



UDC 656.025.4; 656.073.7

DOI: 10.31548/dopovidi/5.2024.21

Development of a simulation model of grain delivery in global supply chains

Yurii Khomenko

Postgraduate Student
Ukrainian State University of Science and Technologies
49010, 2 Lazaryana Str., Dnipro, Ukraine
<https://orcid.org/0009-0003-2386-0062>

Viacheslav Matsiuk*

Doctor of Technical Sciences, Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
<https://orcid.org/0000-0003-2355-2564>

Andrii Okorokov

PhD in Technical Sciences, Associate Professor
Ukrainian State University of Science and Technologies
49010, 2 Lazaryana Str., Dnipro, Ukraine
<https://orcid.org/0009-0006-3532-9393>

Oleksandr Gorobchenko

Doctor of Technical Sciences, Professor
State University of Infrastructure and Technologies
04071, 9 Kyrylivska Str., Kyiv, Ukraine
<https://orcid.org/0000-0002-9868-3852>

Abstract. The main export shipments of grain to Ukraine are carried out through commercial seaports of the Black Sea, while the complex and multiphase transportation process creates delays and leads to additional costs at the points of connection of various types of transport. The purpose of the study was the process of transporting grain cargo for export through commercial seaports. Ukraine is a developed agricultural country that produces a significant share of the world's grain volume, most of which is exported. The optimisation simulation model of multimodal grain cargo transportation developed in the study, in contrast to the existing ones, is a multiphase process with many initial parameters, subsystems, and technological elements that adequately reflect all components of the technological

Suggested Citation:

Khomenko, Yu., Matsiuk, V., Okorokov, A., & Gorobchenko, O. (2024). Development of a simulation model of grain delivery in global supply chains. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 20(5), 21-35. doi: 10.31548/dopovidi/5.2024.21.

*Corresponding author



Copyright © The Author(s). This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (<https://creativecommons.org/licenses/by/4.0/>)

process of organising transportation by road, rail, and sea, and helps to optimise these processes. The model consisted of several transport and technological subsystems, each of which corresponded to the process of grain transportation by road, rail, or water. The minimum total duration of cargo transportation from the place of origin to the moment of sending grain cargo for export by sea was chosen as the optimal criterion. To establish the minimum required number of replications and the minimum required model time, a series of experiments were performed, where the key and systematic modelling measurement parameter is the total time of grain delivery by land, from the point of origin to the sea trade terminal. As a result of modelling, the optimal number of rolling stock of different types of transport and the transportation time for each phase of the process were determined. Logistics operators of the agro-industrial sector can apply the model to improve grain delivery routes and schemes, evaluate and improve technological parameters, and minimise transportation time and costs

Keywords: agent-based simulation model; Java SE (Oracle); AnyLogic University Researcher; technological process; minimising delivery time; optimising business process

Introduction

According to official statistics, the Ukrainian agricultural industry, even during the period of large-scale military aggression by the Russian Federation and the blocking of transport corridors, remains an important player in the world market. A particular problem is the constant blocking of commercial seaports and shipping routes in the Black Sea. According to optimistic data from a number of institutions (the US Department of Agriculture, the Ministry of Agrarian Policy and Food of Ukraine, etc.), Ukraine's exports of grains, legumes, oilseeds and their primary processing products will reach approximately 50-70 million tonnes per year in 2028-2030 (U.S. Department of Agriculture, n.d; Ministry of Agrarian Policy and Food of Ukraine, 2024). This forecast should be highlighted not only in terms of increasing production volumes, but also increasing the carrying capacity of the national transport system within global supply chains. Therefore, the search for new methods of organising grain supplies within such global chains remains relevant.

The problem of cargo transportation in global supply chains is becoming a particularly relevant issue for grain-producing regions and countries. In their study, C. de Faria *et al.* (2024)

investigate the reduction of the negative impact of the Brazilian transport system on the environment. The main problem, according to researchers, is the insufficiently efficient planning of complex, multi-element supply chains for export cargo and the low level of use of railway electric transport, which leads to excessive CO₂ emissions. The result of the study is the developed standard technological models for organising grain routes. However, the researchers do not provide forecast data on ensuring the carrying capacity of these shipments.

Other researchers, representatives of Canada E. Sharifi *et al.* (2024) point to the problems of the supply chains of grain exports from Canada, which are mostly associated with severe climatic conditions – long winters – which make most ports unable to operate fully throughout the year, and the significant length of railway routes, most of which are non-electrified, which creates a negative impact on the environment. The researchers proposed a multi-criteria optimisation model based on the Torabi and Hasini fuzzy programming method and minimax rules, aimed at improving the sustainability and efficiency of intermodal supply chains in the context of modern challenges to the Canadian transport system:

the COVID-19 pandemic, increased demand for transportation due to the military aggression of the Russian Federation against Ukraine. However, the paper does not address the issues of increasing throughput in conditions of uncertainty.

V. Matsiuk *et al.* (2023) present the results of experiments with a developed simulation model of the global grain supply chain using a multimodal route. In addition to the standard optimisation criterion – average transportation time – studies were conducted to assess the fault tolerance of transport technologies. As a result, the range of fluctuations in cargo flows is established, at which the transport system provides the necessary level of fault tolerance. However, the model is implemented only for the land part of the supply chain, which does not cover the entire transportation route.

Improving the efficiency of grain transportation is no less relevant for the countries receiving grain crops. This is especially true in regions that lack fresh water for agricultural production. A. Adenle *et al.* (2019) determine the key role of transport in the rapid delivery of mineral fertilisers, machinery, and workers to the places of sowing, harvesting, etc. The problem is that most regions of Africa have a significant shortage of fresh water. Because of this, the regions of agricultural production are constantly changing, which requires significant mobility of production capacities. The paper by V. Aulin *et al.* (2024) presents mathematical models of the functioning of the transport system under conditions of uncertainty. However, the models are quite abstract, which allows obtaining only an approximate assessment of the effectiveness of decision-making.

It is transportation in the global economy that is becoming a direct link between smart technologies of agricultural production, as noted by O. Zagurskiy *et al.* (2024), thereby increasing the overall economic effect by reducing the logistics component in the final cost of products. S. Garg *et al.* (2023) indicate that transportation

is the production process of the processing and agricultural industries. Therefore, according to P. Yablonskyi *et al.* (2024), elements of precision farming and global positioning should also apply to transport processes, in particular, docking, loading, and unloading points. I. Rogovskii *et al.* (2024) assess the possibility of implementing precision farming principles in the functioning of transport systems. However, the study does not provide models for making effective decisions.

The purpose of the study was to develop a simulation model of the grain delivery process in global supply chains, which, unlike the existing ones, would allow considering the variability of technological processes and the interaction of road, rail, and water transport on the network. To achieve this goal, the following tasks were completed:

- 1) an optimisation mathematical (simulation) model of a transport and technological grain delivery line has been developed with substantiation of the optimisation criterion;
- 2) a set of optimal parameters of the transport and technological grain delivery line in global supply chains has been experimentally established.

Materials and Methods

Optimisation (mathematical) model

The total time of cargo delivery was considered as a system indicator of the functioning of the transport and technological line, since it considers the presence of goods at all stages of transportation – from waiting for rolling stock and free infrastructure, to the time of accumulation to the norm of mass when loading into transport units. Grain delivery in the most productive and rational way, such as multimodal – with the participation of road, rail, and water (sea) transport, is considered.

Then the time of delivery of the cargo from the primary point of accumulation to loading into the sea vessel will be:

$$\overline{t_{del.stnd}} = \overline{t_{del.auto}} + \overline{t_{del.rail}} + \overline{t_{del.ship}}, \quad (1)$$

where $\overline{t_{del.stnd}}$ – average, standard, cargo delivery time, hours; $\overline{t_{del.auto}}$ – average, standard, time of cargo delivery by motor vehicle, hours; $\overline{t_{del.rail}}$ – average, standard, time of cargo delivery by train, hours; $\overline{t_{del.ship}}$ – average, standard, time of cargo delivery by sea, hours.

The organisation of delivery by road was the delivery of grain from the primary points of accumulation and storage of grain to the elevator where the grain route is loaded and served by rail. This process was difficult from the standpoint of the variability of road routes, since it has many points of departure, and, accordingly, many grain delivery routes. The average value of grain delivery time by road largely depended on the characteristics of the entire set of delivery routes in the region of attraction to the point of loading the grain route, the required fleet of vehicles and their cargo capacity, and the time of loading and unloading the vehicle. Then the average value of the duration of grain delivery by road can be represented in implicit terms as a function of the time of accumulation of cargo mass to the loading rate ($f_{accum.auto.}$) and transportation time ($f_{transp.auto.}$):

$$\overline{t_{del.auto}} = f_{accum.auto.}(\lambda_{cargo}; N_{v.a.}) + f_{transp.auto.}(\{M_{a.i.}; M_{a.l.}\}; N_a; N_{v.a.}; t_{load.a.}; t_{unload.a.}), \quad (2)$$

$$\overline{t_{del.rail}} = f_{accum.rail}(\lambda_{cargo.rail}; N_{rail.rout.}) + f_{transp.rail.}(\{M_{rail.i.}; M_{rail.l.}\}; N_{d.c.rail}; N_{car}; N_{locom.}; N_{v.car.}; t_{load.rail.}; t_{unload.rail.}; t_{add.t.rail.}), \quad (3)$$

where $\lambda_{cargo.rail}$ – intensity of cargo arrival at the point of accumulation by road before loading into the railway route, tonnes/day; $N_{rail.rout.}$ – technological rate of loading of the railway route, tonnes; $\{M_{rail.i.}; M_{rail.l.}\}$ – set of parameters that characterise the routes of grain delivery by rail to the commercial seaport; where $N_{d.c.rail}$ – required dedicated capacity for organising ring railway routes, pairs of trains; N_{car} – required fleet of

where λ_{cargo} – intensity of cargo arrival at the storage point before loading into the truck, tonnes/day; $N_{v.a.}$ – average technical load rate of a truck, tonnes; $\{M_{a.i.}; M_{a.l.}\}$ – a set of parameters that characterise grain delivery routes by road in the region where a railway grain route is created; N_a – required fleet of trucks, units; $t_{load.a.}$ – standard time of loading the car with grain, hours; $t_{unload.a.}$ – standard vehicle unloading time, hours.

The organisation of delivery by rail is the creation of grain shipping routes as those that can technologically provide the shortest delivery time by rail. This process was complicated by the specific features of railway transport regarding the need for allocated capacity, the need for rolling stock and locomotives. The average value of grain delivery time by rail routes in most cases depends on the intensity of cargo receipts for loading wagons, the duration of technological operations at marshalling depots, the time when the train is located at transit technical stations when changing locomotives, and the time for cargo operations at loading and unloading points. The average value of the duration of grain delivery by rail can be represented as the product of the functions of the time of cargo accumulation to the rate of loading into the railway route ($f_{accum.rail.}$) and the time of transportation by grain route ($f_{transp.rail.}$):

freight cars-grain carriers, units; N_{locom} – required fleet of locomotives for organising grain routes, units; $N_{v.a.}$ – average technical loading rate of a grain carrier car, tonnes; $t_{load.rail.}$ – standard time for loading a railway route with grain, hours; $t_{unload.rail.}$ – standard unloading time of the railway route, hours; $t_{add.t.rail.}$ – additional time for organising the route at the marshalling depots and destination, hours.

For the marine transport subsystem, the key was the process of forming the cargo mass for loading into the ship and the process of servicing ships in commercial seaports. Therefore, the key time was the accumulation of cargo mass to the norm of loading into the bulk carrier and the time of servicing the ship before departure. The very process of following a ship to the destination port is quite linear and largely depends on technological aspects. So the average time of finding the cargo mass in a commercial seaport is the product of two functions – the time of accumulation of cargo to the rate of loading into a sea ship ($f_{accum.sea}()$) and the time of servicing the ship in the port when loading grain and sending it on a voyage ($f_{transp.sea}()$):

$$\overline{t_{del.tot.}} = f_{accum.sea.}(\lambda_{cargo.port.}; N_{ship}) + f_{transp.sea.}(\{M_{port.i.}; M_{port.I.}\}; N_{sea.port.}; N_{ship}); t_{load.sea.}; t_{add.t.sea.}, \quad (4)$$

where $\lambda_{cargo.port.}$ – intensity of cargo arrival at the storage point by rail before loading into a sea vessel, tonnes/day; N_{ship} – technological rate of loading of a ship, tonnes; $\{M_{port.i.}; M_{port.I.}\}$ – set of parameters that characterise grain delivery routes by rail to commercial seaports of cargo destination; $N_{sea.port}$ required dedicated processing capacity in the commercial seaport for servicing ships, vessels/day; $t_{load.sea.}$ – standard loading time of the ship with grain, hours; $t_{add.t.sea.}$ – additional time for servicing the ship in the port, h. Total grain delivery time from production points to destination port:

$$t_{del.stnd} = f_{accum.auto.}(\lambda_{cargo}; N_{v.a.}) + f_{transp.auto.}(\{M_{a.i.}; M_{a.I.}\}; N_a; N_{v.a.}; t_{load.a.}; t_{unload.a.}) + f_{accum.train.}(\lambda_{cargo.train.}; N_{train.route.}) + f_{trans.train.}(\{M_{train.i.}; M_{train.I.}\}; N_{a.c.rail.}; N_{car.}; N_{locom.}); N_{v.car.}; t_{load.rail.}; t_{unload.rail.}; t_{add.t.rail.}) + f_{accum.sea.}(\lambda_{cargo.port.}; N_{ship}) + f_{transp.sea.}(\{M_{port.i.}; M_{port.I.}\}; N_{sea.port.}; N_{ship}); t_{load.sea.}; t_{add.t.sea.}, \quad (5)$$

and the optimisation task is to minimise this time:

$$t_{del.stnd} \rightarrow \min,$$

under restrictions, in accordance with the recommendations proposed by V. Matsiuk et al. (2023) and M. Namazov et al. (2023):

$$\left\{ \begin{array}{l} N_{d.c.rail} \leq N_{avail.d.c.route}, \\ N_{sea.port} \leq p(N_a) \leq \xi_{b.v.1}, \\ \xi_{p1} \leq p(N_a) \leq \xi_{b.v.1}, \\ \xi_{p2} \leq p(N_{car}) \leq \xi_{b.v.2}, \\ \xi_{p3} \leq p(N_{locom}) \leq \xi_{b.v.3}, \\ \xi_{p4} \leq p(N_{ship}) \leq \xi_{b.v.4}, \\ \{N_a, N_{car}, N_{locom}, N_{ship}\} = total; \end{array} \right. \quad (6)$$

where $p(N_a)$, $p(N_{auto})$, $p(N_{train})$, $p(N_{ship})$ – the actual level of use of the fleet of vehicles, respectively,

the fleet of motor vehicles, railway cars, ships; ξ_{p1} , ξ_{p2} , ξ_{p3} , ξ_{p4} – lower limit of optimal use of the fleet of vehicles, respectively, the fleet of motor vehicles, railway cars and locomotives, ships; $\xi_{b.v.1}$, $\xi_{b.v.2}$, $\xi_{b.v.3}$, $\xi_{b.v.4}$ – upper limit of optimal use of the fleet of vehicles, respectively, motor vehicles, railway cars and locomotives, ships.

All functions of the optimisation model are presented implicitly, which makes their practical implementation difficult. The most appropriate and convenient way to implement this model was computer simulation.

The model was implemented on the example of grain production in the Poltava Oblast in 2021 and its further transportation for export. The main costs of time and speed of vehicles

were determined following standard norms. All demand flows and demand service intensity were the simplest and therefore subject to exponential distribution and Poisson distribution. An experiment was considered for a traffic volume of 883,560 tonnes per year.

Results and Discussion

Development of a simulation model

The simulation model of the grain delivery process in a mixed road-rail-water connection is a complex, multiphase process with many initial parameters, subsystems, and technological elements.

Modelling of the transport and technological line for grain delivery is the interaction of many transport and technological subsystems of road, rail, and sea transport. Each transport subsystem includes subsystems:

- accumulation and formation of cargo mass required to the vehicle loading rate;
- loading and operations to prepare the vehicle for the flight;
- movement of the corresponding transport unit to its destination or connection with another mode of transport.

Thus, the process of functioning of the transport subsystem can be represented as a typical algorithm (Fig. 1). Block 1 corresponds to the process of cargo arrival at the point of accumulation (temporary storage) at the point of origin or production of grain. Blocks 2 and 3 simulate the cycle of checking the sufficiency of cargo to the norm of loading into the vehicle. Block 4 defines the predefined process of finding a free transport unit and cargo means. This process can also be presented as complex, but standard and driven by a cycle of monitoring the changing situation. This block is the most important in terms of time delays due to inconsistent actions regarding the receipt of cargo, preparation of vehicles for the flight, and the creation of a sufficient number of cargo devices. Block 5

is also a predetermined process of moving a vehicle to its destination or connecting to another mode of transport is predefined, since most of them depend only on the length of the route and the average (route) speed of movement.

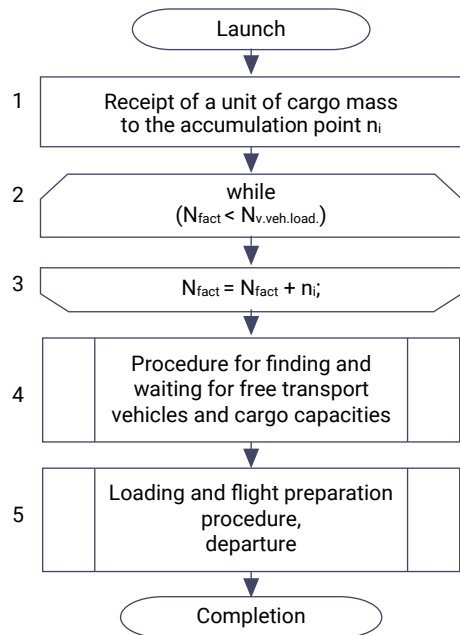


Figure 1. Algorithm of functioning of the transport subsystem of grain delivery

Note: n_i – amount of cargo arriving at the point of cargo formation for shipment; N_{fac} – actual volume of cargo available for loading into the vehicle; $N_{\text{v.veh.load.}}$ – technical loading standard for a vehicle

Source: compiled by the authors

The next step was to develop a simulation model of the grain delivery process: by road to railway loading stations; by rail grain routes to the port of destination, ship handling in the port, and departure. It is this part of the process that is more inherent in the functioning of Ukrainian transport in terms of ensuring sustainable grain exports in global supply chains. In accordance with the agent-based principle, the following agents are formed (Table 1).

Table 1. Specification of simulation model agents

| Agent name | Agent function |
|--|---|
| Automotive line | Modelling of the process of receipt and accumulation of cargo up to the normal weight of loading into a truck. Modelling of the process of managing an existing fleet of trucks. Modelling of the waiting process for free cargo devices and loading points. Modelling of truck traffic in a full cycle of cargo turnover. |
| Railway line | Modelling of the process of receipt and accumulation of cargo up to the standard weight of loading into a railway route. Modelling of the process of managing the existing fleet of freight cars and locomotives. Modelling of the waiting process for free cargo devices and loading points. Modelling of the movement of grain routes in the full cycle of cargo turnover. |
| Sea line | Modelling of the process of receipt and accumulation of cargo up to the normal weight of loading into a sea vessel (bulk carrier). Modelling of the process of managing the existing fleet of cargo vessels. Modelling of the process of waiting for free cargo capacities. Modelling of the movement of sea vessels in the full cycle of cargo turnover. |
| Warrant | Modelling of an information message about the process of cargo mass formation. |
| Truck fleet | Population of agents of the “truck” type for modelling the quality of use of the existing fleet of road transport vehicles. |
| Fleet of freight cars (grain carriers) and locomotives for organising grain routes | Population of agents of the “railway route” type to model the quality of use of the existing fleet of railway vehicles. |
| Fleet of cargo vessels (bulk carriers) | Population of agents of the “bulk carriers” type for modelling the quality of use of the existing fleet of marine vehicles. |
| Grain departure points | Population of agents of the “point of departure” type for modelling the routes of departure of vehicles with grain during the initial accumulation of grain. |
| Railway station | “Railway station” type agent for modelling the organisation of railway routes. |
| Seaport | “Seaport” type agent for modelling the organisation of a loaded grain vessel. |

Source: compiled by the authors

The interaction of these agents allowed modelling different grain delivery scenarios, considering potential delays and resource optimisation. The model helped to analyse the efficiency of each stage of transportation and identify critical points that can reduce the overall performance of supply chains.

Configuring the Main agent

The agent which ensures the interaction of all other agents with each other is the Main agent. This procedure is determined by the standard project development procedure in the Java SE de-

velopment environment (Oracle, USA). The main element of the Main agent is the space marking element – GIS map, which allows developing the processes of agent movement along the labels of existing railway, road, and sea transport maps. In addition, the Main agent includes all key parameters of the transport and technological line in the form of hyperlinks of the Parameters type:

- truckNumber_Polt – accepted number of vehicles involved in the transportation process, units;
- truckCapacity – accepted technical standard for vehicle loading (cargo capacity), tonnes;

- truckSpeed – average (route) speed of trucks, km/h;
- railNumber – accepted number of railway routes (railway cars with locomotives), units;
- railCapacity – accepted technical standard for loading (net tonnes) of a railway route, tonnes;
- railSpeed – route speed of railway routes, km/h;
- shipNumber – accepted number of sea ships, units;
- shipCapacity – accepted net deadweight, tonnes;
- shipSpeed – average (route) speed of the ship, km/h.

In addition to the presentation of the model itself, agent Main displays diagrams of statistical modelling results: delivery time and the required capacity of grain transshipment points.

Setting up the population of agents “Grain departure points”

The population of “Grain departure points” agents is initial when modelling the grain delivery process and simulates the initial accumulation of grain to the size of loading into the machine. The process itself is an ordinary discrete-event process, consisting of only two elements: the source requirements generator and the end of the sink grain receipt process (Fig. 2). The requirements generator produces a simpler (exponential) flow of requirements with a set (available) average intensity λ_{grain} with the density of the probability distribution:

$$\begin{cases} \lambda_{grain} e^{-\lambda_{grain}x}, & x > 0, \\ 0, & x < 0, \end{cases} \quad (7)$$

where λ_{grain} – average flow rate of grain requirements to the point of primary accumulation before loading into cars, tonnes/year. Each requirement generated by the source block represents one ton of grain. When a requirement for the sink element is received, an algorithm is implemented for generating an information request (Order population agent) for loading a batch of cargo ready for shipment into one truck (Fig. 3).

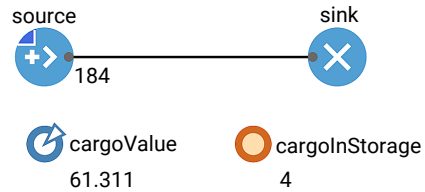


Figure 2. Discrete-event process of agent population “Grain departure points”
Source: compiled by the authors

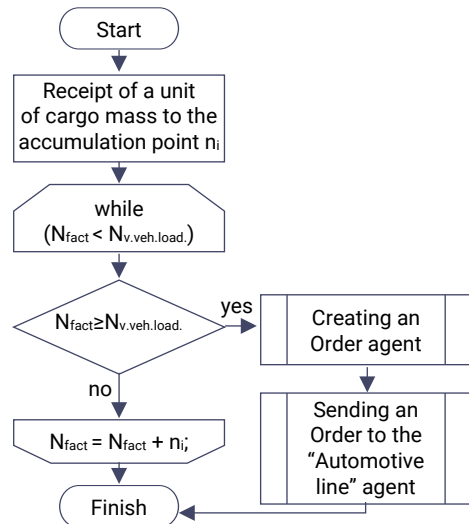


Figure 3. Algorithm for forming a population agent Order

Source: compiled by the authors

The algorithm shown in Figure 3 is implemented with each request received using Java code:

```
cargolnStorage++;
if (cargolnStorage >= main.truckCapacity){
    Order newOrder = new Order ( this );
    send ( newOrder, main.store_Poltava );
    cargolnStorage -= main.truckCapacity;
}
```

Each agent of the population “Grain departure points” simulates the process independently

of the others, thus simulating the accumulation and formation of shipments for each of the grain departure points in the selected region.

Setting up agents “Automobile line”, “Railway line” and “Sea line”

Agents “Automobile line”, “Railway line”, and “Sea line”, according to their functional purpose, intended to simulate the turnover of the corresponding vehicles when organising the transportation of a batch of goods. The process of grain transportation begins with the accumulation of grain to the required loading rate in a truck (population of agents “Grain departure points”). After receiving an information message about a sufficient amount of cargo at a certain point of departure, this message is transmitted to the Enter block of the “Automobile line” agent. Next, the information message is sent to the seize element, where a free resource is captured – a vehicle from the Truck element. In the absence of a free vehicle, the requirement for grain transportation remains pending.

If there is a free car, the full cargo turnover is simulated on the route from the point of origin of the cargo mass to the point of transshipment to the railway car:

- moveTo block – simulation of empty mileage from the place of permanent deployment to the place of loading the car;
- delay block – simulates the time spent loading the car;
- moveTo block – simulation of a cargo flight of a car to the point of reloading into a car;
- delay1 block – simulates the time spent on unloading the car.

After simulating unloading, the vehicle moves to the truck block and then presents a free resource for use. Thus, this approach makes it possible to simulate a full cycle of technological operations related to a single cargo transportation.

At the same time, the delay1 (unloading) block implements an algorithm for forming the cargo mass for the possibility of loading into railway cars (Fig. 4).

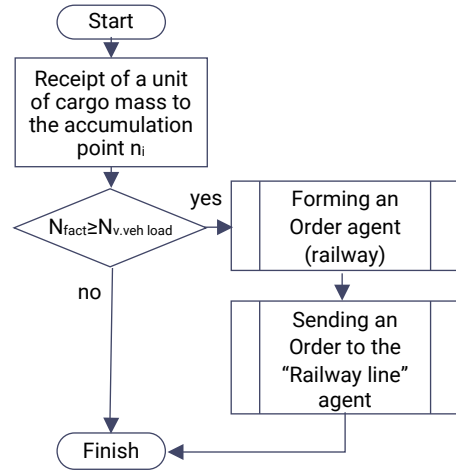


Figure 4. Algorithm for forming a cargo mass for loading into a railway shipping route

Source: compiled by the authors

The algorithm shown in Figure 4 is implemented using Java code:

```

inStorage += main.truckCapacity;
if(inStorage >= main.railCapacity){
main.railLine.source.inject(1);
inStorage -= main.railCapacity;
}
  
```

The end result of executing this code is that when the volume of cargo required for loading the sending route is accumulated, an information message is created in the railway line agent. The procedure for simulating the turnover of a railway departure route and servicing a sea vessel (bulk carrier) in the port is essentially similar to the agent “Automobile line”. All technological operations in these agents – movement, loading, unloading, etc. – can be simulated as discrete or continuous values.

The presented approach simulates centralised management of the vehicle fleet on the cargo delivery network. This approach is especially relevant for the organisation of distribution logistics by road, where there are many points of origin of cargo and grain consolidation warehouses.

In addition, it is also advisable to apply this approach for railway transport, since there may also be several stations for creating grain routes that will act as route bases within the same transport and technological line.

Even with an extended simulation of grain exports from Ukraine, there may be a problem in using several alternative sea grain terminals in different ports at once, which will also allow simulating an extensive network.

Ensuring the reliability of modelling results

The modelling process in the developed simulation model is stochastic and is based on the model runtime. For such models, the simulation result in most cases depends on the duration of the model time and the total number of replications of experiments. This method is valid only when the simulation result, as a random variable, is subject to a normal distribution (Matsiuk *et al.*, 2023; Namazov *et al.*, 2023).

Therefore, to establish the minimum required number of replications and the minimum required model time, a series of experiments was

performed, where the key and system parameter of the simulation measurement is the total time of grain delivery on land, from the point of origin of cargo to the sea trade terminal. First of all, the sample of the general set of experimental data is tested for the hypothesis of approximation by a normal law.

Thus, even with a model time of 3 months, a single replication is sufficient to provide 95% confidence (Table 2).

Simulation results

As a result of experiments for the volume of traffic in 883,560 tonnes per year, the following results were obtained:

- optimal fleet of motor vehicles: 50 units with an average load of 63%;
- optimal fleet of railway routes: five units with an average load of 57%.

Average delivery time of a batch of goods:

- by car: 6.5 hours with a standard deviation of 0.323 hours (Fig. 5a);
- by rail: 82,996 hours with a standard deviation of 7,057 hours (Fig. 5b).

Table 2. Results of estimating the mathematical expectation and standard deviation of samples

| Duration of model time | | 1 month | 3 months | 6 months | 12 months | 30 months |
|------------------------|-------------------------------|---------|----------|----------|-----------|-----------|
| Confidence interval | Left limit of conf. interval | 91.877 | 91.883 | 91.885 | 91.887 | 91.890 |
| | M(x) | 91.891 | 91.891 | 91.891 | 91.891 | 91.891 |
| | Right limit of conf. interval | 91.906 | 91.900 | 91.898 | 91.896 | 91.893 |
| Number of replications | Calculated value | 2.47 | 0.87 | 0.50 | 0.22 | 0.11 |
| | Limit integer value | 3 | 1 | 1 | 1 | 1 |

Source: compiled by the authors

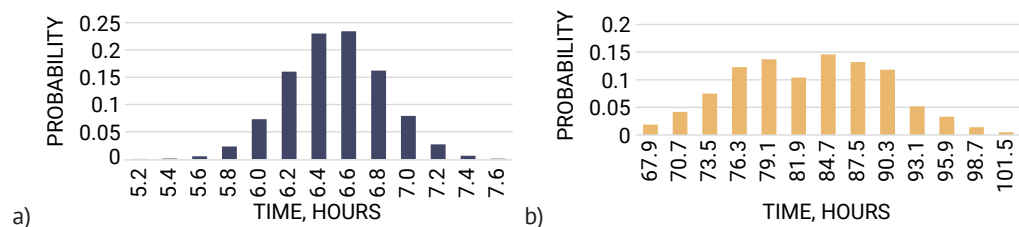


Figure 5. Densities of the probability distribution of the time of stay of the cargo shipment

Note: a) in the road transport subsystem; b) in the railway transport subsystem

Source: compiled by the authors

Maximum cargo volume observed in the transit grain elevator:

- at the railway station 4000 tonnes;
- there are 52,000 tonnes in the commercial seaport.

The presented simulation model optimises the total transportation time (5), (6) in a complex grain supply chain on the network of cargo flow origination. Through the use of GIS technologies, an agent-based and discrete-event approach in one common process, delivery times in road, rail, and water transport and technology systems are optimised (Fig. 2-4).

The model is implemented as interaction at docking points – grain cargo terminals – of individual technological processes of vehicle turnover on the grain cargo flow service network.

The model is developed using agent-based and discrete-based principles in the AnyLogic University Researcher simulation model development environment. Since AnyLogic University Researcher does not provide standard tools for some processes, namely managing oncoming vehicle flows, this subprocess was implemented via Java algorithms (Fig. 3, 4).

The simulation involves the interaction of ten populations of agents and individual agents with each other (Table 1). All agents can be divided into three parts:

- 1) rolling stock parks;
- 2) infrastructure facilities and communication routes;
- 3) informational messages about cargo shipments.

This approach, in contrast to the research by N. Shramenko & V. Shamenko (2020) allowed applying a systematic approach and evaluating the entire transportation process at once by one aggregate criterion – the average cargo delivery time, in accordance with the objective function of the optimisation model (5) and its constraints (6).

The obtained average time and the density of its distribution by transport subsystems (Fig. 5) are normal, which indicates the “naturalness” and reliability of the technological process. In

contrast to the studies by V. Blazek *et al.* (2024), the developed approach allowed applying multi-criteria optimisation. The main optimisation criterion is the average delivery time. In addition, the vehicle fleets themselves have optimal use. This approach is not often implemented, as evidenced by the review by T. Peregrin & R. Stankovic (2023).

A significant number of specialists see the solution to security and efficiency issues in the use of modern information technologies. Thus, at the design stage of transport processes, N. Shramenko & V. Shamenko (2019) offer mathematical models that optimise the parameters of the entire supply chain based on the time criterion. However, the researchers do not point out the possibility of optimal loading of the vehicle fleet and do not fully use probabilistic distributions of the time of technological operations, such as loading, unloading or time in motion of the vehicle. The same situation is observed in another study, where N. Shramenko & V. Shamenko (2020) offer a simulation model of the intermodal transport supply chain. This study also uses only one criterion for finding optimal solutions.

V. Butkovsky & O. Ilina (2023) consider the problems of grain storage not only during storage, but also during transportation. Researchers limit humidity standards and optimise the volume of cargo according to the criterion of safety during transportation. However, the researchers do not focus on the specifics of delivery by different modes of transport, which complicates the decision-making process for organising specific transportation.

Many researchers continue to present transport processes as multi-channel queuing systems, but it is computer modelling of transport processes and systems that is becoming increasingly widespread. This technology opens up very great opportunities for modelling transport processes and systems. A. Gupta *et al.* (2023) prove the possibility of using a systematic approach, multi-element, multi-factorial, and multi-criteria in the study of transport processes, therefore, it

is computer modelling of multiphase and complex processes that is most appropriate when studying the problems of the presented study. A similar conclusion can be drawn from the study by M. Ďuriška *et al.* (2024), which presents a multi-factor simulation model developed using the agent-based principle. The presented models have a large abstraction, which cannot provide the proper level of reliability and adequacy.

The proposed simulation model can use the average level of CO₂ emissions over the entire complex transportation route as an optimisation criterion. In the study of this problem, M. Kumari *et al.* (2023) optimise supply chains based on the average CO₂ emissions per unit of transportation work. The researchers introduce such a concept as an integrated approach to supply chain optimisation solutions. Optimisation is carried out by developing mathematical models and conducting a series of experiments on the model sensitivity. The researchers claim significant economic effects from minimising CO₂ emissions, but do not provide specific measures of cost-effectiveness. C. de Faria *et al.* (2024) in their study cite the results of the creation of a national network of interval grain supply chains in Brazil. This situation partially coincides with the realities of the Ukrainian transport system, since road, rail, and sea transport are involved in the transportation of mass volumes of grain. The researchers cite the results of estimating the total CO₂ emission during grain transportation and propose an approach to sustainable development of the national transport system, which provides for reducing CO₂ emissions by 66.8 thousand tonnes per year. The solution is based on optimising the network of grain cargo mass accumulation points and maximising the use of electric railway transport.

In addition, an important achievement compared to other similar studies, A. Adenle *et al.* (2019) determine the importance of a systematic approach in evaluating the efficiency of any production. Using the example of agricultural business, researchers determine the key role of

transport as a narrowing link in the supply of raw materials and final products. However, the paper does not provide specific decision-making tools.

During the entire modelling period, the maximum capacity of track development of railway stations should accommodate and organise one train (net weight 4,000 tonnes), the terminal capacity in a commercial seaport is 52,000 tonnes.

The model does not consider the actual degree of use of port land routes and the seasonal unevenness of grain cargo formation. In addition, the model does not implement possible failures and stops due to possible technical malfunctions of vehicles and transport infrastructure. The further development of the presented research can be the creation of automated systems in the management of the transportation process, and consideration of the above.

Conclusions

The paper formalises the process of grain delivery in global supply chains by means of an optimisation mathematical model in the form of an objective function that formalises the average time of cargo delivery in a complex, multi-phase, intermodal grain supply chain involving: a road network for the supply of grain mass and its primary accumulation at points of connection with railway transport; a railway transport network with the organisation of railway shipping routes; the maritime transport network and the accumulation of cargo at the grain terminal to the loading rate for a sea vessel. Restrictions on the model provide for an optimal level of vehicle usage. The model is presented as a multi-criteria optimisation mathematical model.

Since most of the optimisation model functions are represented in an implicit expression, the model is implemented as a computer simulation. The simulation model is developed using agent-based and discrete-event principles with developed additional functions (Java, Oracle) for managing oncoming vehicle flows. The simulation model is implemented as a set of technological processes of vehicle turnover with their

interaction at docking points – cargo terminals. This principle provided a systematic approach in estimating the average delivery time of a unit of cargo mass, ensured optimal use of the fleet of vehicles, and assessed the actual loading of planned cargo flows to the transport and warehouse infrastructure of the transport and technological line.

As a result of the implementation of the simulation model and conducting a series of experiments on the example of the grain supply chain from the Poltava Oblast (in the amount of 883,560 tonnes), optimal fleets of cars (load factor 63%), railway shipping routes (load factor 57%) were determined. The average time for grain delivery by land was 6.5 hours (by road subsystem) and 83 hours (by rail subsystem). The density of delivery time distribution within each transport and technological line is normal, which indicates the

naturalness and optimality of the calculated technological parameters. A separate result of experiments is the determination of the actual volume of cargo mass simultaneously located at cargo terminals. This approach helped to establish the required capacity of grain elevators at the primary level of cargo mass formation (automobile – railway connection points) and the second level of cargo mass formation (commercial seaports).

A further area of research on the presented issues may be the substantiation and development of effective automated control systems for the grain transportation process in multimodal traffic.

Acknowledgements

None.

Conflict of Interest

None.

References

- [1] Adenle, A.A., Wedig, K., & Azadi, H. (2019). Sustainable agriculture and food security in Africa: The role of innovative technologies and international organizations. *Technology in Society*, 58, article number 101143. doi: [10.1016/J.TECHSOC.2019.05.007](https://doi.org/10.1016/J.TECHSOC.2019.05.007).
- [2] Aulin, V., Rogovskii, I., Lyashuk, O., Titova, L., Hrynkiv, A., Mironov, D., Volianskyi, M., Rogatynskyi, R., Solomka, O., & Lysenko, S. (2024). Comprehensive assessment of technical condition of vehicles during operation based on Harrington's desirability function. *Eastern-European Journal of Enterprise Technologies*, 1(3(127)), 37-46. doi: [10.15587/1729-4061.2024.298567](https://doi.org/10.15587/1729-4061.2024.298567).
- [3] Blazek, V., Vantuch, T., Slanina, Z., Vysocky, J., Prokop, L., Misak, S., Piecha, M., & Walendziuk, W. (2024). A novel approach to utilization vehicle to grid technology in microgrid environment. *International Journal of Electrical Power & Energy Systems*, 158, article number 109921. doi: [10.1016/J.IJEPES.2024.109921](https://doi.org/10.1016/J.IJEPES.2024.109921).
- [4] Butkovsky, V.A., & Ilina, O.A. (2023). Grain storage. In *ICC handbook of 21st century cereal science and technology* (pp. 199-206). Cambridge: Academic Press. doi: [10.1016/B978-0-323-95295-8.00015-0](https://doi.org/10.1016/B978-0-323-95295-8.00015-0).
- [5] de Faria, C.H.F., Almeida, J.F.F., & Pinto, L.R. (2024). Simulation-optimisation approach for sustainable planning of intermodal logistics in the Brazilian grain export industry. *Decision Analytics Journal*, 10, article number 100388. doi: [10.1016/J.DAJOUR.2023.100388](https://doi.org/10.1016/J.DAJOUR.2023.100388).
- [6] Ďuriška, M., Neradilová, H., Fedorko, G., Molnár, V., & Mikušová, N. (2024). Use of non-fungible tokens for proof of ownership and originality of simulation model in logistics. *Simulation Modelling Practice and Theory*, 134, article number 102949. doi: [10.1016/J.SIMPAT.2024.102949](https://doi.org/10.1016/J.SIMPAT.2024.102949).
- [7] Garg, S., Nelson, P.R., & Swapnila, R. (2023). Smart agriculture and nanotechnology: Technology, challenges, and new perspective. *Advanced Agrochem*, 3(2), 115-125. doi: [10.1016/J.AAC.2023.11.001](https://doi.org/10.1016/J.AAC.2023.11.001).
- [8] Gupta, A., Pal, B., Jindal, A., Bhatia, N., & Gupta, A.K. (2023). Modelling of transport processes: Theory and simulations. *MethodsX*, 10, article number 101966. doi: [10.1016/J.MEX.2022.101966](https://doi.org/10.1016/J.MEX.2022.101966).

- [9] Kumari, M., De, P.K., Narang, P., & Shah, N.H. (2023). Integrated optimization of inventory, replenishment, and vehicle routing for a sustainable supply chain utilizing a novel hybrid algorithm with carbon emission regulation. *Expert Systems with Applications*, 220, article number 119667. doi: [10.1016/j.eswa.2023.119667](https://doi.org/10.1016/j.eswa.2023.119667).
- [10] Matsiuk, V., Opalko, V., Savchenko, L., Zagurskiy, O., & Matsiuk, N. (2023). Optimisation of transport and technological system parameters of an agricultural enterprise in conditions of partial uncertainty. *Machinery & Energetics*, 14(3), 61-71. doi: [10.31548/machinery/3.2023.61](https://doi.org/10.31548/machinery/3.2023.61).
- [11] Ministry of Agrarian Policy and Food of Ukraine. (2024). *Export*. Retrieved from <https://minagro.gov.ua/napryamki/eksport-do-krain-ies>.
- [12] Namazov, M., Matsiuk, V., Bulgakova, Iu., Nikolaienko, I., & Vernyhora, R. (2023). Agent-based simulation model of multimodal iron ore concentrate transportation. *Machinery & Energetics*, 14(1), 46-56. doi: [10.31548/machinery/1.2023.46](https://doi.org/10.31548/machinery/1.2023.46).
- [13] Pereglin, T., & Stankovic, R. (2023). Optimizing vehicle utilization in the cold chain: Literature review. *Transportation Research Procedia*, 73, 167-176. doi: [10.1016/j.trpro.2023.11.905](https://doi.org/10.1016/j.trpro.2023.11.905).
- [14] Rogovskii, I., Sivak, I., Shatrov, R., & Nadochiy, O. (2024). Agroengineering studies of tillage and harvesting parameters in soybean cultivation. *Engineering of Rural Development*, 23, 965-970. doi: [10.22616/ERDev.2024.23.TF195](https://doi.org/10.22616/ERDev.2024.23.TF195).
- [15] Sharifi, E., Amin, S.H., & Fang, L. (2024). Designing a Sustainable, resilient, and responsive wheat supply chain under mixed uncertainty: A multi-objective approach. *Journal of Cleaner Production*, 434, article number 140076. doi: [10.1016/j.jclepro.2023.140076](https://doi.org/10.1016/j.jclepro.2023.140076).
- [16] Shramenko, N., & Shramenko, V. (2020). [Simulation model of the process of delivering small consignments in international traffic through the terminal system](#). In *2020 international scientific and practical conference* (pp. 443-454).
- [17] Shramenko, N.Y., & Shramenko, V. (2019). Optimization of technological specifications and methodology of estimating the efficiency of the bulk cargoes delivery process. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 3, 146-151. doi: [10.29202/nvngu/2019-3/15](https://doi.org/10.29202/nvngu/2019-3/15).
- [18] U.S. Department of Agriculture. (n.d.). Retrieved from <https://www.usda.gov>.
- [19] Yablonskyi, P., Rogovskii, I., Sobczuk, H., Virchenko, G., Volokha, M., & Vorobiov, O. (2024). Computational approach to geometric modeling of plow bodies. *Journal of Engineering Sciences (Ukraine)*, 11(1), E9-E18. doi: [10.21272/jes.2024.11\(1\).e2](https://doi.org/10.21272/jes.2024.11(1).e2).
- [20] Zagurskiy, O., Duczmal, W., Savchenko, L., & Ohienko, M. (2024). Models of formation of reliability of supply chains for the supply of agricultural products. *Research on World Agricultural Economy*, 5(3), 14-23. doi: [10.36956/rwae.v5i3.1123](https://doi.org/10.36956/rwae.v5i3.1123).

Розробка імітаційної моделі доставки зернових у глобальних ланцюгах постачання

Юрій Хоменко

Аспірант

Український державний університет науки і технологій

49010, вул. Лазаряна, 2, м. Дніпро, Україна

<https://orcid.org/0009-0003-2386-0062>

Вячеслав Мацюк

Доктор технічних наук, професор

Національний університет біоресурсів і природокористування України

03041, вул. Героїв Оборони, 15, м. Київ, Україна

<https://orcid.org/0000-0003-2355-2564>

Андрій Огороков

Кандидат технічних наук, доцент

Український державний університет науки і технологій

49010, вул. Лазаряна, 2, м. Дніпро, Україна

<https://orcid.org/0000-0002-3111-5519>

Олександр Горобченко

Доктор технічних наук, професор

Державний університет інфраструктури та технологій

04071, вул. Кирилівська, 9, м. Київ, Україна

<https://orcid.org/0000-0002-9868-3852>

Анотація. Основні експортні відправлення зернових в Україні здійснюються через морські торговельні порти Чорного моря, при цьому складний і багатофазний процес транспортування створює затримки та призводить до додаткових витрат у пунктах стикування різних видів транспорту. Метою дослідження був процес транспортування зернових вантажів на експорт через морські торговельні порти. Україна є розвинутою аграрною країною, що забезпечує виробництво значної частки світового обсягу зернових, більша частина яких спрямовується на експорт. Розроблена в роботі оптимізаційна імітаційна модель мультимодального перевезення зернових вантажів, на відміну від існуючих, являє собою багатофазний процес із множиною вихідних параметрів, підсистем та технологічних елементів, що адекватно відображають всі складові технологічного процесу організації перевезення автомобільним, залізничним та морським транспортом, та дає можливість оптимізувати ці процеси. Модель складалася з декількох транспортно-технологічних підсистем, кожна з яких відповідала процесу транспортування зернових автомобільним, залізничним або водним транспортом. В якості критерію оптимальності обрано мінімум загальної тривалості перевезення вантажу від місця зародження до моменту відправки зернового вантажу на експорт морським транспортом. Для встановлення мінімально-необхідної кількості реплікацій та мінімально-необхідного модельного часу, виконана серія експериментів, де ключовим та системним параметром заміру моделювання виступає загальний час доставки зерна по суходолу, від пункту зародження вантажу до морського торговельного терміналу. В результаті моделювання встановлено оптимальну кількість рухомого складу різних видів транспорту та час перевезення по кожній фазі процесу. Логістичні оператори агропромислового сектору можуть застосувати модель для вдосконалення маршрутів і схем доставки зернових, оцінки та вдосконалення технологічних параметрів, мінімізації часу та витрат на транспортування

Ключові слова: агентна імітаційна модель; Java SE (Oracle); AnyLogic University Researcher; технологічний процес; мінімізація часу доставки; оптимізація бізнес процесу