M. Oliskevych[1],
orcid.org/0000-0001-6237-0785,
I. Taran[2],
orcid.org/0000-0002-3679-2519,
T. Volkova[3],
orcid.org/0000-0001-8546-4119,
I. Klymenko[2],
orcid.org/0000-0002-6263-0951

1 — Lviv National University of Nature Management, Dubliany, Lviv Region, Ukraine, e-mail: oliskevychm@gmail.com
2 — Dnipro University of Technology, Dnipro, Ukraine
3 — Kharkiv National Automobile and Highway University, Kharkiv, Ukraine

SIMULATION OF CARGO DELIVERY BY ROAD CARRIER: CASE STUDY OF THE TRANSPORTATION COMPANY

Purpose. To develop a method of simulation of the process of execution of random orders, which would allow substantiating a set of decisions of the transport company "Trans-Service" Ltd. The decisions concern the use of their own rolling stock, or the involvement of leased vehicles, as well as the rational sequence of orders.

Methodology. A simulation model of transport cycles with discrete time is developed. The smallest indivisible duration of a cycle is one working shift. The incoming flow of orders is reflected by the random coordinates of the point of departure and destination of goods. The coordinates of potential orders are formed by a random number generator. Each order is set with its characteristics, which include: point of departure and delivery point, delivery volume, average delivery time, group size, time window. At each step of route planning, a set of orders is known, which are characterized by their compatibility. Rules for selecting orders and distributing them among existing vehicles have been developed. An algorithm and a computer program for simulation have been developed.

Findings. Simulation was performed for 30 calendar days, when incoming order flows are stationary. The number of simulation steps is appropriate. The simulation was performed with 20 repetitions. The results are presented by the average value of repetitions. The dependences of the number of orders received, executed, and rejected by the carrier, as well as the number of their own vehicles used by the enterprise are obtained. We also received the number of orders that are not fulfilled by Company's own transport, but are accepted for execution with the help of leased fleet. The allowable order compatibility ratio varied for each series of experiments. The corresponding time indicators of cooperation under conditions of different intensity of the input flow were obtained. To perform simulation experiments with the initial data, which were observed in the transport company "Trans-Service" Ltd, Ukraine, an array of initial data was formed.

Originality. For the first time, an indicator of organizational and technological compatibility of orders was used to select orders to be serviced by the transport company during simulation, which made it possible to select orders from the stochastic flow and form a rational sequence of their execution.

Practical value. The obtained results are useful in developing a freight plan based on the data obtained on freight orders and the status and capabilities of partners.

Keywords: *freight transportation, stochastic process, simulation modeling, order compatibility*

Introduction. Competition among road freight carriers causes them to organize the delivery of goods so as to reduce unproductive downtime, idle run, underemployment rolling stock [1]. However, the random nature of the incoming flow of orders, the size of the groups, unforeseen road and transport conditions are too important factors that cannot be overcome to avoid unproductive costs. It is possible to increase the productivity of motor vehicles by cooperating with other carriers. After all, the carrier is sometimes forced to fulfill unrewarding or even unprofitable orders in order to maintain the structure of a rational transport process, retain customers, or oust a competitor from the market [2]. The most effective and objective reasons for unprofitable transportation can be considered as organizational and technological ones [3]. With regard to other orders, a decision should be made: to attract additional leased vehicles or to refuse the proposed transportation (give it to other carriers). The decision in this case is made on the basis of discretion: to have a competitive advantage, or to keep the client. If additional vehicles are rented, the existing orders will be fulfilled, but with less efficiency. Refusal of certain orders actually means that they are fulfilled by other carriers, and requests from these customers are unlikely to reach the carrier. If the existing fleet is underloaded and will stand idle, one needs to take care to lease unused vehicles. These decisions of the carrier must be made promptly, discretely, in a timely manner, for the period of formation of the transportation plan. The plan of transportations is formed in the process of receipt of new orders for delivery of cargoes. When transport processes begin, new orders often arrive, sometimes more profitable than planned. There are also failures to perform the planned transportation process due to unforeseen circumstances. That is why the development of a transportation plan has the character of a dynamic process. This means that management decisions need to be reviewed step by step.

Factors for making a comprehensive decision on cooperation are contradictory. Thus, the problem of increasing the productivity of rolling stock in case of random external factors is solved in close cooperation with other carriers on the one hand. On the other hand, in this way competition increases in the market of road transport. Therefore, optimization should be applied [4]. However, the new approach to justifying the relationship of cooperation with partners requires the definition of new criteria and new variables that are not formal parameters for all the described solutions. Thus, the costs and profits of each order, depending on the sequence of their execution, are the variables of the task of selecting orders from the incoming flow. Productivity factors are used when substantiating the structure and distribution of the fleet of owned and leased vehicles. Time variables or parameters of cargo flows are used when planning the structure of the delivery process. Therefore, the optimization of cooperation relations of several carriers is a multidimensional task of conditional optimization. The target function concerns the maximum profit of the transport company for the given period, and restrictions are formed by properties of a transport network, parameters of known orders and technological possibilities of vehicles. The number of partners with whom cooperation can be considered in this task is limited. After all, each new participant in the cooperation is described by new variables. The number of variables in a multidimensional problem should not exceed the number of con-

straints as known. Otherwise, there will be no solution to the problem. Ultimately, this leads to the need to solve a problem that is NP-hard, given the new variables, to determine their order, which is comparable to the constraints, and to create a model for the dynamic decisions described above. Therefore, there is no guarantee that it has a solution at all.

Literature review. There are known publications in which the problem of downtime, delivery delays and idling is solved with the help of cooperation of carriers [5, 6]. In particular, in the article [6], the authors presented a mathematical description and algorithm of coordination of transportations on the transport network by interacting trucks (without specifying their administrative affiliation). The presented algorithm allows building unique routes on the network with the shortest delivery distances, so that each vehicle has a return with cargo on each segment of routes. In addition, conditions for transport that do not meet this framework have been identified. According to the authors, the problem of maximum coordination of vehicles on the network can be solved using several established transport routes. In this case, the calculation of compliance with the algorithm takes more resources. Heuristic methods may be necessary. A very interesting point here is the definition of individual segments of routes, which are characterized by partial temporal and spatial coordination of trucks. The choice of optimal multiple transport route is possible on the basis of such segments, namely their coincidences. However, time-dynamic route properties were not considered in this article. There may be variations in the timeline that need to be considered.

Time tolerances for the solution of routing problems of several agents were proposed for the first time in paper [7]. The authors argued that the approximation methods are the most promising for large-scale practical problems given the intrinsic complexity of this class of problems. It was found that some heuristic methods have proven themselves in various problem environments. Heuristic methods have actually developed significantly since then. They give good results in optimizing schedules and routes in multi-agent tasks. However, modern approaches based on heuristics and metaheuristics exacerbate the problem of efficient and accurate processing of large arrays of input data, which are their main disadvantages. This is due to the neglect of the relationship between the characteristics of the input data flow [8].

Planning the delivery of goods on the transport network by several agents is limited to a local solution within a predetermined time interval, which is the optimal schedule, which takes into account the time windows [9]. However, scheduling is becoming a global problem for several agents on the transport network and this is due to the difficulty of solving it. Empirical and metaheuristic methods are used. An accurate and stable solution is not guaranteed. Possible ways to reduce the dimension of the problem are the divisions of the transport network into regions [10], the creation of stable routes [11], the use of dynamic programming methods [12], the use of limited time for scheduling with more rigid time windows for orders.

To develop optimal solutions, it is necessary to organize appropriate information supplying. An overview of the factors of information exchange efficiency in supply chain management is made in the paper [11]. This study details the benefits and barriers to information sharing, leading to enhanced supply chain integration. The authors note that the exchange of information can be both useful and harmful, depending on the technological origin of the information flow. However, how to determine the feasibility of such a division is not specified in the article.

High competition in the road haulage market requires solutions that differentiate logistics service providers according to their characteristics. The desired properties of the agents of cooperation in such situations are described in [13]. Solutions that satisfy the following properties are offered. It is also stated that the decision on cooperation should be made on the basis of selected signs of similarity of interaction agents in the publication [14]. However, this does not take into account that the characteristics of agents are variable over time. Therefore, it is necessary to look for situational similarities that have not been studied by the authors.

Chen and co-authors [8] identified 28 factors that affect the effectiveness of cooperation between carriers in supply chains. The exchange of information on supply chains proved to be the most important factor. However, the decision based on the information processed or received in the community of carriers is not given a proper attention.

The interaction of transport enterprises that are not united by a common production schedule is considered in [15]. The author uses a multi-agent approach in process simulation as the main research method. The obtained simulation results were evaluated on two indicators: the average waiting time for the start of service, and the level of service (number of completed shipments/number of orders). The results avoided uncertainty in solving the initial problem of agent coordination. However, there are no developed tools to improve the process of delivery of goods in this work and there are no clear recommendations for solving the problem of cooperation.

Simulation is often successfully used as a tool for the study of complex systems in recent years, which is a system of delivery of goods on a wide network. For example, an important problem of automation in logistics warehouses is considered in the article [16]. An effective solution to such a large-scale problem is difficult to obtain without high-performance computing. A new approach to adjusting the parameters of the warehouse management system was proposed for this purpose in its production use. It is based on the analysis of data in simulation in inhomogeneous distributed computing environments. Using a set of simulation models, the optimization problem was solved to adjust the parameters of the warehouse management system. The developed programs demonstrate high efficiency and scalability for optimization according to nine criteria to meet different production requirements. There are very few such simulation models related to the cooperation of carriers. One of the successful applications of the simulation model is the construction of a logistic system of material flow scheduling reflected in [17]. The authors proposed to apply the latest agent-oriented approach to solving logistics problems in a multi-agent environment. This approach has been found to be well suited for this type of task. The use of simulation is proposed as a method for evaluating the efficiency of the obtained solutions.

Unsolved aspects of the problem. General formulations and effective methods of decision-making regarding the feasibility of cooperation, the volume of selected and transferred to partners orders, the sequence of order execution, ways of cooperation of carriers in their interaction in cargo chains are not presented in known studies. Known methods inform decisions regarding cooperation and choice of carrier strategies observed such disadvantages. First, the models that describe stochastic supply chain maintenance processes are complicated enough. Heuristic algorithms are used to find the target values of the models. These algorithms are not entirely suitable if the structure of the input data is unknown in advance. Secondly, static signs, which lose their weight when circumstances change, are accepted as signs by which carriers accept or reject cooperation. Third, due to the growing complexity of transport systems, the appropriate methods of their study are methods of simulation. In particular, multi-agent modeling is the most modern of them. There are environments where such models can be folded easily. However, not all of them reflect the main purpose and features of these studies. Therefore, there is a need to develop a simulation model that best fits the decision-making process of the carrier.

Purpose. The purpose of these studies is to develop a method of simulation of the order fulfillment process. The application of such modeling should allow to develop at the experimental level tools to justify a set of decisions of the transport company at each step of planning for the use of its own rolling stock, attracting leased funds and execute orders in a rational sequence.

The objects of research of this article are the transport processes of the integrated transport system, in which the interaction of its individual agents takes place.

In order to achieve this goal, the following research tasks were formulated and solved.

1. To develop the rules for: a) selection of orders for execution; b) assignment of vehicles to selected orders; c) attracting additional leased vehicles and using their own. The transformation of stochastic flows in a simulation model is based on these rules.

2. To investigate the influence of the compatibility features of orders in the incoming flow on the efficiency of transportation activities.

3. To develop a method of constructing a rational sequence of orders.

4. To develop recommendations for cooperation of the transport company with partners depending on the production situation.

Methods. This article is based on the known preliminary results of studies that had similar properties [18−20]. The similarity of the proposed and known methods underlies the algorithm. The differences relate to the general rules of decision-making.

Development of general rules for simulation decision making. The following conditions and assumptions are applied. A transport order is a certain amount of cargo that has a point of departure and a destination, as well as a time window, which is the period on the time axis when it can be fulfilled. If the goods are not delivered to the destination during this period, such an order is considered rejected. Each order is random according to the given characteristics. However, similar orders occur on the time axis with a certain frequency, which has been proven in previous studies [20]. It is accepted that the carrier, whose activities are simulated, is able perform order forecasting. The forecast period significantly exceeds the maximum time window of each known order. The assumption is that the carrier is partially limited by the influence of the competitive environment. That is, orders that are known only to them cannot pass to another carrier, unless the conditions of their implementation are violated. The refusal of the cargo owner comes only when all vehicles are already allocated to more profitable transport tasks, for which the number of rides with cargo, the average duration of one ride with cargo is the largest. In this case, the performance of the fleet will be better. It is also taken into account that some long-distance freight transportation requires time that exceeds the duration of the change of driver/crew of one road train. In this case, the accepted order reduces the number of available vehicles for the next simulation cycle (planning period). Thus, the scheme of the model is as follows: one carrier − several customers. The maximum number of customers is limited. Among the transportation of goods there are multi-cycle ones, i.e. those that need to be done in several rides. They can be performed during several shifts in a row by one truck or by several free trucks at the same time. Multi-cycle orders are considered as long-term. Therefore, they are preferred.

Formal content of the simulation model. If the carrier receives a forecast and exclusive rights to service a set of $Z_j = \{z_1, z_2, ..., z_N\}$ orders in the jth step, it selects a subset of $Z_{j.s}$ such orders that have signs of technological compatibility, which can be estimated by the compatibility factor [21]. The indicator that characterizes the compatibility of orders z_i, z_y in the sequence $y{\rightarrow}i$ is defined as the factor of

$$K_{c.y.i} = \frac{a_{0.i}}{a_{y.i}}, \qquad (1)$$

where $a_{0.i}$ is an order z_i execution time in isolation, without any execution of previous orders, as well as without preparatory actions (zero mileage, waiting for shipment, and others); $a_{y.i}$ is a duration of order z_i execution after order z_y.

The highest value of compatibility factor is $K_c = 1$. Therefore, $K_c = 1$ corresponds to a fully compatible order, and $K_c = 0$ is completely incompatible. Two orders, for which $0 < K_c <$

< 1, are called partially compatible. The time relationships $a_{i.y}$, $a_{y.i}$ can be estimated for any pair of orders from a predetermined set of Z_j. In this regard, one can construct a matrix of time relations $\|a_i.y\|$, i, $y = 0...F$, where 0, F are fictitious orders, which mean the formal beginning and end of simulation. One can also build a matrix of compatibility coefficients for the same set of orders. To assess the compatibility of all known orders, one uses the average value of the compatibility factor

$$K_c = \frac{\sum\limits_{i=1}^{N}\sum\limits_{y=1}^{N} K_{c.i.y}}{N}, \qquad (2)$$

where N is the total number of orders in the set of Z_j.

The coefficient (2) shows how compatible the selected orders are in terms of process organization in one set, which is planned to be executed.

After selecting a subset of $Z_{j.s}$, the ranking of orders is performed by routes with the assignment of the appropriate number of trucks on them. This task is similar in content to the well-known problem of multi-salesman. [21] The content of the problem in our research was adapted as follows. In the course of transportation, k own vehicles of the carrier can be involved. They must work synchronously, each fulfilling several orders in a rational sequence. Therefore, the execution of orders can be represented by a graph H, in which one needs to find k chains that start at the fictitious node g_0 (formal beginning of the process), pass through some nodes that relate to the selected ones to execute orders and finish at the node g_{N+1}. The set of such chains reflects k routes. In this version of the task, we are looking for the minimum execution time of all specified orders under the following conditions: 1) execution of each order will take place within its time window; 2) a minimum number of vehicles will be involved in the transportation of goods, which in fact means their maximum productivity. The function of the goal in this problem is the minimum duration of the critical, i. e. the longest chain of executed orders

$$T_c = \min\{\max(a_{0.i} + ... + a_{i.i+1} + ... + a_{j.N+1})\}, \qquad (3)$$

where $a_{0.i}$, $a_{i.i+1}$, $a_{j.N+1}$ are the weights of the arcs of the graph H, which reflect the time relationships between the executed orders, which are reflected, respectively, the initial fictitious, intermediate, final fictitious nodes.

The path from the fictitious node g_0 to any given g_i should not exceed the time window $w_{y.i}$

$$T_i = \max(a_{0.i} + ... + a_{i-1.i}) \leq w_{y.i}. \qquad (4)$$

Desired by the criterion (3) chain of orders have to pass on those nodes, for which the size of the group send is $q_x > 0$. If the chain reaches the node y, and then there is no path in the graph H, the chain goes to the node g_{N+1}. The transport cycle for this truck will be considered complete, despite the fact that there is a reserve of time to fulfill other, not fulfilled orders yet.

Simulation algorithm for servicing cargo orders. The following input values are used in the algorithm. Given:

1) transport network (TN) with transport points and distances between them, which can be displayed in the form of a square matrix $\|as.c\|$ time relations size $Q \times Q$, $s = 1..Q$ − designation of the transport point-sender cargo, $c = 1..Q$ − designation of the transport point, the consumer of the cargo. Each element $a_{s.c}$ is the average travel time between any two points s, c of the vehicle loaded. TN is represented by a strongly connected graph. Therefore, this time can be calculated between any of its two points, using intermediate points. The matrix $\|as.c\|$ is symmetric about the main diagonal. The values of $as.c$ for the transport cycles of trucks remain known and constant during each step of the simulation;

2) the fleet of trucks, which is characterized by the total number of k_{max} of the same type of road trains, which are randomly located on the TN at the initial step of the simulation. The location of the kth vehicle is characterized by the variable

$x_{k,j}$, which is the point number on the TN, where j is the step number of the simulation;

3) the set of orders for cargo transportation is given in the form of coordinates of initial and final points.

There are the following values that characterize random orders at each step j of modeling: $S_{z,j}$ – the initial coordinate of the point where the execution of the order z should start (point of departure); $C_{z,j}$ – the final coordinate of the point where the execution of the zth order should be completed; m – the number of rides that need to be made to fulfill the zth order; $F_{z,j}$ – integer variable, $F_{z,j} = 0$, if the zth order is not accepted for execution by any vehicle; $F_{z,j} = 1$ if the zth order is accepted for execution; $w_{z,j}$ – the time window of the zth order in the jth simulation step, i.e. the number of periods passing from the step when the order is generated to the maximum when it can be delayed in execution.

Simulation is to assign to vehicles loading and unloading points, i. e.

$$X_{k,j} := S_{z,j}; \quad X_{k,j+1} := C_{z,j},$$

for all k vehicles that are able on TN, and for all z orders that are unfulfilled but accepted at the present moment.

The generator of random values of the simulation model gives the following values:
- the total number of available orders;
- characteristics of each zth order.

The model includes a number of rules, which are formulated above in addition to random variables.

When initializing the input data, the start and end coordinates of all orders are reset. At each step, random variables are determined

$$S_{z,j} = random(0; S_{max}); \quad C_{z,j} = random(0; C_{max});$$
$$S_{z,j} \neq C_{z,j}, \tag{5}$$

where S_{max}, C_{max} are boundary serial numbers of TN transport points.

If it is established by expressions (5) that $C_{z,j} = 0$ or $S_{z,j} = 0$ then it formally means the zth order is absent. If the zth order is not executed during the next simulation steps, it exists for as long as its time window allows.

The number of modeling steps is a constant value.

Transportation of goods by z order that has arisen is considered possible if the following conditions are met:
- the order is selected in the set Z_s;
- at its starting point S_z there is at least one free vehicle. At any point of the given transport network the ratio of free vehicles and unfulfilled orders is defined. One of the tactics is chosen depending on this ratio: a) free trucks are distributed to all available orders with the parallel execution of rides and with a shortage of orders; b) only the most advantageous orders are selected with their excess. If there are not enough free trucks (case b), then individual orders may remain unfulfilled or canceled, depending on their time windows and the frequency of their occurrence. We have laid the possibility of fulfilling incompatible orders with rented vehicles in contrast to the known method [22]. The route of leased trucks is not developed. It is assumed that the leased vehicles were located at or near S_z. Idle mileage of leased vehicles was not calculated and was not taken into account. Trucks that remain unallocated in the jth modeling step can be leased to another carrier. Such events were considered reliable in the simulation.

New orders arise at each step of the simulation by expressions (5). They get random characteristics by a random number generator. However, the decision to include each new order in the transportation plan at $j + b$ step by the company's own fleet is made on the basis of the ratio

$$K_c(Z_{j+b} + Z_{j,s}/Z_{j,f}) \geq [K_c],$$

where Z_{j+b} is the set of orders that have arisen and are unfulfilled at $j + b$ step of simulation; $Z_{j,f}$ is the set of orders that were

executed before the step $j + b$; K_c is compatibility factor, which is calculated as a function of available orders; $[K_c]$ is the allowable value of the compatibility factor under study.

If the whole set of unfulfilled orders is such that leads to non-fulfillment of expression (4), then we exclude those orders from it, which have the lowest coefficient of compatibility with any order that is not fulfilled according to expression (1). This continues as long as the condition (4) is not provided. In analyzing the fulfillment of condition (4), the following cases are possible: a) new orders that have arisen significantly increase the compatibility ratio of orders that are already included in the rational plan and increase its size; b) new orders that have arisen significantly increase the compatibility ratio of orders already included in the rational plan, provided that some of the orders accepted for execution need to be excluded from this list; c) no new order affects the increase in the compatibility factor, but the increase in the set Z_s by new orders does not violate the fulfillment of condition (4); d) all new orders degrade the original plan and their compatibility ratio becomes less than acceptable. Cases a–d are evaluated step by step in the simulation and such decisions are made. The carrier has to use its own vehicles that remain unallocated, or to rent additional vehicles from partners and create a new rational route plan with appropriate trucks distribution in cases a, c. It is necessary to revise the established transportation plan without involving additional trucks in case b. No changes in the transportation plan have to made in case d.

The following indicators of the carrier's transport activity were calculated using the relations of cooperation at each j step of the simulation:
- the number of new orders that arise Z_j;
- the number of orders executed by $Z_{j,j}$;
- the number of orders executed by $Z_{j,p}$;
- the number of orders rejected $Z_{j,r}$;
- the number of owned vehicles involved in $Z_{j,k}$ transportation;
- the number of vehicles that are idle/rented $Z_{j,ks}$;
- the number of involved rented trucks;
- duration of rides with cargo T_c;
- duration of idle rides T_{id}.

Results of experimental studies. An appropriate algorithm was created for the developed simulating technique, which was translated into the Delphi programming language. The corresponding computer program was used to perform simulation experiments with the initial data observed during the transportation of bulk cargo by dump trucks of the transport company "Trans-Service" Ltd, Ukraine. The vehicles perform long-distance freight transportation on the territory of the road transport network of the center, southern and eastern regions of Ukraine. The company receives orders for cargo delivery from the freight forwarder every shift. The intensity of orders is seasonal and random. The average intensity of orders varies within $\lambda = 2$–22 orders/hour. Simulating was performed at a fixed average intensity, which was 6 orders/hour (48 orders per shift) for the May, 2021. The actual coefficient of compatibility of the package of incoming orders varies within $K_c = 0.36$–0.8. The duration of travelling between transport points was taken in accordance with the average readings of tachographs of trucks that passed previously known routes. Google Maps data was also taken into account. The company's dump trucks have the same load capacity. Therefore, the question of choosing a truck by load was not raised. The number of such truck is 170 in the fleet. 61 of them operate in a certain region of Ukraine. The company cooperates with its partners, which have smaller fleets of vehicles, and their partners attract advantageous orders for Trans-Service.

The experimental simulation was performed for a period of 30 calendar days, when incoming order flows can be considered stationary, i. e. $\lambda \sim const$. Since the period of order formation at the enterprise is one shift, and the number of shifts is 1 per day, the number of steps of simulating is 30. Each simulation was carried out with 20 repetitions. The results are pre-

sented by the average value of repetitions. The scatter of data with a probability of 0.95 did not exceed the average values: the duration of the processes − ±1.5 hours, the number of orders − ±3. Dynamic time series of random variables: the number of orders received, executed and not accepted for execution by the enterprise, as well as the number of owned vehicles used by the enterprise are given in Figs. 1, 2. The orders that are not fulfilled by the company's own fleet are accepted for execution with the help of leased vehicles of partner carriers. The allowable coefficient of compatibility of orders varied for each series of experiments and was selected from the set [0.3; 0.4; 0.5; 0.6]. Thus, for the first series of experiments K_c was 0.3 (Fig. 1).

For the 4th series of experiments K_c = 0.6. Figs. 3 and 4 show the corresponding dependences of the indicators of order fulfillment with the involvement of cooperative relations in the application of pre-selection of orders.

As the time series show, not all incoming to the carrier order flows are accepted by the carrier for execution. The difference between the input flow and failures is especially noticeable at K_c = 0.6. If we compare the number of failures in Fig. 3, then with a larger value of the coefficient of compatibility of orders, the average number of failures increases by more than 1.8 times.

The number of the carrier's own vehicles involved varies with a standard deviation from the mean value for K_c = 0.3 is within ±10 units and for K_c = 0.6 is within ±5 units. That is, fluctuations in the number of vehicles involved with a higher value of the compatibility factor are smaller.

Both simulation conditions show that the number of vehicles in the fleet 61 is redundant for a given flow of orders. However, it is seen in Figs. 3, 4 that increasing the filtering of the incoming flow of orders for transportation by the compatibility factor significantly improves the performance of the truck fleet. Thus, the total number of executed orders at K_c = = 0.3 is 1186. The total duration of idling vehicle on the routes
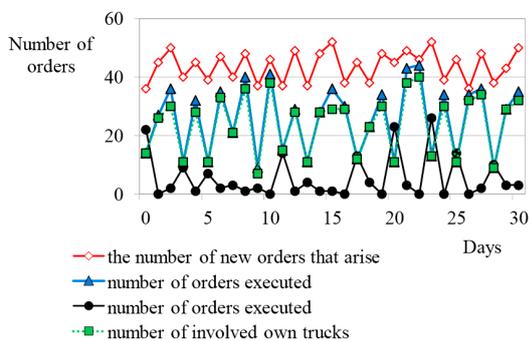

Fig. 1. Time series of indicators of the number of orders at the allowable value of K_c = 0.3 and the intensity of the input flow of 6 orders/hour
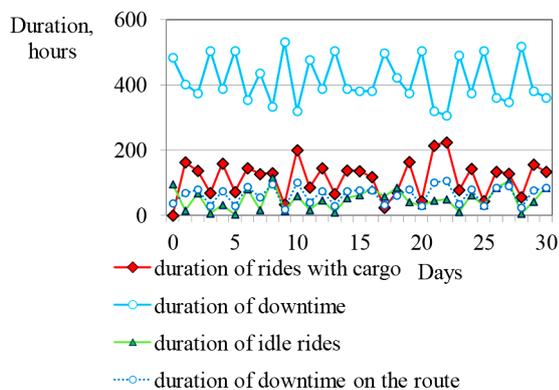

Fig. 2. Time series of indicators of duration of execution of orders at admissible value K_c = 0.3 and intensity of an input flow of 6 orders/hour
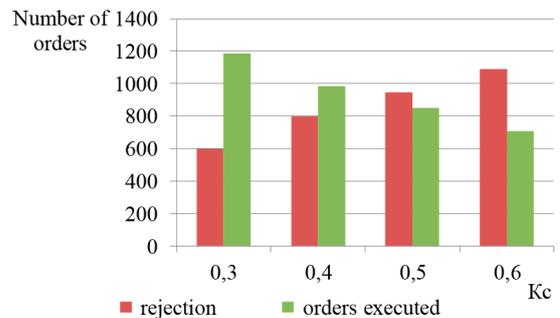

Fig. 3. Indicators of order flow model for 30 cycles at a constant average intensity of the input flow λ = 6/hour (37 orders per cycle) and variable values of the compatibility factor K_c
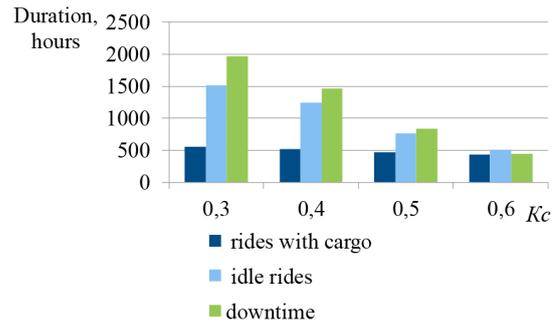

Fig. 4. Dependence of indicators of process of duration of execution of orders at a constant average intensity of an input flow λ = 6/h and variable values of the compatibility factor

was 1515 hours per 30 days. The total duration of vehicles downtime on the routes for the same period is 1966. If a part of the orders is not accepted by the carrier and transferred for execution to the cooperation partners, then the total number of executed orders at the same input flow, but at K_c = 0.6 is 706. The total idle time of vehicle on routes is 506 hours, and the duration vehicles downtime on routes is 438 hours. Therefore, when the number of completed orders is halved, the fleet utilization rates increase more than three times.

Conclusions. The studies performed allow finding reserves of increase in efficiency of use of truck fleet at performance of freight automobile transportations and at establishment of cooperation with partners. It is advisable to use a preliminary assessment of the incoming flow of orders for transportation on the basis of their organizational and technological compatibility. As an assessment of the compatibility of orders to be performed by several interconnected vehicles on ring routes, the coefficient of their compatibility is taken into account, which indicates the need for downtime and idling rides of vehicles. Higher values of the compatibility factor of the set of orders mean the possibility of achieving higher values of the efficiency of transport processes in the network. At the same time, increasing the allowable value of the compatibility factor leads to the need to abandon incompatible orders. It is advisable to assess the compatibility of orders in the incoming, discrete stochastic flow at each step, which is used to compile and review the transportation plan.

References.
1. Sabraliev, N., Abzhapbarova, A., Nugymanova, G., Taran, I., & Zhanbirov, Zh. (2019). Modern aspects of modeling of transport routes in Kazakhstan. *News of the National Academy of sciences of the Republic Kazakhstan, 2*(434), 62-68. https://doi.org/10.32014/2019.2518-170X.39.
2. Nugymanova, G., Nurgaliyeva, M., Zhanbirov, Zh., Naumov, V., & Taran, I. (2021). Choosing a servicing company's strategy while interacting with freight owners at the road transport market. *Naukovyi visnyk Natsionalnoho Hirnychoho Universytetu,* (1), 204-210. https://doi.org/10.33271/nvngu/2021-1/204.

3. Naumov, V. (2012). Definition of the optimal strategies of transportation market participators. *Transport Problems*, *7*(1), 43-52. Retrieved from http://transportproblems.polsl.pl/pl/Archiwum/2012/zeszyt1/2012t7z1_05.pdf.

4. Naumov, V., Taran, I., Litvinova, Y., & Bauer, M. (2020). Optimizing Resources of Multimodal Transport Terminal for Material Flow Service. *Sustainability*, *12*(16), 6545. https://doi.org/10.3390/su12166545.

5. Gansterer, M., Hartl, R. F., & Vetschera, R. (2019). The cost of incentive compatibility in auction-based mechanisms for carrier collaboration. *Networks, 73*(4), 490-514. https://doi.org/10.1002/net.21828.

6. Apfelstädt, A., Dashkovskiy, S., & Nieberding, B. (2016). Modeling, optimization and solving strategies for matching problems in cooperative full truckload networks. *IFAC-PapersOnLine, 49*(2), 18-23. https://doi.org/10.1016/j.ifacol.2016.03.004.

7. Pasha, J., Dulebenets, M. A., Kavoosi, M., Abioye, O. F., Wang, H., & Guo, W. (2020). An optimization model and solution algorithms for the vehicle routing problem with a "factory-in-a-box". *IEEE Access*, *8*, 134743-134763. https://doi.org/10.1109/ACCESS.2020.3010176.

8. Mehrdad, R., Kamal, B., & Saman, F. (2021). A novel community detection based genetic algorithm for feature selection. *Journal of Big Data*, *8*(1). https://doi.org/10.1186/s40537-021-00483-1.

9. Wang, D., Zhu, J., Wei, X., Cheng, T. C. E., Yin, Y., & Wang, Y. (2019). Integrated production and multiple trips vehicle routing with time windows and uncertain travel times. *Computers & Operations Research*, *103*, 1-12. https://doi.org/10.1016/j.cor.2018.10.011.

10. Qiu, M., Fu, Z., Eglese, R., & Tang, Q. (2018). A Tabu Search algorithm for the vehicle routing problem with discrete split deliveries and pickups. *Computers & Operations Research, 100*, 102-116. https://doi.org/10.1016/j.cor.2018.07.021.

11. Liu, Y. (2019). An optimization-driven dynamic vehicle routing algorithm for on-demand meal delivery using drones. *Computers & Operations Research*, *111*, 1-20. https://doi.org/10.1016/j.cor.2019.05.024.

12. Chen, L., Zhao, X., Tang, O., Price, L., Zhang, S., & Zhu, W. (2017). Supply chain collaboration for sustainability: A literature review and future research agenda. *International Journal of Production Economics*, *194*, 73-87. https://doi.org/10.1016/j.ijpe.2017.04.005.

13. Colicchia, C., Creazza, A., Noè, C., & Strozzi, F. (2019). Information sharing in supply chains: a review of risks and opportunities using the systematic literature network analysis (SLNA). *Supply chain management: an international journal*, *24*(1). https://doi.org/10.1108/SCM-01-2018-0003.

14. Hezarkhani, B., Slikker, M., & Van Woensel, T. (2016). A competitive solution for cooperative truckload delivery. *OR Spectrum, 38*(1), 51-80. https://doi.org/10.1007/s00291-015-0394-y.

15. Gorbachev, P. F., & Mospan, N. V. (2017). Simulation model of service of one-time orders for long-distance cargo transportation. *Bulletin of KhNADU, 76*, 32-39. Retrieved from https://dspace.khadi.kharkov.ua/dspace/bitstream/123456789/2033/1/V_06_76.pdf.

16. Bychkov, I., Oparin, G., Tchernykh, A., Feoktistov, A., Bogdanova, V., Dyadkin, Y., & Basharina, O. (2017). Simulation modeling in heterogeneous distributed computing environments to support decisions making in warehouse logistics. *Procedia engineering, 201*, 524-533. https://doi.org/10.1016/j.proeng.2017.09.647.

17. Dzinko, A. M., & Yampolsky, L. S. (2017). Modeling of the material flow scheduling function based on discrete-stochastic dynamic programming. Interdepartmental scientific and technical collection. *Adaptive automatic control systems*, *2*(29), 52-59. https://doi.org/10.20535/1560-8956.30.2017.117703.

18. Sahin, C., Demirtas, M., Erol, R., Baykasoğlu, A., & Kaplanoğlu, V. (2017). A multi-agent based approach to dynamic scheduling with flexible processing capabilities. *Journal of Intelligent Manufacturing, 28*(8), 1827-1845. https://doi.org/10.1007/s10845-015-1069-x.

19. Consonni, C., Sottovia, P., Montresor, A., & Velegrakis, Y. (2019). Discovering order dependencies through order compatibility. In *Advances in Database Technology-EDBT 2019*, 409-420. https://doi.org/10.5441/002/edbt.2019.36.

20. Sharai, S., Oliskevych, M., & Roi, M. (2019). Development of the Procedure for Simulation Modeling of Interrelated Transport Processes on the Main Road Network. *Eastern-European Journal of Enterprise Technologies, 5*(3), 70-83. https://doi.org/10.15587/1729-4061.2019.179042.

21. Azi, N., Gendreau, M., & Potvin, J. Y. (2012). A dynamic vehicle routing problem with multiple delivery routes. *Annals of Operations Research*, *199*(1), 103-112. https://doi.org/10.1007/s10479-011-0991-3.

22. Roy, M. (2020). Method of optimization of integrated transport process of freight road transport. *Scientific notes of TNU named after V. I. Vernadsky. Series: technical sciences*, *31*(70(5)), 220-227. https://doi.org/10.32838/2663-5941/2020.5/36.

Моделювання доставки вантажів автомобільним перевізником: приклад транспортної компанії

М. Оліскевич[1], *І. Таран*[2], *Т. Волкова*[3], *І. Клименко*[2]

1 — Львівський національний аграрний університет, м. Дубляни, Львівська область, Україна, e-mail: oliskevychm@gmail.com

2 — Національний технічний університет «Дніпровська політехніка», м. Дніпро, Україна

3 — Харківський національний автомобільно-дорожній університет, м. Харків, Україна

Мета. Розробити методику імітаційного моделювання процесу виконання випадкових замовлень, яка б дала змогу обґрунтувати комплекс рішень транспортної компанії ТОВ «Транс-Сервіс». Рішення стосуються використання власного рухомого складу, або залучення орендованих засобів, а також раціональної послідовності виконання замовлень.

Методика. Розроблена імітаційна модель транспортних циклів із дискретним часом. Найменшою неподільною тривалістю циклу є одна робоча зміна. Вхідний потік замовлень відображено випадковими координатами пункту відправлення та призначення вантажів. Координати потенційних замовлень формуються генератором випадкових чисел. Кожне замовлення задається його характеристикою, до якої входять: пункт відправлення й пункт доставки; обсяг доставки; середній час доставки; розмір партії; часове вікно. На кожному кроці планування маршрутів відома сукупність замовлень, що характеризуються їхньою сумісністю. Розроблені правила вибору замовлень і їх розподілу між наявними транспортними засобами. Розроблено алгоритм і комп'ютерна програма імітаційного моделювання.

Результати. Імітаційне моделювання здійснювалося для 30 календарних днів, коли вхідні потоки замовлень є стаціонарними. Відповідною є кількість кроків імітаційного моделювання. Моделювання здійснювалось із 20-разовим повторенням. Результати представлені за усередненим значенням повторів. Отримані залежності кількості замовлень, що надходять, виконуються й не приймаються до виконання перевізником, а також кількість власних автотранспортних засобів, які використовуються підприємством. Отримана також кількість замовлень, що не виконуються власним транспортом, але приймаються до виконання за допомогою орендованих засобів. Допустимий коефіцієнт сумісності замовлень змінювався для кожної серії дослідів. Отримані відповідні часові показники кооперації за умов різної інтенсивності вхідного потоку. Для виконання імітаційних експериментів із початковими даними, що спостерігались у транспортній компанії ТОВ «Транс-Сервіс» (Україна), сформовано масив початкових даних.

Наукова новизна. Уперше для вибору замовлень, які будуть обслуговуватись транспортною компанією під час імітаційного моделювання, застосовано показник організаційної та технологічної сумісності замовлень, що дало змогу провести відбір замовлень зі стохастичного потоку та сформувати раціональну послідовність їх виконання.

Практична значимість. Отримані результати є корисними при розробленні плану перевезень вантажів на основі отриманих даних про замовлення на перевезення вантажів і про стан і можливості партнерів.

Ключові слова: *вантажні перевезення, стохастичний процес, імітаційне моделювання, сумісність замовлень*

The manuscript was submitted 10.06.21.