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Igor TARAN[1]*, Gaziza ZHUMATAYEVA[2], Myroslav OLISKEVYCH[3], Mateusz SZARATA[4]

METHOD OF TRUCK CREW WORK COORDINATION ON INTERNATIONAL ROUTES

Summary. The article deals with the problem of increasing the productivity of trucks in the performance of international road freight transportation in Eastern Europe and the European Union. There are restrictions on cabotage transportation (domestic cabotage), as well as time limits for the execution of orders and penalties for the execution of the entire volume of transportation in this case in addition to the restrictions of the European Agreement E/ECE/TRANS/564. The task of optimizing the required number of vehicles, drivers/driving crews, and route configuration was formulated and solved by mathematical programming with time constraints. At the same time, a variable method of organizing the work of drivers on adjacent routes was applied, by which drivers/crews are not assigned to a specific vehicle but are changed after a certain number of work hours. This minimized the non-productive idling of trucks, ensured compliance with the work and rest regulations of drivers, and minimized truck mileage on routes. In contrast to known methods and research results, the problem is solved with a guaranteed achievement of the optimum in an acceptable search time. This result was achieved due to the appropriate formulation of the solution conditions. The results can be applied in the logistic planning of transport processes.

1. INTRODUCTION

The use of modern road trains for freight transportation requires a high intensity of transport processes, as it increases the efficiency of the use of fixed assets of the transport enterprise. Idling without a load/with a load, and idling run are inadmissible. However, transport processes have many limitations, making it difficult to adhere to the criterion of maximum intensity. Firstly, trucks are driven by drivers or crews of drivers who must comply with the rules of the European Agreement on the work of crews of vehicles engaged in international road transport – AETR. Mandatory time for their daily and weekly rest leads to the downtime of vehicles. Also, taking into account EU regulations No. 561/2006 and their probable inconsistency with the time windows of loading/unloading points, unproductive downtimes occur due to unsuccessful coordination of the subjects of the transport process: senders and consumers of goods and carriers.

At the same time, carriers from Eastern Europe rarely use the shift method of work for drivers because they feel it is unreasonable for drivers to be on business trips abroad. In addition, there is

[1] Rzeszow University of Technology, Department of Roads and Bridges; Powstańców Warszawy Ave. 12, 35-959 Rzeszów, Poland; e-mail: i.taran@prz.edu.pl; orcid.org/0000-0002-3679-2519
[2] Academy of Logistics and Transport; Shevchenko 97, 050022 Almaty, Kazakhstan; e-mail: gaziza120793@gmail.com; orcid.org/0000-0002-3835-1346
[3] L'viv National University of Nature Management, Department of Agricultural Engineering and Technical Service; V. Velykogo 1, 79020 Dubliany, L'viv Region, Ukraine; e-mail: oliskevychm@gmail.com; orcid.org/0000-0001-6237-0785
[4] Rzeszow University of Technology, Department of Roads and Bridges; Powstańców Warszawy Ave. 12, 35-959 Rzeszów, Poland; e-mail: matsza@prz.edu.pl; orcid.org/0000-0003-0227-2811
* Corresponding author. E-mail: taran.i@prz.edu.pl

doubt about the expediency of the personal "fixture" of drivers to vehicles, which negatively affects decision-making regarding the change of truck crews. Because of this, coordinating the work of drivers, taking into account the requirements of the regulations (EC) No 561/2006 and the time windows of freight transport points, has become very relevant.

If we assume that specific drivers are not attached to trucks, then the duration of their rest will not be reflected in the duration of transport downtime. There is such a system of transport cycles in which trucks are operated with minimal downtime and maximum productivity while the time of work and rest for drivers complies with international regulations. The solution to this problem presented in this article includes two successive stages: first, routes are built that are optimal in terms of the total mileage of trucks, and second, the modes of operation of drivers/crews are selected for these routes so as not to violate the norms of 561/2006. The first stage is solved by methods of integer programming. The second stage is solved by a heuristic method, which is applied to the problem of dense packing of containers. If the second stage does not yield a positive result, then we try to solve it with an alternative outcome of the first stage, which is characterized by the same indicators.

2. CONDITIONS AND LIMITATIONS OF PROBLEM SOLVING

It is necessary to consider all legal aspects, choose the optimal route scheme of transportation, and organize a clear interaction of the executors of the transport process for successful business of international transportation of goods. International transportation requires the consideration of such restrictions as the customs regime of transit and cabotage and the modes of work and rest of drivers. Cabotage transportation by road transport is the transportation of goods within the country, which is carried out by foreign international carriers. This requires a special license, but in some countries, this type of activity is partially restricted or prohibited. This approach aims to support national road carriers. For example, the goods must be unloaded at the point closest to the border and transported to the final point by a national carrier in countries where cabotage road transportation is prohibited. When carrying out international cargo transportation on routes from Eastern Europe (Ukraine, Moldova) to the European Union, the rules remain in force stating that Eastern European carriers can import and export goods to/from the European Union using pendulum road routes with/without reverse loading as well as circular routes with breaks that run between a maximum of three points (Fig. 1).

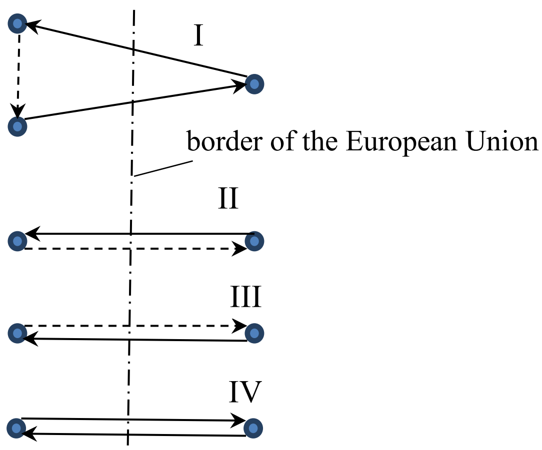
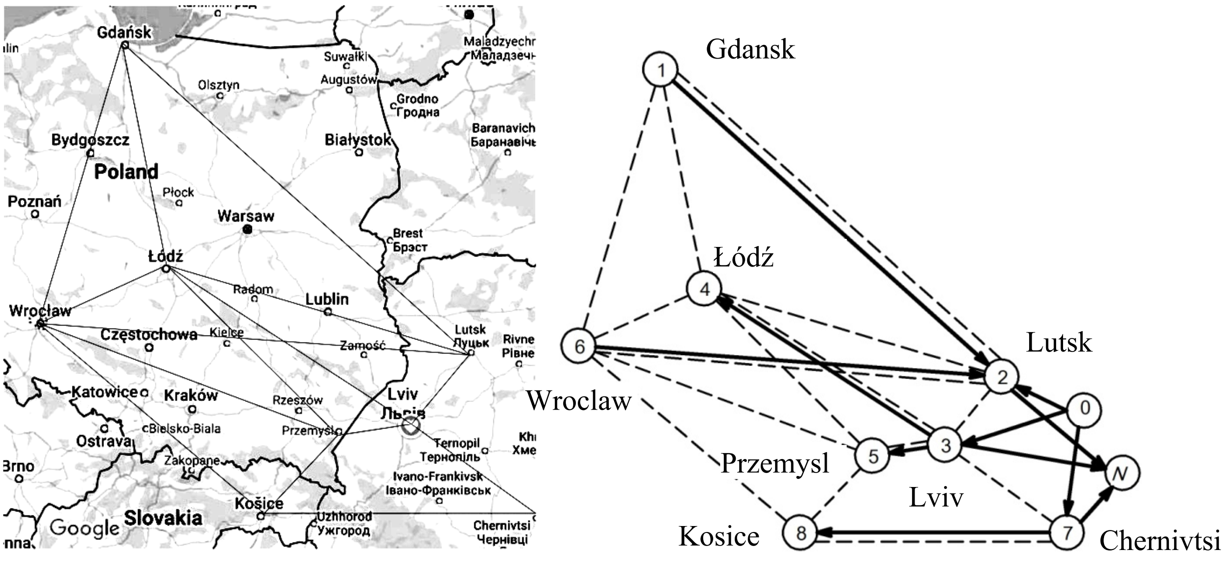


Fig. 1. Three types of routes restricted by non-EU carriers: I – ring route with a gap; II, III, IV – pendulum routes

Such routes are unprofitable and make it impossible to achieve the conditions of the efficiency of goods transportation for one truck because they contain a considerable mileage without cargo, or idle time waiting for loading. However, if we consider such a set of orders for which the total wasted mileage is minimized, this gives a positive meaning in achieving a solution to the problem. For example, if we combine two orders that are executed on routes of type II and III, we will get a more profitable route. The task acquires distributive content. The physical content of the problem is as follows. The truck freight carrier has production bases in various cities in Eastern Europe (Ukraine), from which cargo is transported. During a certain horizon of work planning, the carrier receives orders for large-group transportation, which relates to the exchange of goods between Ukraine and the countries of the European Union. As a rule, carriers in Eastern Europe receive orders for cargo transportation in three ways: through logistics intermediaries, from Internet resources, and from regular customers. Among the conditions of transportation, the permissible period of order execution is indicated, which we will call the order execution time window W (hereinafter, the time window). For some cargo transportation routes, the initial and final points coincide (Fig. 2).



a b

Fig. 2. Transport routes: a) the map and b) the model of routes: solid line – a trip with cargo, dashed line – trip without cargo

Each truck can be operated by a single driver or a crew of two drivers. The second method of team driving allows one to drive the truck for a long cycle without downtime for the drivers to rest. On the other hand, the use of tour drivers as part of the crew leads to low efficiency in their work. The driver's trip in the vehicle, but not behind the wheel, can be compared with spending time and money on the driver's rest outside the vehicle. However, drivers cannot adapt to the route of the vehicle while making transfers between points abroad on adjacent transport. According to rules 561/2006, such trips are not considered inter-shift rest, and this leads to the loss of the driver's time fund. The crew of each truck can change both on the territory of the country where the carrier is registered and on the territory of a neighboring country. In each case, the work and rest of the drivers must comply with the AETR agreement. Drivers can rest or change trucks only in the settlements indicated on the map. Drivers must return to the depot from abroad at the end of the transport cycle. Taking into account all the existing restrictions, it is necessary to form the work schedule of the drivers of all the vehicles involved in the process so that the total mileage and simple trucks were minimal, the orders were fulfilled in the shortest time corresponding to the horizon W, and the total amount of time spent by the drivers on a foreign business trip was minimal. The number of rolling stock units is not limited. However, it is not obvious that using more trucks translates into faster completion of the project.

3. LITERATURE REVIEW

The vehicle routing and crew scheduling problem (VRCSP) consists of simultaneously planning routes for a fleet of trucks and scheduling both individual drivers and all crews involved in a project [1, 2]. In these studies, the drivers are assigned to trucks, but there is a problem with their work schedule due to the inconsistency of the norms 561/2006 and the configuration of the routes. At the same time, it is assumed that the correspondence between the work of the crew and the duration of the use of the truck is not fixed (i.e., there is an absence of “binding” in time). This allows for more flexible planning and the more efficient use of the vehicle fleet. However, at the same time, the issue of coordination of the work of different crews and different cars becomes much more acute. In [3], a variant of VRCSP is presented in which pick-up and delivery requests with a time window are to be fulfilled within a given planning horizon using trucks and drivers. The crew can consist of one or two drivers, any of whom can be replaced in a given list of route points. In addition, drivers can move between cities in order to ensure a minimum number of trucks in the event of a lack of available drivers. The novelty of this task is that the trucks play a dual role: in addition to fulfilling transportation orders, they can be used to transport freelance drivers between cities. The authors propose a hybrid meta-heuristic algorithm for planning the work of crews according to the characteristics of truck routes determined at the first stage. This algorithm can provide a solution when crews can consist of one or two drivers using two stages of problem-solving. The results show that the effectiveness of the algorithm is mostly due to the possibility of partially violating some restrictions related to the possibility of changing the start time of orders. However, the conditions and limitations of the problem do not fully correspond to those that we formulated. In particular, the transportation described in the article is internal long-distance, so a greater variety of routes is possible. Secondly, according to rule 561, drivers who make trips between cities to take control of a free vehicle cannot rest. Thirdly, as a rule, the coordination of the work of drivers on international routes involves a partial determination of the duration of traffic on the route; thus, in this case, the transport task is solved.

There is a large gap between the practical requirements and the corresponding scientific work in the simultaneous planning and planning of the vehicle and crew. This refers to a situation in which the required vehicles do not have a fixed schedule and the combination of driver and vehicle is not considered an indivisible unit. The problem of simultaneous vehicle and crew routing and scheduling has been studied in works [4-6]. However, these works use two-stage heuristic algorithms, and the accuracy of the results is difficult to verify.

Regardless of the order fulfillment options selected, the hours of operation regulations are designed to help truck drivers get adequate rest and work safely [7]. However, the new AETR rules could lead to significant cost increases for international carriers, which have already been hit hard by rising fuel prices and reduced shipping demands. In addition, the new rules complicate drivers' schedules, not only limiting a driver's consecutive hours of driving but also increasing the amount of free time [8]. A mixed integer programming model and metaheuristics of annealing modeling were developed in [9] to cope with this complex problem. However, the proposed model should be extended to include the element of uncertainty (stochasticity) involved in the time windows, as well as to take into account the travel time between transport nodes. The model and procedure need to be modified to account for the multi-objective aspect (e.g., the trade-off between driver preferences and customer delivery requests) of the vehicle routing and scheduling problem.

Future research in this direction could dynamically account for changes in the delivery schedule using real-time communication between the dispatcher and drivers (i.e., to add new delivery requests or cancel existing delivery requests on the fly) [10, 11]. Blockchain technology could aid in this matter, as it provides a secure and transparent way to exchange data between different parties involved in the supply chain.

The model presented in [12] is flexible and can be adjusted to accommodate different sets of rules established by government regulations and union contracts. A dynamic programming approach is presented, and its effectiveness in regulating the working hours of drivers in the United States and the European Union is demonstrated. However, this model does not provide decisions regarding the selection and distribution of cars on routes—that is, the optimization of cargo flows is not performed).

In the classical formulation, the transport problem, which is actually the problem of optimizing cargo flows has undergone many changes related to its adaptation to real logistics processes. In particular, in recent scientific works, the method of solving it is substantiated, taking into account the capacity of communication routes, the time factor, as well as with the use of information technologies [13, 14]. There are also known problem statements for non-homogeneous cargo flows and limitations on the allowable delivery time.

The use of intelligent transport systems requires a more thorough approach to the analysis of operational information. Accordingly, the work presented the improvement of the methodology of drawing up schedules of cars and drivers and their implementation, taking into account the increase in requirements for their quality [14]. If the classification of known cargo transportation orders is based on compatibility, geographic location, organization, and urgency, a guaranteed solution to the complex task of operational management of transport crews under dynamic conditions of process execution can be found.

The task of forming an integrated delivery system for a set of non-interchangeable cargoes is considered in the study of the synergistic effect associated with the integration of elements of transport systems [14]. Each cargo flow was considered as given and consisted of admissible shipping groups. Each group $q_{i.j.l}$ is matched with sets of indices *i, j, l*, which refer to the point of origin, the point of destination, and the number of the group from the point of departure, respectively. The mathematical model of the formation of the integrated delivery scheme for this production made it possible, on the one hand, to clearly design the delivery route for each cargo group and, on the other hand, to take into account the possibility of simultaneous passage of cargo groups along the communication routes in order to reduce overall system costs. Such a model combines the constraints related to the optimization of the flows of individual groups of goods, which were solved by finding the shortest chains between two given vertices of the graph of the given network. However, the solutions derived from this approach are not completely adequate because the presence of several shipping groups at one transport point implies several transport cycles. In graphs containing loops or other closed contours, it is impossible to construct an unambiguous shortest path between any two vertices by existing mathematical means. Therefore, in the work mentioned [12], this difficulty was bypassed by applying, again, the decomposition and aggregation of the general problem. With such a decomposition, the guaranteed optimum is not provided; instead, it is replaced by a lower estimate.

The objects of ordering in each of the known problems of flow optimization on networks are single (non-cyclic) flows that need to be processed during a limited and known fixed period [16]. Only a few works attempted to consider the problem of flows on networks in dynamics, that is, the duration of the period when information about them changes [9,11,14]. However, these works relate to the long-term planning of the development of transport networks and cannot be used for operational planning.

Therefore, the solutions to the dispatching problem have a higher level of quality, if they are obtained in a complex way with routing and distribution of trucks according to known orders. This is achieved by the integration effect and a high number of alternative solutions. The formalization of the planning problem for a single route is not successful because a very large number of variables are required here. Considering the restrictions on drivers' work and rest modes, drawing up a schedule tied to a specific route is a complex problem and does not have a clear solution. Dynamic programming reduces the accuracy of decisions. Instead, the use of mixed graphs and binary variables creates the problem of scheduling truck drivers for a fleet of vehicles in a way that provides a guaranteed exact solution.

The purpose of this study is to develop a technique and a corresponding algorithm for finding a guaranteed optimal solution to the problem, which concerns the optimal distribution of fixed cargo flows between a limited number of vehicles, taking into account the norms of the duration of driving by drivers, with the prohibition of the use of circular routes in international transportation.

The methodology should increase the intensity of the operation of trucks by reducing their idle time, which is associated with the application of the variable method of work of teams of drivers, as well as idle driving on a set of routes. At the same time, the specified amount of cargo must be transported in full.

4. DESCRIPTION OF THE BASIC MATERIAL

A typical production problem that arises in medium-sized freight road carriers on international routes is as follows. For a certain period, there are known orders that must be completed according to their time windows W. Orders are fulfilled by a fleet of R trucks that have the same nominal capacity q_n. The order can be submitted as a set of trips ZW $=\{z_{i,j}\}$, where i, j are the numbers of the departure point and, respectively, the destination point of an indivisible group of goods $q_{i,j}$. Items i, j, which refer to one order, must be located on different sides of the EU border (see Fig. 2b). Groups of goods can be sent in any order, but each must be delivered to the destination no later than the allowed period W end. The size of the group cannot exceed the load of any of the given trucks (i.e., $0<q_{i,j}<q_n$). It is assumed that transportation cannot be combined by combining groups from different senders in one means of transport (consolidated cargo). Therefore, the problem concerns large-group transportation. A $z_{i,j}$ non-divisible group of goods can be exported from i sender to j customer. After transporting group $q_{i,j}$, some trucks of the existing fleet can travel to the next point x to load another group of goods and deliver it to point y. However, it has to make a useless run. If a truck can be loaded at point j, then, accordingly, there will be no wasted mileage. If not, then all cargo has to be removed from the point. Then, the truck can return there, making a repeated transport cycle with the maximum load power. Therefore, all R trucks from the fleet perform combined routes consisting of cargo and idle runs, along with pendulum and ring routes. All trucks must complete the joint task for the directive period W for the minimum total duration of movement, $T=\Sigma tr_i$, where tr_i is the duration of the transport cycle of truck i. In one cycle, truck i can be used to fulfill several orders. At the same time, the condition of movement must be fulfilled, where t_i is the duration of the transport cycle of truck i. Truck i can be used to fulfill several orders in one cycle duration. At the same time, the condition must be

$$tr = td_1 + \ldots + td_i + \ldots + td_u,\ i = 1 \ldots u, \tag{1}$$

where td_i is the duration of daily work of the i-th driver/crew of drivers, after which the driver must have their daily rest according to the corresponding selected cycle, and u is the maximal number of drivers. The time td_i should not exceed the maximum values allowed by regulations 561/2006. If condition (1) is not fulfilled because the duration of the cycle tr is greater than the right part of the expression, then one of the following actions is taken:

a) the nine-hour maximum daily driving time of the driver is replaced by 10 hours, which is allowed twice a week;

b) the single trip mode of drivers is replaced by a 21-hour maximum working time of two drivers in a crew;

c) the number of changes n in expression (1) increases;

d) the number of orders that one truck fulfills in one transport cycle decreases;

e) the structure of the truck transport cycle is revised, as a result of which the left part of expression (2) changes.

If condition (1) is not fulfilled because the duration of the cycle t_r is less than the right-hand side of the expression, it does not violate the conditions of the task, but the working time of the drivers is used incompletely. Therefore, this task must be solved according to another criterion which compares the cost of transport downtime, late order fulfillment, and drivers' wages.

Due to the variety of routes, there will be uneven employment of trucks for the execution of various orders:

$$W > \frac{T}{R}. \tag{2}$$

The greater the numerical value of W, the greater the volume of transportation (with stationary sources of cargo flows). On the other hand, large volumes of transportation require significant transportation capacities of the fleet (i.e., an increase in R). We will consider the optimal transportation plan to be that which achieves the minimum duration of all vehicle trips and maintains equality (1) and for which inequality (2) leads to equality, which entails an even loading of the truck fleet. According to this formulation, the task of compiling the work and rest schedules of drivers consists of applying the algorithm of the most dense "packing" of cycles $t_{d.i}$ in each cycle t_r, which is developed first, based on the solution of the problem of routing trucks when fulfilling given orders [11]. The routing problem is presented in the form of a graph, and the solution is presented as the operations on it.

The mixed graph of the transport network $A(G,U,V)$ is considered (see Fig. 2b), where G_i – set of vertices – transport nodes, i=0...n, U – set of arcs, and V – set of edges (i.e., connecting paths). The arcs of Graph A are weighted. Each arc is given a weight of $t_{i.j}$ – the duration of the run along the specified connection path plus the duration of preparatory and final work with the cargo at points i,j. If there is no direct connection between any two vertices i,j, then $t_{i.j}= +\infty$.

The arcs are also matched with a matrix of potential cargo flows ($Q_{i.j}$). Considering the load of the vehicles $q_{i.j}$ carrying out the transportation, the potential freight flow $Q_{i.j}$ consists of several trips. If $Q_{i.j}>0$ and $t_{i.j}>+\infty$, but $t_{i.\xi} \ll +\infty$ and $t_{\xi.j} \ll +\infty$, then the flow $Q_{i.j}$ decomposes into two elementary flows: $Q_{i.j}=Q_{i.\xi} = Q_{\xi.j}$. So, each nonzero element of the matrix ($Q_{i.j}$) corresponds to a pair of adjacent vertices of graph A.

Among the vertices of Graph A, there is a set G_φ of those from which the cargo flows originate (i.e., the sources: $Q_{i.j}\neq 0$, $g_i \in G_\varphi$) and the set G_ψ of absorption vertices for which $Q_{i.j}\neq 0$, $g_j \in G_\psi$. One of the features of this model, in contrast to known models of transport flows, is that the source vertices can be sink vertices: $G_\varphi \cap G_\psi \neq \{\varnothing\}$. These are vertices 2 and 6 in Fig. 2b. However, Graph A has no loops (i.e., weights $t_{i.i}$=0 and $q_{i.i}$=0).

Graph A has the vertex g_0, which we call the initial vertex, which is connected by arcs to the vertices of the set G_φ (i.e., the following conditions are fulfilled: $q_{0.i}\neq 0$, for any $g_i \in G_\varphi$ and $g_{j.0}$=0 for any j). The final vertex of the graph is g_N. The value $q_{j.N} \neq 0$ for final vertex N, and for any other vertex $g_j \in G_\psi$. Between the initial and final vertices of Graph A, there is a countable number μ of chains. Each chain of $\upsilon_1 \ldots \upsilon_\mu$ consists of at least one arc (0, i), one arc (j, N), and one arc (k,p), $i,j,k,p=\overline{1,n-1}$. Some integer, non-negative number R>0 is given, which corresponds to the number of trucks on the routes. It is necessary to find R chains that run from g_0 to g_N such that:

- the sum of the weights of all arcs included in all these chains: $\sum_{r=1}^{R} q_{i.j.r} = \sum_{i=1}^{n-1}\sum_{i=1}^{n-1} Q_{i.j}$;
- any arc included in the r-th chain has a weight of $q_{i.j.r} \leq q_n$.

Each r-th chain, $r=1,2,\ldots\mu$ is characterized by the following period:

$$\tau_r = \sum_{i=1}^{n-1}\sum_{j=1}^{n-1} t_{i.j}, \tag{3}$$

where i,j are $g_j, g_i \in v_r$. The chain for which $\tau = \max_R \{\tau_r\}$ is a critical path of Graph A.

The distribution of the fleet of vehicles according to tasks that have not yet been formulated but whose components are specified on the transport network has the content of such a task of ordering. Variables $x_{i.j}$ are used to symbolize the number of trips that a truck with a load capacity of q_n must make from the i-th to the j-th point, $x_{i.j}$={0,1,2,...}, carrying out transportation $q_{i.j}$. At the same time, the truck can pass through transit points. A linear model is formed. The criterion is the minimum total duration of the cycle is as follows:

$$\sum_{i=1}^{n-1}\sum_{j=1}^{n-1} t_{i.j} \cdot x_{i.j} \to \min. \tag{4}$$

This criterion corresponds to the purpose of this research because the transport cycle consists of trips with cargo, idling and downtimes associated with loading/unloading, and rest periods for drivers. At this stage of solving the problem, we can only affect the total mileage when performing routes. Therefore, criterion (4) does not provide an opportunity to evaluate vehicle downtime.

The variable restrictions are

$$\sum_{j=1}^{n-1} x_{i.j} - \sum_{i=1}^{n-1} x_{i.j} = 0, \tag{5}$$

which means that the number of flows entering any vertex except the final one is equal to the number of flows leaving this vertex,

$$\sum_{j=1}^{n} x_{0.j} - \sum_{j=1}^{n} x_{j.0} = R \tag{6}$$

means that the number of flows leaving the zero vertex is equal to the number of vehicles given by an integer R , and

$$\sum_{i=0}^{n} x_{n.i} - \sum_{i=0}^{n} x_{i.n} = -R \tag{7}$$

means the number of flows that enter the final vertex is equal to the number taken with the minus

$$x_{i.j} \geq \frac{Q_{i.j}}{qn}, \tag{8}$$

restriction on the minimum number of trips from the *i*-th to the *j*-th consumer, which will ensure the fulfillment of the known transport task (volume of transportation). This is the first stage of the problem since the determination of the number of trips $x_{i,j}$ does not indicate their temporal ordering. Solving this stage is not difficult, as it is generally suitable for the formulation of linear integer programming problems. Solver of Excel of MS Office 2010 was used under the simplex method option to solve this problem.

Graph has such a structure: $B(G, V_2)$, where G is the set of vertices, the same as those of Graph A, and V_2 is the set of arcs obtained as a result of solving the previous stage of the problem. The number and direction of the arcs correspond to the set of variables ($x_{i,j}$) of the problem, which is equal to 1. Graph B of the optimal runs obtained as a result of solving the linear programming problem contains cycles. From the 0-vertex to the final N-th, this graph has R chains (Fig. 3).

However, it is impossible to write them down due to the presence of cycles. Cycles are displayed by edges, which are pendulum routes or consist of closed loops. Transformations that lead to the elimination of cycles are used to arrange the mixed graph and find the critical path in it [12]. To do this, the edges are replaced with arcs, or they are removed. In this case, this cannot be done with the graph because each edge and arc has the content of actually planned runs with or without a load. Therefore, a method is proposed that involves two additional transformations: 1) the transition from multiple arcs (edges) to multiple vertices of the derived graph and 2) the synthesis of the event graph from the state graph.

A graph containing cycles can be detected by the matrix of variables ($x_{i,j}$). If the number ρ is determined for any *i*-th vertex, and it is equal to

$$\rho = \sum_{j=1}^{n} x_{i.j} > 1 \tag{9}$$

this is a sign that the graph has ρ cycles associated with the vertex *i*. Such a graph can be transformed into a set of chains leading from the common initial vertex g_0 to the common ending one g_N.
However, Graph B may contain several variants of such chains due to the uncertainty present in the structure of this graph. Therefore, for example, due to the branching of the paths from vertex 5 and the existing cycle 3-5 in column B, two variants of vertex chains can be written if there are two trucks on the routes (see Fig.3):

variant 1
truck I: 0–7–8–5–6–2–N
truck II: 0–3–5–3–4–1–2–N
variant 2
truck I: 0–7–8–5–3–4–1–2–N
truck II: 0–3–5–6–2–N.

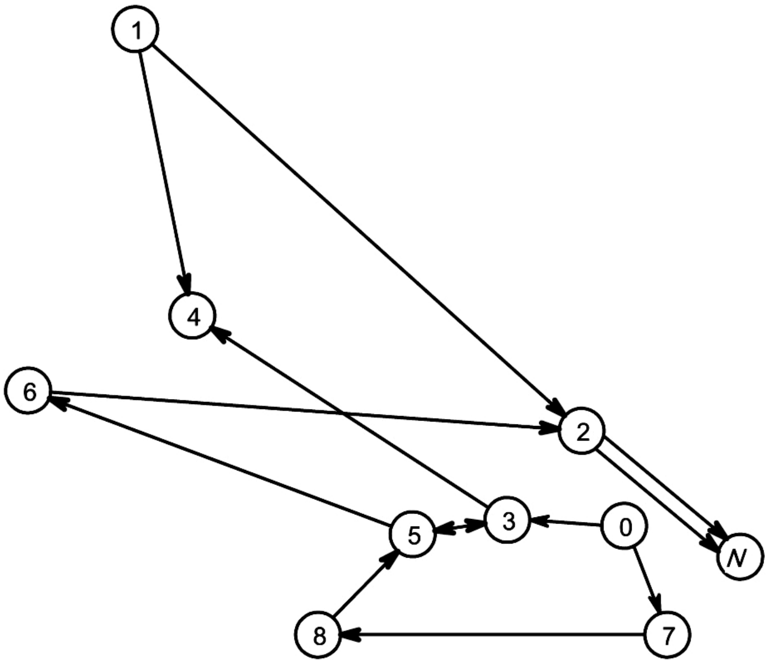


Fig. 3. Graph B of the optimal duration of runs on a given transport network of two trucks

As you can see, all the chains of vertices are united in some graph $C(G_2,V_3)$, where G_2 is the vertices of graph B plus duplicate vertices from B as many times as there are chain variants in Graph B, and V_3 is a subset of such arcs from the set of V_2 that connect all vertices (there are no isolated vertices) and do not form contours The number of chains in the graph is equal to the number of vehicles R involved in transportation. The arcs of Graph C are paths of alternative routes. Next, the variants of Graph C are denoted by indices C_k. A characteristic feature of each variant is that they do not differ among themselves in the parameters of the total duration of the transport cycle but only in the structure and maximum duration of order fulfillment. The set of options is shown in the complex Graph C, which has multiple vertices and the same arcs as Graph B. However, the complex Graph C does not contain contours, and from this graph, it is possible to synthesize an unambiguous optimal schedule of drivers.

Graph C_k is guaranteed to reflect the optimal schedule of vehicle trips, provided that the entire planned volume of cargo flows is fulfilled. Its functions are the total duration of all runs (with and without cargo) of trucks involved in the process, as well as time, as the critical path of this graph.

However, an ordered graph of truck routes C_k may not satisfy the work regulations of drivers and driving crews. Therefore, taking into account expression (1), which must remain equal, we select truck driving periods to obtain the minimum difference between its right and left parts.

However, equation (1) does not take into account the idleness of trucks, which occurs for such reasons as the loading/unloading of vehicles, the need for refueling or maintenance, and the need for regulatory rest of the driver/crew. In these studies, we assumed that the duration of cargo work and maintenance is a constant value that does not depend on the structure of the route or the schedules of drivers. Therefore, for the second stage of the algorithm, we offer a specification of Equation (1):

$$t_{mov} + t_{stop} + t_{load} + t_{fuel} = \sum_i \left(t_{drive} + t_{rest} + t_{serv} + t_{wait} \right)_i , \qquad (10)$$

where the left side values are driving time, idle time due to driver rest, loading time, and truck maintenance time, including refueling. The right-side values concern the i-th driver; these are driving time, rest time, vehicle and cargo maintenance time, and waiting time.

The task of the second stage is to select such components of the right-hand side of equality (10), in which the value t_{stop} on the left-hand side will be minimal while observing the general balance of time tr and regulatory restrictions of the components of the right-hand side. Considering that all the components of the left part of expression (10), except for the time of stops t_{stop}, are constant values found by the solution of the first stage of the algorithm, the criterion of the second stage is the minimum value *tr*. On the other hand, the components of the right-hand side of Equation (10) have regulatory restrictions that depend on the selected driving modes (nine-hour, 10-hour, and tour trip by a crew of drivers), as follows:

- t_{drive} – no bigger than 4.5 hours;
- t_{rest} – not less than 45 minutes per shift;
- t_{serv}, t_{wait} depends on the transportation process structure.

Thus, the only variable is $t_{drive.i}$ since t_{rest} might be minimal and $t_{drive.i}$ should be reduced.

The bin packing algorithm applied to this problem can be represented as a container of length *tr* in the time scale, which must be "filled" with segments of length $td_{.i}$, which are related to driving a truck. If the starting moment of the driver's required rest does not coincide with one of the moments when a new driver's shift can begin or the moment when the truck arrives at the loading point or at the depot, then the duration of the driver's rest is added to the length of the truck's cycle. Therefore, bin packing should be carried out such that, as often as possible, the duration of the driver's regulatory rest is not included in the duration of the vehicle cycle. In this way, the total length of the segments does not exceed the length of the container on the one hand, and the container must be filled. Such a task belongs to heuristics since there is no clear algorithm that guarantees its best solution. The following are used as signs of optimality:

a) if there are few $td_{.i}$ selection options, then the td_i selection priority is applied in descending order;

b) if there is a choice between decisions such as choosing the variant of routes design, which differ by the length of the container *tr*, or using a larger/smaller segment td_i, then, considering the indicator of the degree of freedom of the option, the choice should be made according to the option for which the remaining free time will be greater (Fig. 4).

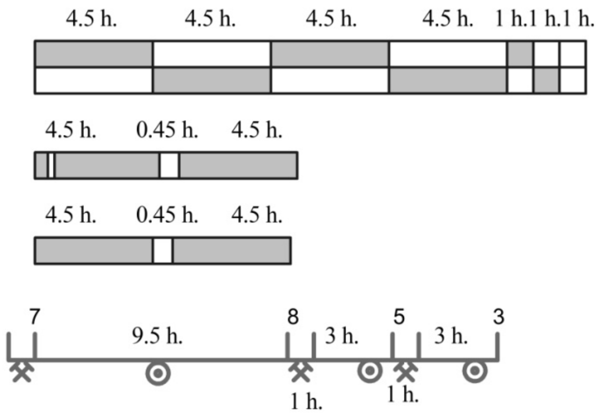


Fig. 4. Initial conditions and restrictions for driver schedules

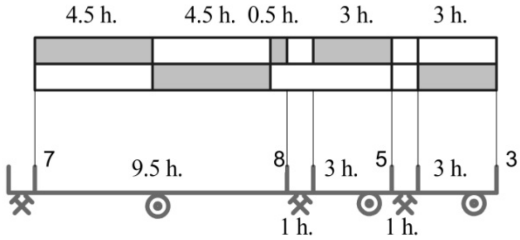


Fig. 5. "Packing containers" when making a driver's schedule

Let's consider an example. The container to be "filled" consists of six sections, each of which represents a specific type of truck occupancy on the route. In particular, the movement of the truck is planned for 9.5 + 3 + 3 hours. The other three sections are truck service at points 7 (depot 1), 8, and 5. The route ends at point 3 (depot 2). At depot 7, the truck is serviced, and this time is excluded from the duration of the transport cycle. We have a choice of three regulatory work and rest cycles for drivers in the form of time charts. The top loop shows the work of a two-driver crew. The shaded blocks of the time charts represent the driving time of the vehicle. These blocks need to be selected and the container needs to be filled, given that the blocks in each diagram are already partially ordered. Blocks can only be reduced in length, and unshaded blocks can only be increased. Using the sign (a) of optimality, we choose the top cycle of the work and rest of the drivers and arrange it relative to the prepared container. This choice gives us the advantages seen in Fig. 5. If our choice was a different nine-hour cycle, then the duration of the idle time of the truck increases by at least 0.45 hours. Since a dense schedule of truck traffic is obtained, the purpose of ordering is achieved.

5. APPLICATION

The proposed methodology was used on a practical example of the execution of orders for international cargo transportation by a Ukrainian carrier that has a fleet of trucks based in three cities: L'viv, Lutsk, and Chernivtsi. The carrier carries out the international transportation of goods by heavy-duty road trains both for import and export, mainly to neighboring Poland and Slovakia. The carrier receives the order from the logistics intermediary. The average intensity of receiving orders is five per week. Typical transportation routes are shown in Fig. 2b by solid thickened arrows. The carrier does not apply either the variable method of work of drivers or the trips of crews consisting of two drivers. Therefore, to fulfill five orders per week with a time window of three to four days each, the carrier uses five trucks per week. Based on the single-trip method, it was calculated that the average duration of one truck cycle for these orders is 44 hours, after which the driver should have another 45 hours of weekly rest.

We applied the developed methodology with a variable number of trucks using variable driving.

If R=1, the truck route looks like this: 0–7–8–5–3–4–1–2–3–5–6–2–9. The duration of movement along this route is 76 hours. The duration of the cycle is 84 hours, which fully corresponds to the allowance for cargo delivery in four days. At the same time, the truck runs for 55 hours with a load and idling under loading/unloading. However, the downtime for rest for drivers cannot be avoided. A shift driving method is also used, in which such a transport cycle is served by five drivers. There are forced stops in Kosice, L'viv, and Lutsk (Fig. 6).

The diagram shows the places of loading/unloading (crossed hammers), which conditionally take one hour according to the norms for one road train. The number of drivers participating in the process (not resting) is also shown. The drivers take turns driving the truck on sections 7-8, 8-5, 3-4, 4-1, 3-5, 5-6, 6-2. All norms of the maximum duration of driving and the minimum duration of rest are observed. Drivers rest outside the vehicle. Loading/unloading takes place with the participation of one driver from the crew.

When two trucks are used, R=2, their routes look like this (Fig. 7):

1st route: 0–7–8–5–3–5–6–2–9;

2nd route: 0–3–4–1–2–9.

The duration of the first route is 36 hours. There are no empty runs on this route, and there is no downtime associated with driver rest.

The duration of the second route is 47 hours. There are two trips without cargo on the second route, but there is no forced downtime. The total time of trucks used on the routes is 83 hours. In this case, the vehicles are driven by six drivers who work in pairs, shifting at the crossing points of both routes, for example, point 4 (Lodz). The use of a work shift method and three crews makes it possible to organize a daily rest for one of the crews and the non-stop movement of two trucks. However, such an organization is possible only if individual routes have common crossing points, where a truck or cargo is handed over to a changing crew.

The second necessary condition is that the start of the second route must be shifted by 4.5 hours relative to the start of the first. This was resolved after adjusting the schedules of the two trucks. An additional adjustment was made due to the need to reduce the required number of drivers.

If one organizes three optimal routes, they will look like this (Fig. 8):

1st route: 0–3–4–1–4–2–9, t_{r1}=36 hours, seven hours of running without cargo, no forced downtime;

2nd route: 0–3–5–6–4–2–9, t_{r2}=34 hours, 18 hours of run time without cargo, no forced downtime;

3rd route: 0–7–8–3–9, t_{r3}=16 hours, seven hours of running without cargo, no forced layover.

This type of schedule requires four drivers working in shifts.

A further increase in the number of trucks does not change the configuration of the received routes or drivers' schedules. Thus, with R=4 or R=5, we get similar routes with three trucks. This means that the circuit with three cars is maximally branched. The other involved trucks do not leave the park.

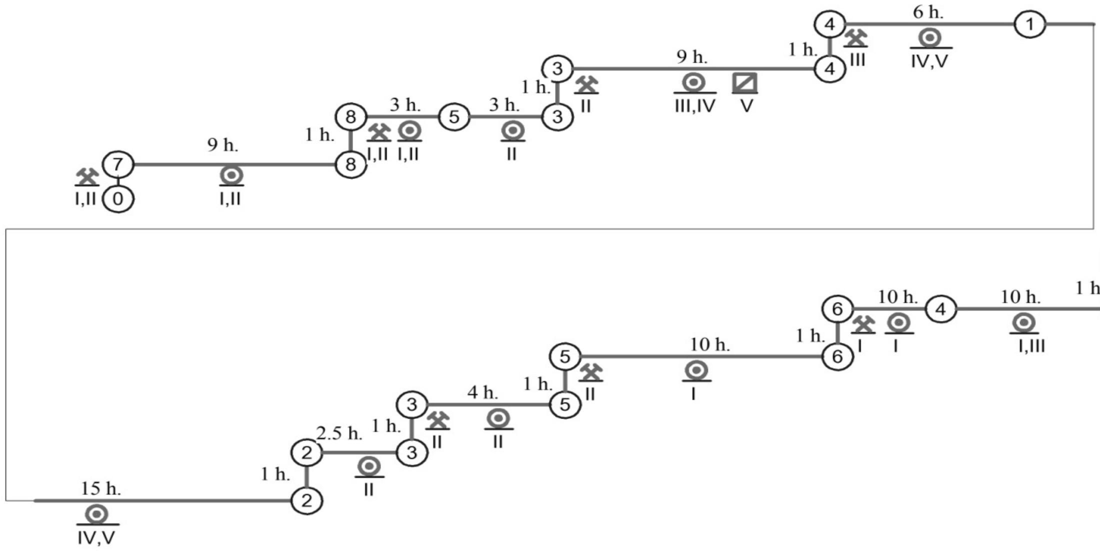


Fig. 6. The order fulfillment scheme when using one truck (a straight-line scheme)

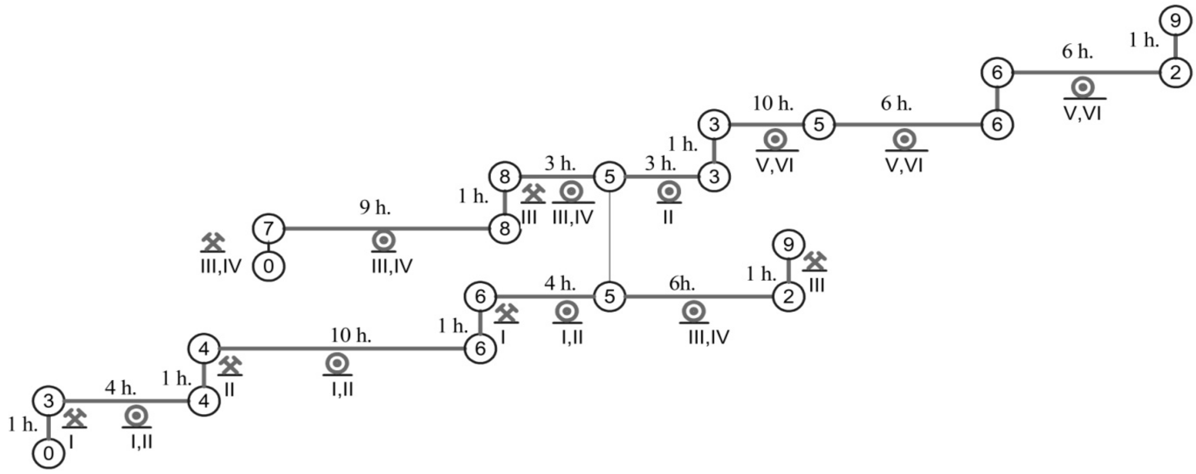


Fig. 7. The order fulfillment scheme when using two trucks (a branched scheme)

6. CONCLUSIONS

We came to the following conclusions after comparing the obtained results of organizing the work of drivers on international routes when applying the proposed method with those practically used by carriers, as well as analyzing various variants of the obtained results:

1. The contradiction between the problem of increasing the intensity of the use of trucks on long-distance and international routes and the requirement to observe the work and rest regimes of drivers can be resolved by applying variable methods of organizing the work of drivers. At the same time, the accompanying task of coordinating the work of individual crews and drivers arises.
2. In contrast to known methods, we obtained a set of exact, guaranteed optimal solutions to the problem of routing a group of trucks on international routes according to the criterion of maximum productivity while observing order fulfillment time windows. Previously, this task was solved together with the development of the optimal duration of the drivers' work schedules. Such a task is NP difficult in a strong sense due to the large number of variables and due to multicriteria. Often, the task did not present solutions that meet the restrictions set by regulations 561/2006. Because we

split up the complex task, the number of variables to design the driver schedule was greatly reduced. The second part of the complex problem can be interpreted as a container packing problem and solved by heuristic methods. At the same time, the field of possible solutions has been expanded due to the possibility of choosing variants of the vehicle control mode and the use of complex motor vehicle cycles. A necessary condition for successful coordination is the presence of a non-empty set of intersection points of various transport cycles.

3. The number of solutions to the problem can be varied if different numbers of trucks are used simultaneously and synchronously. So, when using one truck on several connected routes, we get a direct flow scheme. If several trucks that work at the same time are applied, the scheme is branched. The maximum possible number of used trucks forms a maximally branched circuit. It was shown that the direct-flow scheme is characterized by a long duration and significant downtimes and mileage without cargo using the example of international transportation between Ukraine and the European Union. The number of drivers that must be involved in the transportation is maximal. Branched schemes of transport cycles execute orders of a given planning horizon in a permissible time, which is included in the time window. They can be organized with the minimal forced downtime of trucks without idle mileage. A highly branched scheme is characterized by the minimal duration of the execution of all orders. However, with such a scheme, it is difficult to ensure that there are no wasted runs and no downtime.

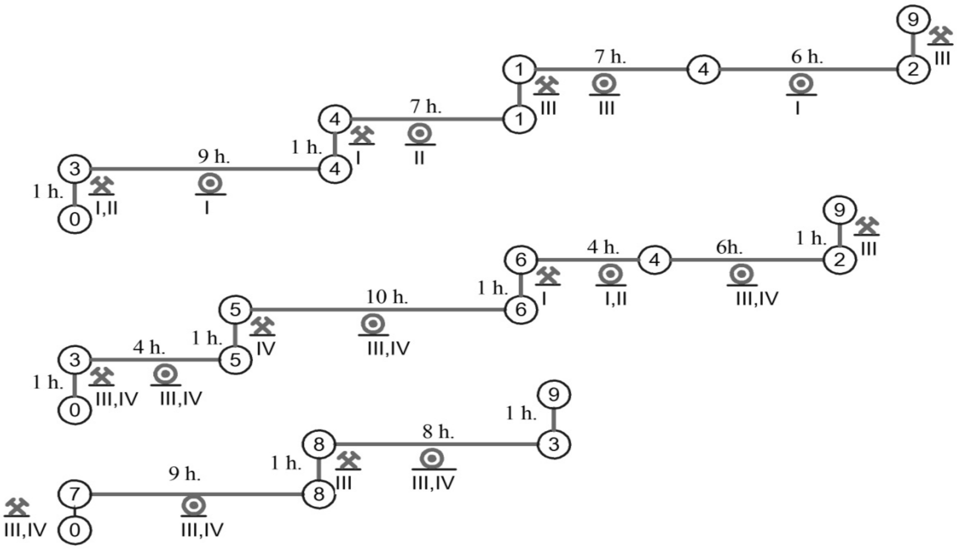


Fig. 8. The order fulfillment scheme using three maximally branched trucks

The proposed method for coordinating the driver's work can be used as a methodological basis for 5PL logistics. Further research involves the analysis of a wider base of transport and logistics processes and the systematization of the obtained results of their optimization.

References

1. Hokey, M. *Combined Truck Routing and Driver Scheduling Problems under Hours of Service Regulations Final Report.* Bowling Green State University. 2009. 47 p.
2. Maden, W. & Eglese, R. & Black, D. & et al. Vehicle routing and scheduling with time-varying data: A case study. *Journal of the Operational Research Society*. 2010. Vol. 61. No. 3. P. 515-522.
3. Lucci, M. & Severín, D. & Zabala, P. A metaheuristic for crew scheduling in a pickup-and-delivery problem with time windows. *International Transactions in Operational Research.* 2023. Vol. 30. No. 2. P. 970-1001.

4. Drexl, M. & et al. Simultaneous vehicle and crew routing and scheduling for partial-and full-load long-distance road transport. *Business Research.* 2013. Vol. 6. P. 242-264.
5. Lam, E. & Van Hentenryck, P. & Kilby, Ph. Joint vehicle and crew routing and scheduling. *Transportation Science.* 2020. Vol. 54. No. 2. P. 488-511.
6. Domínguez-Martín, B. & Rodríguez-Martín, I. & Salazar-González, J.-J. The driver and vehicle routing problem. *Computers & Operations Research.* 2018. Vol. 92. P. 56-64.
7. Melachrinoudis, E. & Min, H. & Shah, V. Combined truck routing and driver scheduling problems under hours of service regulations. *International Journal of Operations and Quantitative Management.* 2011. Vol. 17. No. 1. P. 29-47.
8. *European agreement concerning the work of crews of vehicles engaged in international road transport* (AETR) (Consolidated version). ECE/TRANS/SC.1/386/Add.1. 2010. 48 p.
9. Oliskevych, M. & et al. The optimization of trucks fleet schedule in view of their interaction and restrictions of the European agreement of work of crews. *Transport Problems.* 2020. Vol. 15. No. 2. P. 157-170.
10. Goel, A. & Vidal, T. Hours of service regulations in road freight transport: An optimization-based international assessment. *Transportation Science.* 2014. No. 48(3). P. 391-412.
11. Potvin, J.-Y. & Xu, Y. & Benyahia, I. Vehicle routing and scheduling with dynamic travel times. *Computers & Operations Research*. 2006. Vol. 33(4). P. 1129-1137.
12. Goel, A. The minimum duration truck driver scheduling problem. *EURO Journal Transportation and Logistic*. 2012. Vol. 1. No. 4. P. 285-306.
13. Prokudin, G. & Chupaylenko, O. & Dudnik, O. & et al. Application of information technologies for the optimization of itinerary when delivering cargo by automobile transport. *Eastern-European Journal of Enterprise Technologies.* 2018. No. 2/3(92). P. 51-59.
14. Maden, W. & Eglese, R. & Black, D. & et al. Vehicle routing and scheduling with time-varying data: A case study. *Journal of the Operational Research Society*. 2010. Vol. 61. No. 3. P. 515-522.
15. Pavlenko, O. & Muzylyov, D. & Shramenko, N. & Cagáňová, D. & Ivanov, V. Mathematical modeling as a tool for selecting a rational logistical route in multimodal transport systems. *EAI/Springer Innovations in Communication and Computing*. 2023. P. 22-37.
16. Yao, Yu. et al. ADMM-based problem decomposition scheme for vehicle routing problem with time windows. *Transportation Research Part B: Methodological*. 2019. Vol. 129. P. 156-174.
17. Oliskevych, M. & Taran, I. & Volkova, T. & Klymenko, I. Simulation of cargo delivery by road carrier: case study of the transportation company. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu.* 2022. No. 2. P. 118-123.

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