrow agent3\{agents8, agents5\}, \quad (7)$$

where $\{agents\}$ is a population (set) of agents identical in properties.

In addition to the interaction of agents, the model built also uses the principle of discrete transitions between functional modules, both within agents and between them. This property, together with the interaction of the population of agents 5 (cargo module), makes it possible to programmatically record the moment of entry into the i-th module of the model and the moment of exit of the requirement (cargo module) from the i-th module of the model. Thus, the total time of stay of the cargo module during transportation within the entire intermodal route will be determined as

$$T_{tr.B\,od.} = \sum_{i=1}^{i=N} T_i, \quad (8)$$

where T_i is the time of stay of the cargo module in the i-th module of the discrete-event process of the simulation model; N – total number of modules of the discrete-event process of the simulation model.

At the same time, it became possible to experimentally investigate the average time and density of the distribution of the time of stay of the cargo module within each of the stages of cargo transportation, namely in agents 1–3. For this purpose, elements for collecting and processing a statistical sample were designed and the program collects and analyzes statistical information regarding the time of stay of all cargo modules in the corresponding technological elements according to the general principle

$$t_{ij} = t_{i.exit} - t_{Venter}, \quad (9)$$

where $t_{i.exit}$ is the moment of exit of the j-th cargo module from the i-th module of the discrete-event process of the simulation model; $t_{i.enter}$ – moment of entry of the j-th cargo module into the i-th module of the discrete-event process of the simulation model.

For example, to analyze the density of the distribution of waiting time by cargo modules of a free truck, the code will be implemented via Java at the moment of exit of the request (cargo module) from the *seaze* module (Fig. 3).

"*dataTimeWaitRoad*.add(time() – agent.timeInRA);", (10)

where *dataTimeWaitRoad* is a software subprocess for collecting and analyzing a statistical sample of waiting times by cargo modules of a free truck; time() is the current moment of model time. At the moment of the request (cargo module) leaving the module, the moment of model time will be equal to the moment of the start of loading into the truck; timeInRA is the moment of the start of waiting by the cargo module of a free truck.

The search for optimal parameters of the transport and technological line for grain supply in a mixed road-rail-water connection was carried out using the example of a real supply chain. The supply of grain from Ukraine (Poltava oblast, Table 1) was considered via the sea trade ports in Odesa: MTP Chornomorsk, Odesa, and Pivdenny. This supply chain is the most typical for the realities of Ukraine when organizing export supplies of grain to global markets, that is, with the participation of sea transport.

The model is implemented for the transportation of the maximum during the observation period (2021) and forecasted volumes of grain (Table 1). All norms of time for performing technological operations are taken as typical and in accordance with current norms and regulations (Tables 2, 3). One ton of grain is selected for one cargo module.

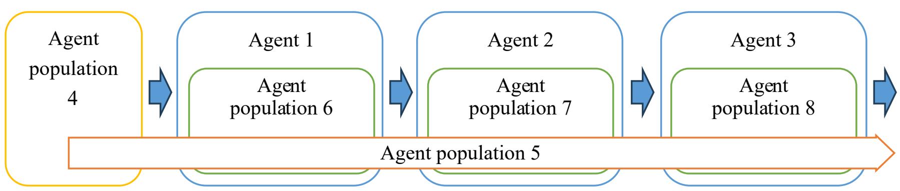

Fig. 3. Functional diagram of agent interaction within the model

Table 1

Initial volumes of cargo shipments (grain) to the main points in the Poltava oblast

Point of origin of cargo mass	Production volume according to 2021 data, tons	Estimated volume, tons	Projected volume for 2030 (optimistic), tons
Orzhytsia	63,111	71,429	107,143
Dykanka	63,111	71,429	107,143
Velyky Sorochyntsy	63,111	71,429	107,143
Poltava	63,111	71,429	107,143
Romodan	63,111	71,429	107,143
Butenky	63,111	71,429	107,143
Pyryatyn	63,111	71,429	107,143
Globyne	63,111	71,429	107,143
Gadyach	63,111	71,429	107,143
Bilatserkivka	63,111	71,429	107,143
Zinkiv	63,111	71,429	107,143
Zavodske	63,111	71,429	107,143
Karlivka	63,111	71,429	107,143
Novi Sanzhary	63,111	71,429	107,143
Total in Poltava oblast	883,560	1,000,000	1,500,000

Table 2

Technical and operational characteristics of vehicles and transport process units of simulation modeling

Indicator	Measurement unit	Pcs.
1. Average technical speed		
– trucks	km/h	60
– railroad ring (departure) routes	km/h	35
– ships (bulk carriers)	km/h	15*
2. Technical loading rate		
– trucks	tons	20
– railroad ring (departure) routes	tons	4000
– ships (bulk carriers)	thousand tons	50**

Note: 1 – this item refers to cruising speed; 2 – this item refers to net deadweight.

Table 3

Characteristics and parameters of the main time costs for performing technological operations

Parameter	Measure-ment unit	Pcs.	Note
Freight turnover time standards:			
1) trucks:			
travel time to loading point	hour	estimated	
time at loading point*	hour	$M(t) = 2.0$	triangular(0.75 $M(t)$, $M(t)$, 1.5 $M(t)$)
travel time to unloading point	hour	estimated	
time at unloading point	hour	$M(t) = 1.5$	triangular(0.75$M(t)$, $M(t)$, 1.5 $M(t)$)
2) railroad routes:			
travel time to loading point	hour	estimated	
time at loading point*	hour	$M(t) = 24$	triangular(0.5 $M(t)$, $M(t)$, 1.5 $M(t)$)
travel time to unloading point	hour	estimated	
time at unloading point	hour	$M(t) = 24$	triangular(0.5 $M(t)$, $M(t)$, 1.5 $M(t)$)
3) loading time and vessel's stay in port	24 h	$M(t) = 5$	triangular(0.9 $M(t)$, $M(t)$, 1.3 $M(t)$)

*Note: * – here and below, only the time for loading, initial-final, and other operations is taken into account, and the waiting time for technological operations is not taken into consideration. Delay times and waiting times for technological operations are calculated programmatically when implementing the simulation model.*

The first experiment was based on 2021 data with an annual traffic volume of 883,560 tons. The second experiment considered a projected annual traffic volume of 1 million tons. The third experiment was aimed at analyzing a projected volume of 1.5 million tons.

5. 2. Results of experimental studies based on the actual grain supply chain

It was experimentally established that typical technological operating conditions of vehicles and technological systems for transporting grain crops in the amount of 883,560 tons per year. In this case, the optimal parameters of the working fleet are 79 trucks (with a fleet load factor of 0.54) and three railroad dispatch routes (with a fleet load factor of 0.63%).

For transportation of one million tons of grain per year, the optimal working fleet is 92 trucks (with a load factor of 0.52) and four railroad dispatch routes (with a load factor of 0.54%). In the case of transporting 1.5 million tons per year, it is necessary to use 106 trucks (with a load factor of 0.68) and five railroad dispatch routes (with a load factor of 0.64%). In each of the cases considered, the optimal level of loading of the vehicle fleet is ensured, which makes it possible to achieve the minimum possible time for delivery of goods by land. According to the serial numbers of the experiments, this time is 322 hours, 292 hours, and 217 hours.

The experimental studies included three series of experiments aimed at analyzing different volumes of freight transportation from Poltava oblast. The first experiment was based on 2021 data with an annual transportation volume of 883,560 tons. The second experiment took into account a projected annual transportation volume of 1 million tons. The third experiment was aimed at analyzing a projected volume of 1.5 million tons (Table 4).

Another series of experiments revealed regularities in the formation of key technological parameters for the functioning of automobile and railroad transport and technological lines depending on the estimated fleet of trucks and railroad dispatch routes (Fig. 4, 5), which is consistent with the results of research, especially in terms of assessing the efficiency of multi-phase technological processes by system indicators [4, 21].

Table 4

Optimal values of the sizes of working truck fleets and railroad dispatch routes

Optimization experiment	Total cargo traffic tons/year	Truck fleet		Railway route fleet		Estimated value of the objective function (3.6), hours
		Optimal value, units	Estimated fleet load	Optimal value, units	Estimated fleet load	
Experiment 1	883,560	79	0.54	3	0.63	322.63
Experiment 2	1,000,000	92	0.52	4	0.54	292.82
Experiment 3	1,500,000	106	0.68	5	0.64	217.823

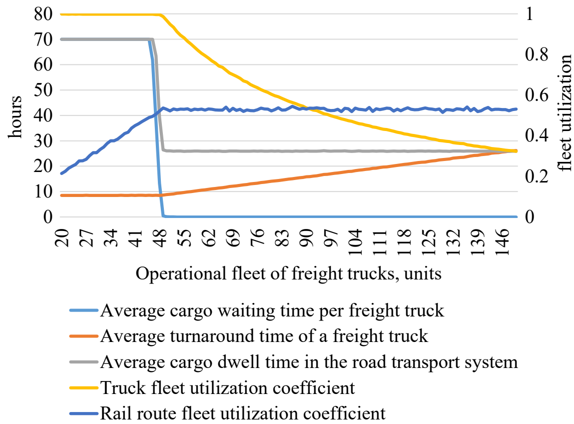

Fig. 4. Dependence of basic indicators for the functioning of an automobile transport and technological line on the working fleet of trucks at a projected annual transportation volume of one million tons

Three critical levels of the size of the working fleet of vehicles have been established:

– optimal limit – at which the optimal operation of the transport system is ensured;

– critical limit – at which the transport system approaches exceeding the optimality limit;

– maximum permissible limit – at which the system operates with an increased risk of disruptions in the technological process and complete stoppage.

Based on the data obtained, the conditions under which excess cargo stocks are formed at transit points of transshipment were determined. Such inventories arise due to inefficient use of the transport fleet, which is due to technological delays, failures during cargo operations, or a reduction in the size of the working fleet.

Dependences between the average time of delivery of goods by land and the volume of cargo mass formation for the road and rail transport systems have been established (Fig. 6, 7). For the road transport system, these dependences are approximated with high probability by logarithmic functions, while for the rail transport system, by linear functions.

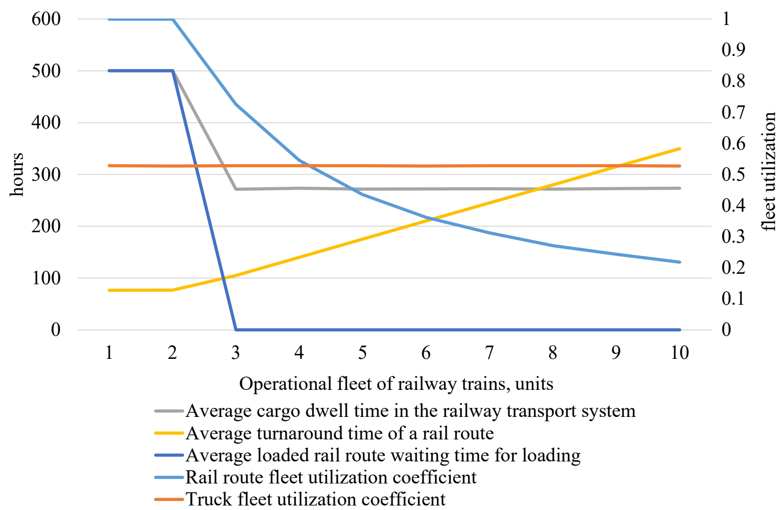

Fig. 5. Dependence of basic indicators for the functioning of a railroad transport and technological line on the working fleet of dispatch routes at a projected annual transportation volume of one million tons

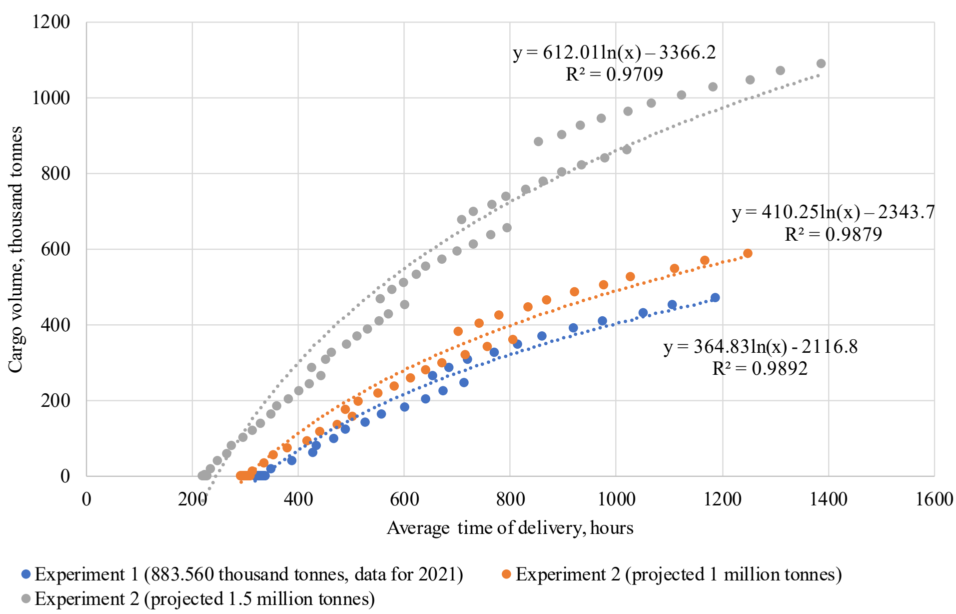

Fig. 6. Experimental and theoretical relationships between the average time of cargo delivery in reality and the volume of cargo mass formation before loading into a vehicle

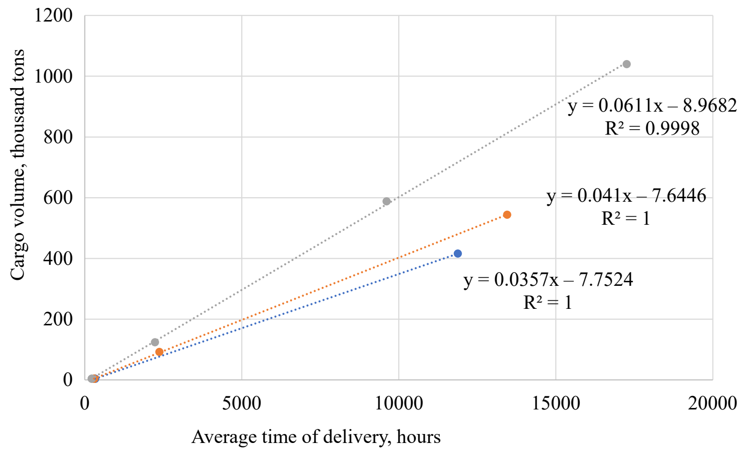

Fig. 7. Experimental and theoretical relationships between the average time of cargo delivery in reality and the volume of cargo mass formation before loading into railroad trains

For the road transport system, these dependences are most likely approximated by logarithmic functions, while for the rail transport system, they are approximated by linear functions.

6. Discussion of results related to investigating the conditions for the formation of excess cargo mass

Our results for the dependence of basic indicators of the functioning of automobile and railroad transport and technological lines on the working fleet of vehicles (Fig. 4, 5) are very similar to the results reported in study [1, 3], in which the authors give the results of the construction and implementation of a multifactorial simulation model of the functioning of industrial transport operating under conditions of unevenness. This can be explained by the fact that the indicated studies use similar research tools, namely agent simulation of multiphase processes and take into account the variability of the duration of the elements of technological processes. The model simulates the process of cargo delivery and makes it possible to optimize key production resources, such as a fleet of shunting locomotives and cargo heating points. At the same time, the indicated simulation model does not take into account the functioning of the connecting railroad station and its throughput capacity, and therefore the systematicity of the intermodal and multimodal process is lost.

At the same time, in the results presented in these studies, thanks to the implementation of a systematic approach, it was possible to identify the patterns of the annual volume of excess cargo weight and its monetary equivalent depending on the size of the working fleet of vehicles to the maximum extent. In particular, a critical decrease in the need for rolling stock was established compared to the previously defined limit levels of sustainable operation of transport systems (4), (5).

The established patterns of changes in the volume of excess cargo weight at cargo points depending on the average delivery time turned out to be different. Thus, for the road transport system this dependence is nonlinear (Fig. 6), while for the railroad transport system it is linear (Fig. 7). This contradicts the results of [1], in which the authors investigated the multimodal process of delivering another bulk cargo – iron ore concentrate. The discrepancy in the results can be explained by the fact that the presented studies model an extensive automobile supply network, which leads to variability in technological indicators. This fact is confirmed by the results of research reported in [22]. At the same time, it is difficult to explain the discrepancy in the types of theoretical models of these dependences: logarithmic – for the automobile, and linear – for the railroad subsystem. This issue is the basis for further research.

When reducing the working fleet of trucks by 12 units (25% of the maximum allowable fleet size), at the end of the year of operation, 237,000 tons of cargo mass accumulate, which according to 2025 data is equivalent to USD 45 million. A similar reduction in the working fleet of railroad dispatch routes by one unit (50% of the maximum allowable level) leads to the formation of 544,000 tons of cargo mass, which at stock prices in 2025 is USD 106 million.

The results obtained in our study differ from other similar studies, for example [23], in which the authors model land multimodal grain routes based on fuzzy logic. Or in relation to study [24], in which the authors use the constructed periodic mixed integer nonlinear optimization problem to determine the total costs and other cost indicators. Certain discrepancies with the mentioned studies occur due to the different boundaries of the transport and technological systems under study, a different set of initial parameters, and other local conditions, including legislation.

The results of the experiments show that an increase in the working fleet relative to the optimal calculated values does not improve the technological indicators of the functioning of transport systems, in particular the average cargo delivery time. Instead, this leads to an increase in the waiting time of cargo vehicles for shipment and an increase in the duration of cargo turnover of vehicles.

Our study focuses on large-scale transport and technological processes and does not take into account the limitations of throughput and processing capacity, in particular, port railroad stations and their adjoining areas. In addition, despite the wide possibilities of simulation modeling, the proposed model does not cover the entire transport network of Ukraine and neighboring countries.

The shortcomings of the study include the lack of sufficient verified initial data on the volumes of cargo shipments for each individual departure point, as well as the lack of field observation data on the actual duration of technological operations, which led to the use of normative values.

7. Conclusions

1. A mathematical (simulation) model of the transport process of the intermodal grain supply chain has been built, covering road, rail, and sea transport. The following approaches have been implemented when constructing the model:

– agent principle – for simulating the interaction of cargo modules (ton of grain) with transport and technological subsystems of road, rail, and sea transport, cargo terminals, infrastructure elements, and transport units of the specified subsystems;

– discrete-event principle – for detailed simulation of transport processes, in particular the technological turnover of vehicles and the process of accumulation of cargo mass at cargo terminals.

This approach has made it possible to cover the entire transport and technological system of grain delivery – from the network of departure points and transit points, as well as the network of communication routes, to the final destination – within a single experimental model, which ensured maximum systematicity of the study.

2. When numerically implementing the model using the example of one of the typical grain supply chains from Ukraine to China, regularities in the formation of the annual volume of excess cargo weight were revealed, depending on the size of the working fleet of vehicles. When the number of trucks is reduced by 12 units (25% of the maximum permissible level), 237,000 tons of cargo weight accumulates at the end of the year, which corresponds to USD 45 million (at stock prices in 2025). Reducing the number of railroad routes by one unit (50% of the permissible level) leads to an accumulation of 544,000 tons of cargo weight, which is equivalent to USD 106 million. An increase in the working fleet relative to the optimal calculated values does not improve the technological indicators of the functioning of transport systems. In particular, the average cargo delivery time does not decrease. Instead, there is an increase in the waiting time for cargo vehicles to be dispatched and an increase in the duration of the cargo turnover of vehicles.

It has been experimentally established that for the transportation of one million tons of grain per year, the optimal working fleet consists of 92 trucks (with a load factor of 0.52) and four railroad dispatch routes (with a load factor of 0.54). For the transportation of one and a half million tons per year, it is necessary to attract 106 trucks (with a load factor of 0.68) and five railroad routes (with a load factor of 0.64). In each of the considered scenarios, the optimal level of vehicle loading is achieved, which ensures the minimum (from the set of possible) time for delivering goods by land. According to experimental data, this indicator is 322 hours, 292 hours, and 217 hours.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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