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Optimisation of transport and technological system parameters of an agricultural enterprise in conditions of partial uncertainty

Abstract. At the stage of production of a wide range of agricultural products, to ensure the smooth operation of agricultural enterprises, it is necessary to solve the problems of fast and efficient delivery of relevant equipment, spare parts, and consumables with the rational use of available production resources. The research aims to improve the transport and technological system for the supply of orders in the form of consignments to meet the needs of the production activities of an agricultural enterprise. For this purpose, an simulation model was developed in the AnyLogic University Researcher environment using the Java compiler, since this toolkit allows simultaneously combining discrete-event and agent-based approaches. The model was implemented on the example of an enterprise of a separate subdivision of the National University of Life and Environmental Sciences of Ukraine "Agronomic Research Station". As a result, a comprehensive, optimisation mathematical model of the supply of goods on an extensive network of road routes using the agricultural

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enterprise's fleet of vehicles under conditions of partial uncertainty was obtained. In the course of experiments and calculations based on the real process of an agricultural enterprise, a range of values of the size of the truck fleet that meets the optimisation conditions has been found. It has been determined that the range of values close to the optimal size of the unloading truck fleet varies from 9 to 14 units. It has been established that the values of the optimisation criterion describing the average delivery time from the beginning of the need for an order to the moment of its delivery vary from 9.96 to 12.78 hours. The limit level of load of the transport and technological system is determined, at which the limit level of technological fault tolerance is ensured. It is 135 or more orders per year for each supplier with an estimated fleet of 12 trucks. The results of the study, such as the use of analytical tools and algorithms to optimise routes and allocate resources, can be used to improve transport efficiency, and help companies choose the most profitable and environmentally friendly routes for transportation

Keywords: agent-based simulation; vehicle fleet composition; technological fault tolerance; distribution logistics; component supply

INTRODUCTION

Global agricultural supply chains play a crucial role in ensuring the availability and accessibility of food for the world's population. As the world's population grows, demand for agricultural products is increasing, putting pressure on existing supply chains. By adopting technological innovations such as blockchain, vertical farm integration strategies, and precision agriculture, these supply chains will be better able to meet the needs of a growing global population and contribute to a more sustainable and equitable future (Latest agri-food trade report..., 2023).

The efficiency and performance of global agricultural supply chains are ensured by infrastructure components: transport systems, including road, rail and maritime networks, storage and warehousing systems, communications and connectivity that allow for information exchange, coordination, and digitalisation. Agricultural supply chains are complex networks that involve many stakeholders, including agricultural associations, farmers, cooperatives and agricultural processing organisations, wholesalers, retailers, and consumers.

M. De Bok & L. Tavasszy (2018) noted that modern agro-industrial enterprises are powerful high-tech industries with complex equipment that requires special and timely maintenance. To ensure the proper working condition of such equipment, enterprises periodically purchase spare parts from planned and unplanned deliveries, expendables and components, and other materials representing small and medium-sized consignments. The supply network through a variety of different suppliers is usually quite extensive. Coordinating and managing the movement of goods from the point of origin to the end customer is critical to success. R. Granillo-Macías (2021) argues that to ensure the efficiency and effectiveness of distribution logistics operations, several factors must be considered, including delivery efficiency, real-time tracking and visibility, regulatory compliance, technology, sustainability, and customer service.

The provision of transport services on an extensive network of routes, due to the need for unscheduled procurement, can be considered partially unpredictable. At the same time, according to L. Leng *et al.* (2020), and A. Bekrar *et al.* (2021), it can be seen that with significant volumes of deliveries, it is advisable to maintain its fleet of vehicles. In such cases, the issue of fleet optimisation always arises, both in terms of size and equipment. Thus, there is a certain scientific and applied task of developing models and methods for planning distribution logistics on the network of planned and unplanned purchases and deliveries under conditions of partial uncertainty. P.T.W. Lee *et al.* (2022), and G. Zhang (2023) have sufficiently covered the issues of improving the efficiency of transport processes and systems, optimising the technological parameters of supply chains, improving technological schemes and models of cargo flow management. A. Prokhorchenko *et al.* (2019) study the problem of the safe operation of critical transport infrastructure in conditions of partial uncertainty of the occurrence and elimination of the consequences of unauthorised interference. At the same time, these studies do not study the intra-technological conflicts inherent in the stochastic phenomena of transport processes. Stress test modelling, in particular agent-based simulations, is a fairly common practice in various fields of activity (Cichosz, 2020; Muñoz & Iglesias, 2021). However, such studies have not been conducted for transport and technological systems due to the accepted "safe" reliability threshold.

Thus, the issue of distribution logistics has been sufficiently studied, including with the help of agent-based simulation. However, there are not enough examples of optimisation of vehicle fleet parameters under conditions of partial uncertainty and stochasticity of transport processes. In addition, the issue of stress tests of the functioning of transport and technological processes has not been sufficiently studied. Therefore, the purpose of the study was to develop measures to improve the transport and technological system for the delivery of small consignments of goods under the condition of centralised fleet management. To achieve the goal of the plan, it was necessary to solve the following tasks: to develop a simulation model of the process of small consignments distribution under the condition of centralised management of the vehicle fleet; to optimise the parameters of the transport and technological system for small consignments distribution under the condition of centralised management of the vehicle fleet.

MATERIALS AND METHODS

One of the main indicators of the efficiency of logistics systems is the regularity and timeliness of delivery with the rational use of available production resources. The criterion for optimal planning and implementation of technological processes of cargo delivery is the average delivery time from the moment the order is required to be delivered to the moment it is delivered:

$$T_{avg} = f_{pr}(a_1, \ldots, a_n; p(a_1), \ldots, p(a_n)) \rightarrow \min, \quad (1)$$

where $a_1, \ldots, a_n$ – set of possible parameters of the fleet of vehicles, delivery routes, order conditions, suppliers working hours, etc.; $p(a_1), \ldots, p(a_n)$ – probabilistic description of the conditions for the use of the corresponding production resource and the conditions of the organization of supply.

The focus of optimisation was to reduce the selected indicator. The average delivery time was broken down into fixed and variable components:

$$T_{avg} = \overline{t}_{route} + \overline{t}_{technological\ downtime.} + \overline{t}_{unproductive\ downtime.}, \quad (2)$$

where $\overline{t}_{route}$ – truck driving time; $\overline{t}_{technological\ downtime}$ – technological downtime of trucks during scheduled operations: loading, unloading, etc.; $\overline{t}_{unproductive\ downtime}$ – time of unproductive downtime in the form of delays arising from technological conflicts due to the stochastic nature of transport and technological processes and the discrepancy between the processing capacity of the transport system and its loading volumes.

Elements $\overline{t}_{route}$ and $\overline{t}_{technological\ downtime}$ depend on the physical and technical characteristics of the transport system parameters, and therefore can be considered constant during operation. Whereas the element $\overline{t}_{unproductive\ downtime}$ is a variable component, which in most cases arises due to the unpredictability of the situation. Therefore, the optimisation of the objective function was to minimise the component $\overline{t}_{unproductive\ downtime}$ which theoretically, depending on the level of conflict, can vary within $\overline{t}_{tunproduct.downtime} = [0, \infty]$.

Given that the process of ordering components, spare parts, and other materials for the needs of agricultural companies is partially unpredictable, and this applies to both the possible delivery route and the time of the order, the entire technological process of order delivery and the use of vehicles was considered quasi-stochastic. Under such conditions, the request for the use of existing production resources (vehicles, staff time) should be optimal, and therefore their degree of use (utilisation) should be within limits:

$$\begin{array}{l} \xi_r \leqslant \varphi_{truck}(a_1, \ldots, a_n), \\ \xi_u \geqslant \varphi_{truck}(a_1, \ldots, a_n), \end{array} \quad (3)$$

where φ_{truck} – the average load of vehicles, which corresponds to the part of the time of direct use of the vehicle relative to the total time of its operation; ξ_u – the limit of rational use of the selected production resource; ξ_r – limit of reliability (fault tolerance) of the use of the selected production resource.

At that time, the optimisation model was as follows:

$$\begin{gathered} \bar{t}_{route} + \bar{t}_{technological\ downtime} + \bar{t}_{unproductive\ downtime} = \\ = f_{pr}(a_1, \ldots, a_n; p(a_1), \ldots, p(a_n)) \rightarrow min \\ \begin{cases} \xi_r \le \varphi_{truck}(a_1, \ldots, a_n), \\ \xi_u \ge \varphi_{truck}(a_1, \ldots, a_n). \end{cases} \end{gathered} \quad (4)$$

Since the objective function had a significant set of parameters and was presented in an implicit form, one of the possible solutions to this problem was to develop and implement a simulation model. The simulation model represented the interaction of agents, most of which had a discrete-event formalisation (Table 1):

Table 1. Simulation model agents

Agent Name	Agent function	Agent task
Main	Base model agent	The main window of the model presentation.
Suppliers	The population of "Suppliers" agents with a set of coordinates on the suppliersPoints GIS map	Simulation of the work of suppliers of goods for the needs of agricultural production
BusinessProcess	Agent of the technological process of order delivery	Simulation of the process of receiving an order, planning, and organising the delivery of an order by a fleet of own trucks
Truck	The population of agents "Truck fleet"	Simulation of a fleet of vehicles ready for dispatch
Order	The population of agents of the "order" type	Simulation of an information order for the delivery of goods with a set of required characteristics: supplier, quantity of goods (cargo), terms of delivery.

Note: GIS – geographic information system
Source: compiled by the authors

The entire technological process of supplying own truck fleet begins with the receipt of an order, which can be formalised as an information message with a set of characteristics:

$$M = \{m_1, \ldots, m_n\}, \qquad (5)$$

where m_1, ..., m_n – a set of information characteristics: point of departure, time of departure, amount of cargo, conditions of transportation, etc.

The information message is received by the dispatcher, after which the transport is planned as a sequence of organisational measures:

$$N = \{n_1, \ldots, n_n\}, \qquad (6)$$

where n_1, ..., n_n – a set of organizational actions of the dispatching point, which is mostly associated with the choice of the required (according to the technical conditions of the M_i order) truck among currently available vehicles, documenting the route, etc.

The simulation model was implemented in the AnyLogic 8.7 environment using the Java compiler. The chosen development environment allows to implementation of business processes of goods supply through a combination of agent-based and discrete-event approaches. The main tools for modelling dynamic transport processes and recording changes in the state of system elements in each agent were the units of the *Enterprise* and *Ststchart* libraries built into *AnyLogic*.

The adequacy of the model was checked by comparing the results of the baseline experiment with the normative indicators of the work performed by the enterprise of the separate subdivision of the National University of Life and Environmental Sciences of Ukraine "Agronomic Research Station". The reliability of the results was ensured by determining the minimum number of replications and the minimum required modelling time. A level of reliability of at least 95% (with an error probability of no more than 5%) will be achieved with a minimum of ten replications and six months of simulation time.

RESULTS AND DISCUSSION

The *Enterprise library* allowed us to model various stages, such as the arrival of vehicles for loading, transportation to the unloading point, unloading, return with empty mileage, as well as all inter-operational downtime (Fig. 1).

Initial conditions and key parameters are summarised in Table 2.

Built-in GIS mapping technology was used to create a network of possible supply routes (Fig. 2).

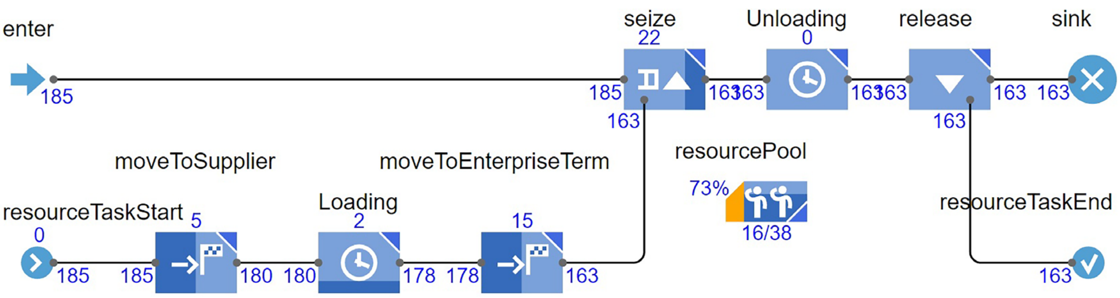


Figure 1. Discrete-event simulation of the technological process of order supply and turnover of trucks
Source: compiled by the authors

Table 2. Initial parameters of the simulation model implementation

Parameter	Value	Note
Supplier locations	Vinnytsia, Dnipro, Zhashkiv, Zhytomyr, Kyiv, Lviv, Kharkiv, Odesa, Sumy, Kherson, Zaporizhia, Khmelnytskyi, Cherkasy.	
Location of the company's cargo terminal	Pshenychne, Vasylkiv district, Kyiv region.	
The average intensity of orders from each supplier	1 in a week 52 in a year.	Exponential distribution
Drivers' working week, working conditions	5 days, irregular working hours.	
Average vehicle speed on the route	50 km/h	

Continued Table 2.

Parameter	Value	Note
Time spent by the vehicle at the loading point	8 hours	The distribution of the indicator is triangular [0.95*t*; *t*; 1.25*t*].
Average time spent at the unloading point	8 hours	The distribution of the indicator is triangular [0.95*t*; *t*; 1.25*t*].

Source: compiled by the authors

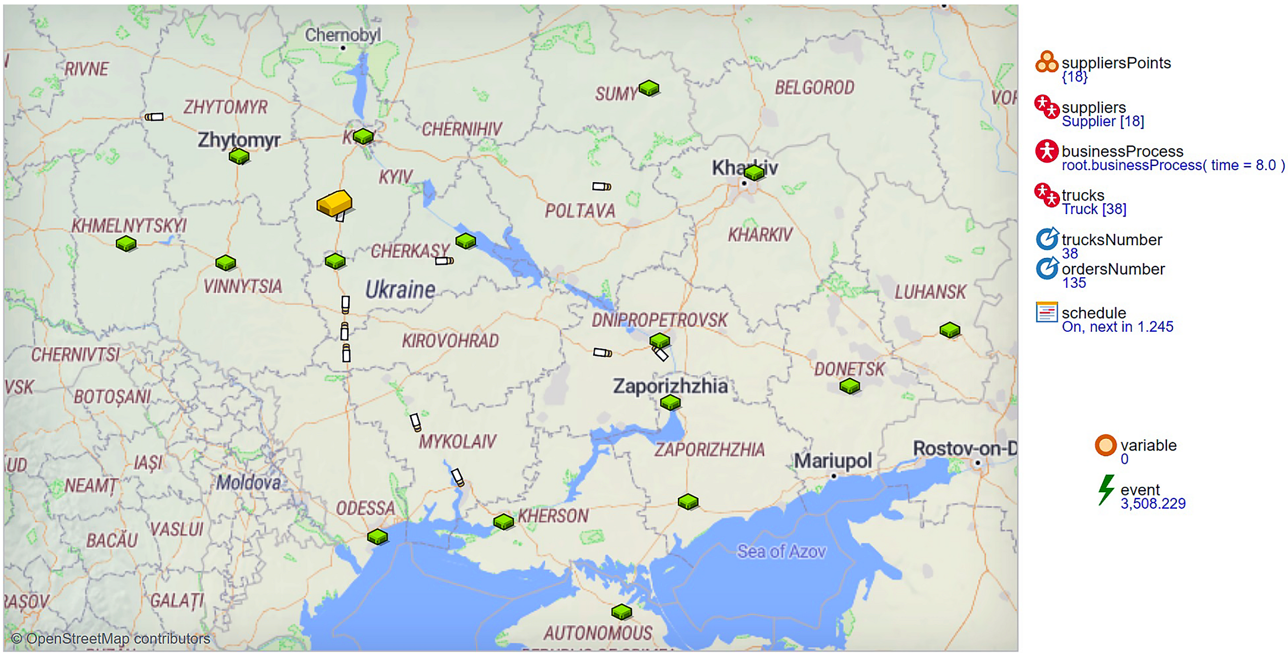


Figure 2. General view of the GIS map with supply points and possible routes at the presentation of the agent's Main
Source: compiled by the authors

The modelling of the emergence and formation of purchase orders is carried out by a population of Supplier agents (Fig. 3) using a discrete transition at a set intensity that simulates the random occurrence of the need to purchase goods according to an exponential distribution with an average intensity of *n* orders per week.

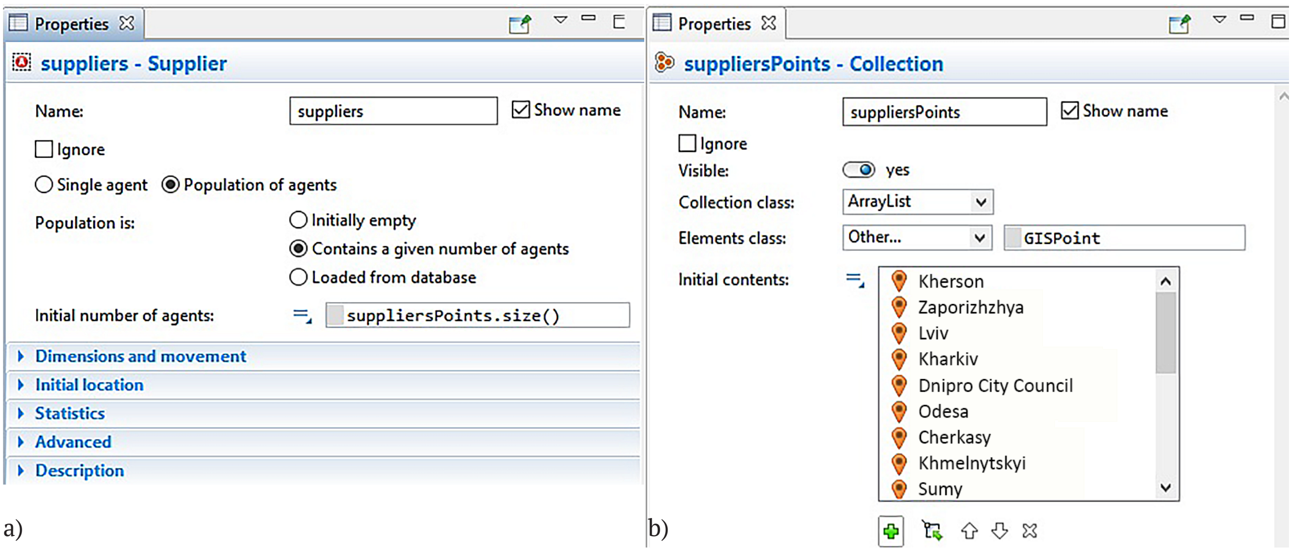


Figure 3. Discrete-event process of forming (generating) new supply orders in the agents of the population *Suppliers*
Note: a – agents of the population *Suppliers*; b – the process of forming new orders
Source: compiled by the authors

When the need for an order arises, a new agent of the *Order* type is generated using the corresponding Java code:

"Order order = **new** Order (**this**);
send (order, main.businessProcess);".

An instance of the *Order* class is passed to the *BusinessProcess* agent for processing. The simulation of the technological process of supplying goods by own car fleet is carried out in the *BusinessProcess* agent. The *seize* block simulates the processing of an order and the "seizure" of the necessary resources to process the order. The resource is a free truck that is located in the *resource pool* block – a fleet of vehicles.

In a situation where there are no available trucks, the order waits for its turn. If there is a free truck, control is transferred to the first subprocess, which simulates the first part of the truck's production cycle – driving to the loading point and loading: *resourceTaskStart* – the start of using a resource of the *truck* type.

The second subprocess begins with the *release* block and corresponds to the second half of the truck's production cycle – the return route and unloading of the order at its cargo terminal. To make the model more adequate, the simulation implements a scenario for scheduling access to the fleet of vehicles through the *scheduling* tool. This approach allows you to set the working hours of drivers during the days of the week.

To establish the optimal value of the number of trucks, an optimisation experiment was created in AnyLogic, based on the optimisation model (4). The model delivery time is defined as the time interval between the time a new order leaves the *Unloading* block and the time this order enters the *entered* block:

"dataTimeOrderIn.add(time() – timeInOrder);"

The validation of the software code was carried out step by step with the compilation of the Java code of all agents separately. The developed simulation models adequately simulate the transport and technological process of supplying orders from a plurality of suppliers on an extensive network of transport links. As a result of the development of the simulation model, it was possible to consider the variability of delivery routes in the conditions of the existing road transport infrastructure of Ukraine, as well as the Poisson nature of the receipt of orders for transportation.

As a result of the optimisation experiments and calculations based on the real process of an agricultural enterprise, a range of values of the indicator that meets the conditions of the optimisation model (4) was obtained (Fig. 4): from 9 to 14 trucks. At the same time, the average order delivery time, which is the optimisation criterion, varies from 9.96 to 12.78. For calculations, the option corresponding to the middle of the range was chosen, i.e., 12 trucks.

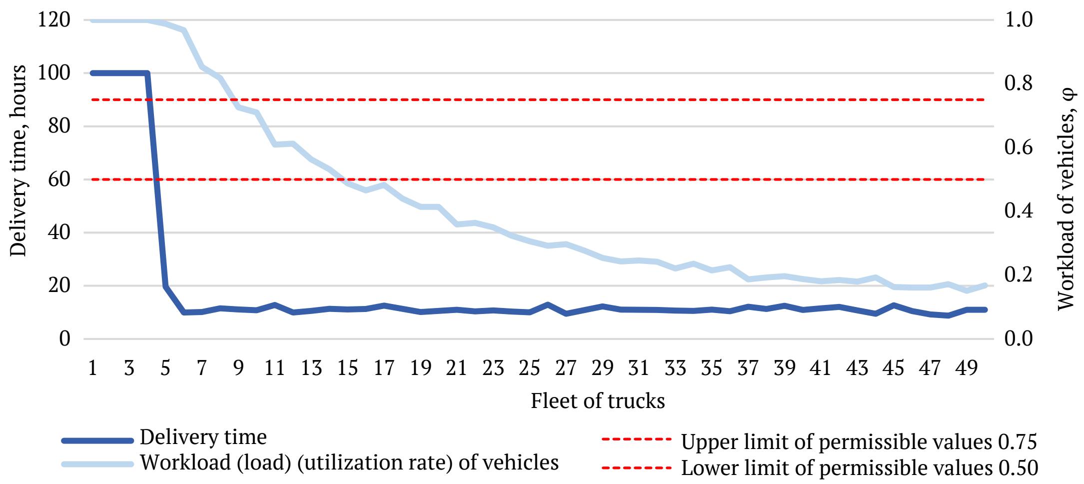


Figure 4. Dependencies of order delivery time and vehicle fleet loading on the working vehicle fleet
Note: delivery time is limited to 100 hours
Source: compiled by the authors

To determine the limit level of load, namely the intensity of orders, at which the transport and technological system of the enterprise will provide an appropriate level of fault tolerance, a sensitivity experiment of the model was conducted, in which the intensity of delivery orders was gradually increased with the estimated fleet of trucks (N_{cargo} = 12). As a result of a series of experiments, it was found that the queue of unfulfilled orders begins to grow significantly after the intensity of 140 orders per year (about 2.7 orders per week) (Fig. 5).

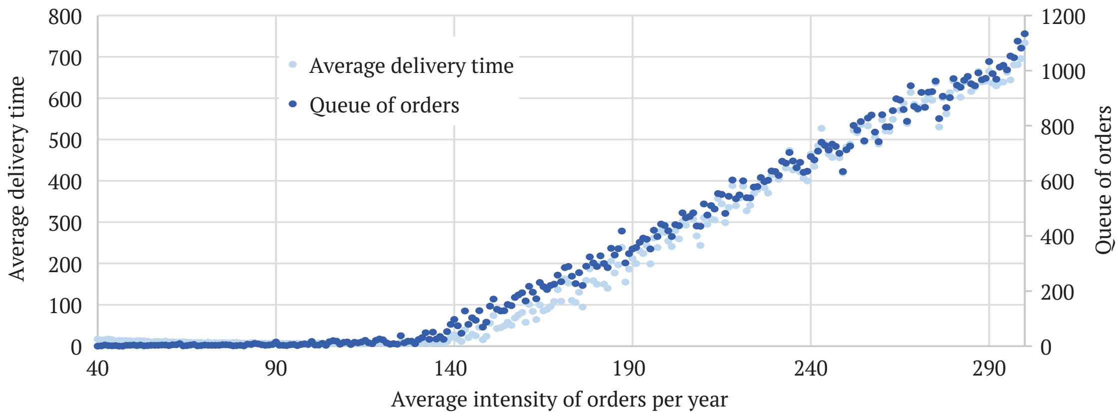


Figure 5. Dependence of the number of orders in the queue (at the end of the experiment) and the average delivery time on the average intensity of transportation

Source: compiled by the authors

A detailed analysis of the formation of the order backlog during the simulation period indicates a gradual increase in unfulfilled orders with an order intensity of 135 orders per year or more (Fig. 6).

At the same time, the value of the waiting time for an application for a free truck has an exponential distribution density, which confirms the naturalness of the process (Fig. 7).

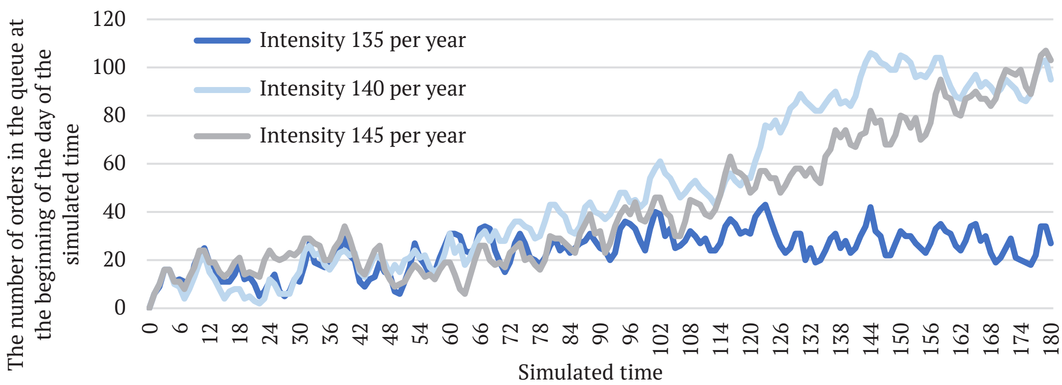
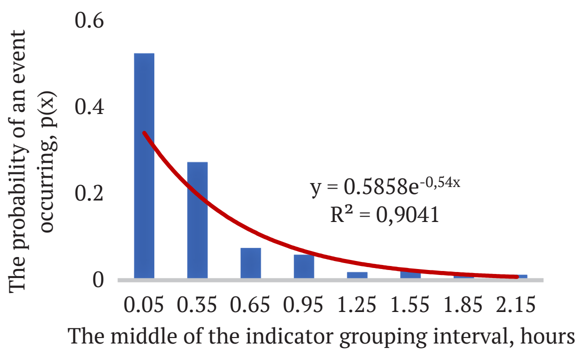
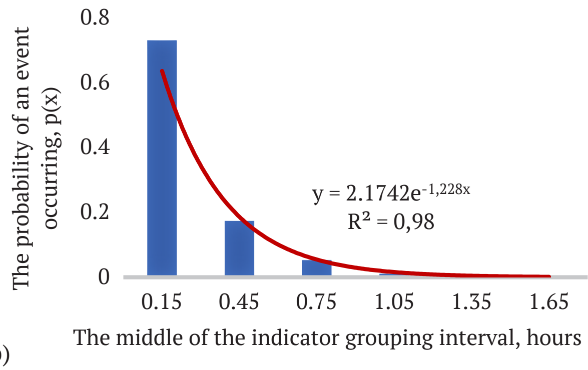


Figure 6. Dependence of the size of the order queue depends on the average intensity of receipt of transportation orders

Source: compiled by the authors



a)



b)

Figure 7. The probability density of the distribution of the waiting time for the execution of a transportation order due to the lack of a free truc

Note: a) for the calculated loading conditions on the system (number of vehicles 12, average intensity of orders 52 per year); b) For critical loading conditions on the system (number of vehicles 12, average intensity of orders 135 per year

Source: ompiled by the authors

Thus, it can be assumed that the maximum load of the transport and technological system of an enterprise with an estimated fleet of 12 trucks is 135 or more orders per year for each supplier. At the same time, the experimental models presented in these studies do not consider the complexity of multimodal transport, as noted by V. Shramenko *et al.* (2020). Only the last stage of delivery, the "last mile" stage, was considered. Therefore, it is impossible to state that the study of cargo delivery is complete, systematic and comprehensive, which, if possible, will be taken into account in further research.

Thus, the study systematically studied the problems of improving the efficiency of the transport and technological line using computer simulation, which made it possible to:

- consider the process as a single, complex and large transport system;
- to consider the slope of processes and phenomena, which minimised the abstractness of the model;
- to investigate the centralised management of the vehicle fleet and the issue of process resilience;
- establish the optimal parameters of the transport and technological process, considering a systematic approach.

However, the study could not consider:

- branching of delivery routes, considering the number of delivery points within each route;
- the process of transporting goods within the entire transport and technological line of multimodal supply chains.

Optimising transport routes is key to improving supply chain efficiency. One of the most modern and powerful tools for comprehensive optimisation of all key parameters of transport and technological systems of various types and levels is agent-based simulation (Liu *et al.*, 2022), including in the study of distribution logistics implementation conditions (Tang *et al.*, 2022; Alimohammadi & Behnamian, 2023), as well as based on GIS (geographic information system) components of the spatial orientation of transport infrastructure facilities on the ground (Chen *et al.*, 2021). At the same time, such models do not fully use the discrete-event approach, which allows for modelling technological subprocesses with a sufficient level of reliability.

In addition, the main feature of the developed model is the consideration of centralised fleet management. In other words, the model dynamically considers the possibility of changing the routes of trucks when organising the next flights and cargo delivery. A similar problem was solved by V. Matsiuk *et al.* (2021), where mainline locomotives were optimised for the delivery of iron ore concentrate. However, unlike these studies, this paper modelled the centralised management of trucks.

To study the resilience of the transport system, similar tools to the methods of queuing theory were used, as described by D. Ziemke *et al.* (2021). The methods of queuing theory were used to solve the scientific task of increasing the efficiency of processes to counter illegal and unauthorised interference with critical infrastructure. While the processes are similar, fleet management has certain differences, starting with greater discretion in events, sequencing (vehicles are serviced in a certain order) and less variation in the intervals of service requests and the duration of the service itself. Thus, the main value of this research is the focus on the problem of road transport of small consignments of goods in a wide variation of delivery routes under conditions of stochastic processes and systematic research.

At the same time, another rather powerful research tool, agent-based simulation, is gaining popularity. Simulation models developed based on this paradigm allow for the most comprehensive study of a wide range of activities, production, service, etc. For example, E. Derkenbaeva *et al.* (2023) presented the results of experiments with spatial microsimulation to predict the development of residential areas in one of the European countries. The agnostic approach made it possible to consider specific factors in human behaviour, such as the role of tenants and investors in shaping demand in the country's regions, and to forecast electricity consumption in the near future. Based on the study's findings, the researchers presented an effective decision-making support tool for the country's political leadership, including local authorities in the regions.

In another example, R. Faia *et al.* (2023) successfully addressed the problem of optimising the daily energy consumption of a region with intensive use of electric vehicles. With the help of the developed agent-based computer simulation, the researchers solved the problem of the optimal location of charging stations in the selected area. This problem successfully combines the approaches of linear programming and integral calculations in the process of parameter search.

The most similar results are obtained by O.V. Horbova & N.S. Murkovych (2021), as they present the results of experiments with agent-based simulation in the delivery of small consignments. At the same time, these studies are based on the task of a salesman and do not fully consider the simultaneous operation of several vehicles in the centralised organisation of transportation work.

In summary, the problem of distribution logistics is a complex and multifaceted issue that requires an integrated approach to overcome. By adopting a holistic approach, companies can ensure the success of their business and meet the ever-increasing demands of their customers.

CONCLUSIONS

A comprehensive optimisation (simulation) model for the delivery of orders on an extensive network of road routes by a truck fleet under conditions of partial uncertainty has been developed. The model is based on agent-based and discrete-event principles, considering the stochastic nature of the receipt of orders for transportation and the duration of the technological elements of the transportation process. The model was tested based on one of the operating units of the National University of Life and Environmental Sciences of Ukraine. This allowed the model to be adapted to the specific requirements and features of the enterprise in question, which contributed to higher efficiency and accuracy of the results. The adequacy of the model was determined by comparing the performance indicators of the enterprise and the modelling results. The degree of reliability is 89%.

The results of the optimisation and sensitivity experiments of the model have established that, according to the criterion of the average delivery time of order and under the given initial conditions, there is a range of close to optimal values of the size of the truck fleet, namely from 9 to 14, while the optimisation criterion itself ranges from 9.96 to 12.78 hours. The average value of the specified range, namely 12 vehicles, was chosen as the calculated value.

The sensitivity experiment of the model, with the selected calculated value of the vehicle fleet, determined the maximum level of load on the transport and technological system, which ensures its efficient operation. The critical load of the system is the number of transport orders in the amount of 135 per year (from each supplier), which is 160% more than the existing level of orders of 52 per year. The density of the distribution of the waiting time for the fulfilment of transportation orders is approximated by an exponential distribution, which indicates sufficient fault tolerance of the process and, as a result, is evidence that the transport and technological supply system of the enterprise has a sufficient margin of safety.

Further research is needed to improve the simulation model since it did not consider the randomness of the formation of consignments of different sizes (weight and mass) and the different intensities of order formation in the supplier network.

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None.

CONFLICT OF INTEREST

None.

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Оптимізація параметрів транспортно-технологічної системи аграрного підприємства в умовах часткової невизначеності

Анотація. На етапі виробництва широкого спектру сільськогосподарської продукції для забезпечення безперебійної роботи аграрних підприємств необхідно вирішити задачі швидкої та ефективної доставки відповідного обладнання, запчастин, розхідних матеріалів при раціональному використанні наявних виробничих ресурсів. Метою дослідження було вдосконалення транспортно-технологічної системи постачання замовлень у вигляді партій вантажів на потребу виробничої діяльності аграрного підприємства. Для цього було розроблено імітаційну модель у середовищі AnyLogic University Researcher із використанням компілятора Java, оскільки цей інструментарій дозволяє одночасно поєднувати дискретно-подієвий та агентний підходи. Модель реалізовано на прикладі підприємства відокремленого підрозділу Національного університету біоресурсів і природокористування України «Агрономічна дослідна станція». В результаті була отримана комплексна, оптимізаційна математична модель постачання товарів на розгалуженій мережі автомобільних шляхів сполучення власним парком автотранспортних засобів агропідприємства в умовах часткової невизначеності. Під час проведення експериментів та обчислень на основі реального процесу аграрного підприємства було знайдено діапазон значень розміру парку вантажних автомобілів, що відповідає умовам оптимізації. Визначено, що діапазон близьких до оптимального значень розміру парку вивантажних автомобілів змінюється в межах від 9 до 14 одиниць. Встановлено, що значення критерію оптимізації, що описує середній час доставки від початку виникнення потреби в замовленні до моменту його доставки, змінюються в межах від 9,96 до 12,78 годин. Визначено граничний рівень навантаження транспортно-технологічної системи, при якому забезпечується граничний рівень технологічної відмовостійкості. Він складає 135 та більше замовлень у рік у кожного постачальника при розрахунковому парку вантажних автомобілів у 12 одиниць. Результати дослідження, такі як застосування аналітичних інструментів та алгоритмів для оптимізації маршрутів та розподілу ресурсів, можуть бути використані для підвищення ефективності транспорту, для допомоги підприємствам у виборі найбільш вигідних та екологічних маршрутів для перевезень

Ключові слова: агентна симуляція; склад парку транспортних засобів; технологічна відмовостійкість; дистрибутивна логістика; постачання комплектуючих