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OPTIMIZATION OF DRIVER WORK SCHEDULE TO PERFORM A SPECIFIED VOLUME OF INTERCITY FREIGHT TRANSPORTATION

Summary. *The article is devoted to the global problem of driver shortages in road freight transportation. One promising way to mitigate this labour shortage is to enhance the logistics of order fulfilment for the fleet of trucks and the drivers who operate them. This study proposes to discard all restrictions on the organization of work for drivers, except those established by European Union Regulation 561/2006, which affect fatigue and road safety. The object of the study is the work schedule of drivers while performing a given volume of intercity cargo transportation. The subject of the study is the influence of methods of work organization and driver interaction on achieving the minimum required number of drivers, provided that the given volume of transportation orders is completed on time and in accordance with EU Regulation 561/2006. In particular, it is proposed to abandon the assignment of drivers to vehicles and introduce a variable method, with the beginning and end of each driver's shift coinciding with the points of loading and unloading of goods. In this case, the complexity of the active schedule development methodology increases, as it is necessary to consider the organizational interactions of drivers on routes. Drivers are given the opportunity to transfer vehicles to each other and perform combined tasks. However, at the same time, they can rest only at the end of the shift without violating regulations 561/2006. Thus, the drivers' working time is used more efficiently. The task of building schedules is, in this case, NP-complex and its exact and guaranteed solution is not always available. However, the study used a modified method of ordering mixed disjunctive graphs to find such a solution. One of the modifications is that the field of possible solutions is limited by operations on the auxiliary graph used in the methodology. The structure of the auxiliary graph depends on the number of drivers who can be involved in transportation. Thus, the chromatic number of the auxiliary graph should not be greater than the specified maximum number of drivers. Another modification concerns the preparation of the content and the list of arcs of the main graph. The arcs are formed taking into account the early possible beginnings and late completions of transportation. It became possible to develop a heuristic algorithm for ordering the graph and obtain a guaranteed optimum with these changes. The algorithm was applied to a test model of transportation performance with different numbers of drivers and different options for limiting their work. It was demonstrated that under different conditions, it is possible to achieve varying efficiencies of order fulfilment, to use the minimum number of personnel. Thanks to the proposed method, it is possible to reduce the required number of drivers by at least 7 % compared to the current organization of their work, that is, without a variable method, fixed points of stay of drivers. The practical value of the proposed methodology and the corresponding algorithm lies in their ability to be successfully applied in the activities of road freight carriers, thereby partially addressing the problem of labour shortage. The results demonstrate the possibility of organizing the work and rest of a limited number of hired drivers in such a way that they will be able to complete 24 % more orders in the same amount of time,*

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while ensuring the maximum permitted duration of their truck driving and the minimum duration of shift and inter-shift rest.

Key words: *driver scheduling, shift method, driver interaction, mixed graph ordering, transportation logistics optimization.*

1. INTRODUCTION

Road freight transportation is a crucial area of business activity in Ukraine, particularly during wartime. According to the State Statistics Service of Ukraine, 354 million tons of cargo were transported by road in 2024, representing a 7.8 % increase from 2023. Freight turnover increased by 13 % to 184.5 billion ton-km. Experts predict further growth in these volumes. However, a significant obstacle to this is the exacerbation of the driver shortage problem. There is an acute shortage of truck drivers in Ukraine, which amounts to approximately 40,000 people, resulting in 30 % of the entire available fleet being idle [1]. The main reasons include mobilization, the migration of personnel abroad, and insufficiently attractive working conditions, primarily due to the lack of organized rest areas and an insufficient number of reservations for drivers. The same problem is recognized as active in other countries worldwide [1, 2]. In the USA, for example, the nationwide shortage of truck drivers was approximately 80,000 people in 2020, and it is predicted to increase to 160,000 by 2030 [1]. In the European Union, this figure has already exceeded 224,000 people, according to official statistics. Of course, the reasons for the outflow of personnel in Ukraine are significantly different from those of foreign carriers. Common reasons for the shortage of drivers in developed EU countries and Ukraine relate to aging, low attractiveness of the profession (irregular schedules, long downtime, and business trips). Furthermore, most importantly, the conditions for performing freight transportation are becoming more complicated due to increased regulatory requirements for drivers' work and rest periods [3–5, 6].

To solve this problem, transport industry experts predict the successful application of measures in three directions. First, it involves impoving methods for drawing up driver schedules, taking into account the restrictions outlined EU Regulation 561/2006, on the one hand, and enhancing methods for organizing the work of interconnected driver teams. The new schedules include requirements for their density, guaranteed accessibility, and reliability of execution, as well as the ability to find a guaranteed optimal option with an extensive database [5–8]. This direction is the most realistic in the short term. The second direction involves the use of autonomous vehicles controlled by automated systems, which reqiure minimal driver participation and therefore with minimal driver fatigue [1–3]. And the third direction is to increase the level of organization of transport processes using the appropriate telecommunication technologies that are being developed [9]. However, the last two directions can give the desired effect in the long term and are risky in terms of the payback of the relevant projects.

2. STATEMENT OF THE PROBLEM AND RELEVANCE OF THE STUDY

This study proposes a method to partially solve the problem of the shortage of qualified drivers by refining the methodology for creating optimal schedules for a team of drivers serving a single truck fleet. The research concerns the so-called fully loaded trucks. Transportation by a fully loaded truck is described as a transport chain with one link, where the source and sink are connected through direct, non-combined transportation, i. e., without changing vehicles and reloading. The type of cargo (except for special classes of cargo) does not affect the way to solve the problem. Universal vehicles are used for transportation.

Carriers receive a set of orders daily or over a more extended period (2–4 days) that need to be fulfilled by the existing fleet of trucks and the team of drivers assigned to them for a predetermined planned period of duration W. An order is the need to move a group of goods between specified points of the transport network. If the carrier is unable to fulfil the order in period W, then it is an opportunity to lose both the order and the client. The fleet of trucks is based in a depot. The fleet of trucks can be stored, serviced, and subjected to necessary repairs in the depot for an extended period. In some cases, there may be a requirement that the driver who has fulfilled the next order returns the vehicle to the depot. However, this article shows that such requirements significantly limit the actual time available to drivers. It is also assumed that drivers are not assigned to trucks, but use a shift method of work. At the same time, drivers can transfer the vehicle to their partners at any transport point through which the cargo delivery route(s) pass. The main condition that drivers must adhere to is compliance with the working regimes in accordance with the European Agreement on Road Transport Teams (EUTR). Here, the principle contradiction arises in ensuring the coordinated logistics of drivers: the duration of driving a vehicle does not always correspond to the permitted driving time as specified in regulatory acts. Similarly, the permissible duration of a driver's shift / inter-shift and variable rest does not always correspond to the duration of the order / several orders in a row, which can cause delays in the delivery of goods or result in the actual time of drivers being significantly underutilized. When building an optimal joint work schedule for a team of drivers, it is necessary to use the maximum number of drivers to fulfil N orders. The maximum number of drivers, P_{max}, is equal to the number of orders for the period W. In this case, the carrier will be able to fulfil all orders in the shortest possible time, but the drivers will not be busy for the entire working time, and the problem of their shortage will be exacerbated. On the other hand, drivers can be assigned tasks in such a way that each of them works the maximum shift duration within the permissible norms and at the same time fulfils several orders in a row or parts thereof, while meeting the requirements of the EUTR, and the number of drivers in the crew is minimal [4]. In this regard, the following goal was set to solve the formulated problem: to develop a methodology for optimizing the work schedule of a team of drivers, which would allow us to maximally exclude unproductive idle and unloaded trips from the schedule and increase the productivity of direct performers of a given volume of intercity transportation. Driver productivity will be defined as the amount of transportation work performed (in terms of mileage with cargo) per unit of time. To achieve this goal, it is necessary to solve two tasks: 1) to develop a methodology for building the densest schedule for a group of drivers considering the restrictions on the duration of their work and rest; 2) to conduct a study of the influence of initial conditions and data on the ability to obtain an optimal schedule for the implementation of a transport order by drivers. The main way to achieve the goal of the study is to save the working time of drivers, which is determined by EU Regulation 561/2006; however, the actual time may be significantly lower due to the absence of a dense work schedule.

3. ANALYSIS OF THE RECENT RESEARCH AND PUBLICATIONS

Analysis of recent publications has shown that the constructing effective schedules encompasses a wide range of transportation problems, where it is necessary to determine the optimal sequence or time intervals for performing a specific set of logistics operations [5, 7, 10, 11]. For some of these problems, effective analysis algorithms are known. For example, these are network planning problems, and the simplest tasks of determining the sequence of processing of different orders from two consecutive devices. For all other problems of this range, the proposed algorithms [5] are either heuristic or are built based on exhaustive search. For many schedule planning problems with different initial formulations, algorithms are needed that allow transforming the known schedule according to the variety of business situations [12]. However, there are no known formulations and methods for studying the task of compiling a schedule of operations that meet the following conditions at present moment:

- each order consists of consecutive operations: preparatory and working;
- the duration of the preparatory operation is unknown in advance, it depends on the sequence of orders being executed;
- each order requires resources, namely a truck and a driver / drivers, the number of drivers depends on the selected order execution sequence;
- each job requires a certain number of shared resources, the number of which is limited;
- the sequence of order execution is not limited, i. e. the tasks are independent;
- performers of different jobs are different and have different requirements for the quality of the schedule;
- there are no consolidated quantitative indicators of the quality of the schedule.

The main objective of the research presented in [13] was to propose a concrete mixer truck routing model to improve the efficiency of concrete delivery operations in terms of cost-effectiveness and optimal routing. In the process of formulating the problem in the mathematical model, it was represented as a mixed-integer linear programming model, based on the problem of routing large-capacity vehicles with time windows. This model was considered using both exact and heuristic methods. First, the model was considered by an exact method, the Gurobi optimizer, which uses the branch-and-bound method. However, considering that the vehicle routing problem is NP-hard, the complexity of the model increases with the number of customers and vehicles, leading to a corresponding increase in calculation time when solving the model.

In [14] and others, it has been shown that graphs are powerful tools for modelling service systems and scheduling problems. However, the complexity of these systems and their scheduling problems has increased significantly due to continuous technological development. Thus, it is essential to develop robust graph-based modelling approaches to address these complex issues. Despite the significant number of publications that apply graphs to scheduling problems, a comprehensive review is lacking in the literature.

Intelligent scheduling has been widely studied to manage transportation operations and increase the transportation capacity of carriers [8]. Some existing truck scheduling methods consider the critical parameter (i. e., truck speed) as a constant, which is impractical in real industrial scenarios. The authors proposed a multi-criteria optimization algorithm for truck scheduling, based on the criteria of minimizing waiting time, maximizing productivity, and minimizing financial costs. However, this algorithm is not suitable for driver scheduling, as it does not account for the time constraints of their work.

The complexity of the driver scheduling problem must match customer time windows, work periods, and regulatory rest requirements. These limitations were discussed in [5]. Although truck driver scheduling is a well-known problem, existing algorithms cannot cope with interdependent routes. In particular, the authors applied the route interdependence condition in the aforementioned publication. A mathematical model and label propagation algorithm are proposed in this paper to address the problem in accordance with EU regulations. Experiments show that the proposed algorithm can quickly plan a large number of interdependent routes and outperforms the mathematical programming approach [10]. The algorithm generates valid schedules for multiple drivers and thus becomes the basis for future vehicle routing algorithms that consider interdependent routes and work rules. However, this algorithm does not utilize the variable method of driver operation. It also does not account for the need for their interaction on the transport network when fulfilling a pre-known set of orders.

The influence of a fair attitude of the carrier towards hired drivers is of crucial importance for the personnel provision of motor transport enterprises. The uneven complexity of transport orders is often disproportionate to the drivers' salaries. This problem was solved in the article [15]. The authors tried to eliminate deviations from the average duration of trips on different tasks. Mathematical programming was applied. However, it is worth accepting the high price of the achieved fairness. It is an increase in the total time for performing all transport tasks.

We showed in the article [16] that algorithms based on the arragement of mixed (disjunctive) graphs are quite effective for compiling an optimal schedule in terms of speed. Heuristic approaches were used for this ordering, which ultimately led us to find a guaranteed optimum in terms of speed with acceptable accuracy and within a reasonable simulation time. However, the results obtained concerned truck schedules with no restrictions on the duration of their operation. The permissible number of drivers was not taken into account.

Researchers quite often use a two-stage process for schedule optimization due to the difficulty of providing a guaranteed solution to the problems. This approach, for example, was used in articles [17, 18]. However, the two-stage approach does not always ensure the accuracy of the solution.

Another type of problem combines two or three related problems in a single algorithm. The condition for the success of such a combination is to reduce the level of uncertainty at each step of the modelling [17]. The same approach has been applied in the complex planning of automobile transportation, considering the volume and duration of delivery [19].

After analysing the well-known publications on truck scheduling, it can be stated that multi-criteria, complex, or problems with many constraints require a heuristic approach to their solution. A promising methodology is the use of graphs as the most universal process models.

4. PRESENTATION OF THE MAIN MATERIAL

4.1. Formulation of a typical transport task

A typical transport task was considered on the example of transport services provided by a transport company in one of the territorial communities of Ukraine. The data were selected from real reports of an automobile company and are episodes from its past activities. One of these typical tasks is cargo transportation, which is carried out by a company between seven points, as shown in the graphic model of Fig. 1. Point *D* is the administrative centre of the community, where the truck fleet depot is located. The average time of movement of trucks between neighbouring points of the transport network is indicated above the edges of the graph in hours. This time was determined, taking into account the known average operating speed of trucks on each section of the transport network and the actual length of the section. The task of determining the shortest distance between any two transport points is trivial, known, and was not performed in these studies.

During the day, the carrier whose activity is being considered receives *N* orders, where the content of each order is the transportation of goods between some points g_i and g_j. The order must be executed no later than time *W*.

The carrier has at its disposal the maximum number of drivers (P_{max}) and *R* units of trucks to fulfil orders. The ratio $R/P_{max}>1$, according tothe research problem. In the example of the carrier mentioned above, this ratio reaches a value of 1.3 in specific periods (26–30 % of the rolling stock fleet remains in the depot due to the absence of drivers). Therefore, to save drivers' working time funds, they must: (a) not be "attached" to a specific vehicle, because this makes it impossible to use the shift method; (b) to start the work shift at the point that belongs to the shortest route of this order (first loading, transit point); (c) use the shift method of work, that is, transfer the vehicle (with or without cargo) at those points, the arrival times of which most closely correspond to the driver's fullest load in terms of time. In this case, work and rest regimes must be observed in accordance with EU Regulations 561/2006. Thus, if there is a known order for the delivery of goods $g_2 - g_6$, then, according to Fig. 1, the duration of driving the truck is 6 hours, and the duration of loading operations is 1 hour. Therefore, the possible schemes for fulfilling this order may be as follows.

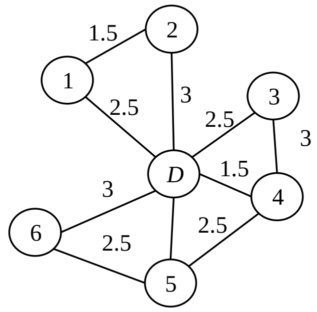

Fig. 1. Graph of transport links

The first scheme: driver No. 1 took over truck No. 1 at point g_2, where it was loaded. Then driver No. 1 drives the truck to depot *D*, where he hands it over to driver No. 2. In this case, driver No. 1 spent 3.5 hours of working time without a break for a rest and did not exceed the duration of the permitted continuous driving time (4.5 hours). In this case, the driver's No. 1 work shift has not yet ended, as he can take over another truck that is involved in executing another order. Driver No. 2 takes over truck No. 1. He drives this truck to the point g_5, where he participates in the unloading process. Driver No. 2 spends 3.5 hours of working time, also does not exceed the continuous work norm, and is ready to start executing another order that starts at point g_5. The total working time spent by drivers according to the first scheme is 7 hours, including 6 hours of continuous trips with cargo. There are no trips without cargo.

The second scheme: driver No. 1 took over truck No. 1 at point g_2, where he loaded it. Then, driver No. 1 arrives via a transit route to depot *D*, where he must make a short-term rest stop lasting at least 45 minutes. After that, driver No. 1 continues to move towards point g_5, where he unloads the cargo. After that, driver No. 1 is forced to stop his work shift, since its duration is already 7.75 hours, which is approximately equal to the maximum allowed value (9 hours) according to EU Regulation 561/2006. Driver No. 1 will not be able to start fulfilling any other order available on this transport network.

Comparing two elementary schemes for fulfilling only one order, we can note the following differences. The first scheme is flexible and economical in terms of working time, and its schedule is tight. However, implementing such a scheme requires a large amount of data on order availability , an effective algorithm for building an accurate schedule, and a corresponding system for its strict adherence. The second scheme is reliable in terms of the random nature of logistics operations, as it provides drivers with more lenient working conditions. However, the drivers' working time funds are underused, and the duration of order fulfilment is longer.

4.2. Schedule construction methodology

The mixed graph ordering methodology [16] was applied to display the process of fulfilling a set of orders on a transport network. The transport network graph $H(G, L)$ is considered, where G is a set of vertices $G = \{D, g_1, \ldots g_Z\}$, (transport points), L is a set of edges, communication routes (it is assumed that all network routes are two-way and the duration of travel along each route in the forward and reverse directions is the same (see Fig. 1)). The vertex D symbolizes the carrier's depot. Unlike known solutions, not all routes begin and end with D here. In this case, the depot serves as a temporary (inter-shift) storage point for trucks and a point for their maintenance.

The carrier must have a free vehicle with a driver at point g_x, or such a truck must arrive at the given point from the nearest one on time to start fulfilling an order for the delivery of goods between points g_x – g_y,. Thus, the initial data for compiling the driver schedule includes the graph $A(N, U, V)$, where $N = \{S, n_1, n_2, \ldots n_{\max}, F\}$ is the set of known transportation orders, S, F are fictitious vertices that symbolize the formal start and formal finish of the entire project (all orders specified for the period W), $n_{\max}$ is the maximum number of orders in the project; U, V are, respectively, the set of arcs and edges of the graph, each of which symbolizes the sequence of order execution. The arcs and edges of graph A are given the following content and quantitative assessment of arc weight:

$$a_{i.j} = t_{e.i} + t_{b.j} + t_{e.j}, \tag{1}$$

where $t_{e.i}$, $t_{b.j}$, $t_{e.j}$ – time points, respectively, of the latest completion of order execution n_i, the earliest start of order execution n_j, and the latest completion of order execution $n_{j.}$

Thus, the duration of the order execution by the driver significantly depends on the transport task performed before and whether this order was handled by another driver in cooperation. If there is an edge $v_{i.j} = \{u_{i.j}, u_{j.i}\}$ in the graph A, then this means that the orders n_i, n_j can be executed in any order. However, in order to determine the unique schedule of the drivers, there must be no positive weight contours in the graph A, i. e., the condition must be satisfied for any pair of orders $n_{i,}$ n_j:

$$-a_{j.i} \le t_{e.j} - t_{bi} \le a_{i.j}. \tag{2}$$

If there is an arc $a_{i.j}$ in the graph A for which inequality (2) is not satisfied, then it is called conflicting, and it is necessary to review the graph A in order to remove the arc.

Also, it is necessary to review all edges in the graph A and perform the following possible transformations with each of them:

a) remove the edge $[a_{i.j}]$, which means that orders n_i and n_j will be executed by different drivers independently;
b) replace the edge $[a_{i.j}]$ with the arc $(a_{i.j})$, which means that order n_i will be executed by the same driver before order n_j;
c) replace the edge $[a_{i.j}]$ with the arc $(a_{j.i})$, which means that order n_j will be executed by the same driver before order n_i.

The decision to change an edge is made based on the analysis of the degree of conflict of the edge. The first-priority transformations should concern the most conflicting edge [18]. The decision (a) to delete an edge is made based on the analysis of the available number of drivers. To do this, in addition to operating with the main graph A, we create and operate with an auxiliary undirected graph $H(N, V)$, the vertices of which are members of the set N. The graph H is constructed as follows. If the operation α_1 with the main graph is the destruction of the edge $[a_{i.j}]$, then the graph $H(\alpha_1)$ is obtained from the graph $H = H(\alpha_0) = (N,\varnothing)$ as a result of adding the edge $[a_{i,j}]$. If the operation α_1 is the replacement of the edge

$[a_{i,j}]$ by one of the arcs $(a_{i.j})$, or $(a_{j.i})$ in the graph A, then the graph $H(\alpha_1)$ is obtained from the graph H, identifying the vertices n_i, n_j with one vertex. If α_1 is the transformation of the edge $[a_{i,j}]$, $H(\alpha_1) = H(\alpha_0)$. The number of vertices in the graph H is not greater than the predetermined number of drivers $P_{\max}$. Having calculated the chromatic number $\chi(H(\alpha_{step}))$, we can determine the constraint that the presence of drivers imposes on the final optimal schedule:

$$\chi\left(H\left(\alpha_{step}\right)\right) \le P_{\max}, \tag{3}$$

where *step* is a number of modelling steps.

This condition means limited possibilities (to execute several orders simultaneously) due to the lack of the required number of drivers, an organizationally established sequence of execution, etc.

The understanding of a conflict edge is used to conduct a targeted search for conflict edges in graph A, i. e., one for which the inequality condition (2) is not satisfied. Among the conflict edges of graph A, the most conflicting ones can be found, i. e., those whose transformation leads to a greater search effect. To do this, for each conflict edge, it is necessary to find the heuristic value:

$$h_{ij} = t_{e.j}\left(N,U\right) + \vartheta_j\left(N,U\right) + a_{i.j} - \vartheta\left(N,U\right), \tag{4}$$

where $\vartheta_j(N,U)$ is the maximum weight of the path in graph A starting at vertex n_j; $\vartheta(N,U)$ is the longest path in graph A.

When choosing the most conflicting edge from all conflicting edges of the set V, we are guided by the value $\min(h_{i.j}, h_{j,i})$. For which edge the value found is the largest, we will call it the most conflicting.

The formal content of the task of constructing a schedule is that it is necessary to find ways ϑ_{ij} for all orders $i,j = 1\ldots N$. The weights of these paths determine the latest start times for each i-th order. In order for the desired schedule to be unambiguous (there was no time discrepancy), the condition must be met:

$$a_{i.j} \ge t_{e.j} - t_{e.i}. \tag{5}$$

The moment of the start of execution of any i-th order is searched together with:

$$t_{S.i} = \max_j\left(0, \vartheta_{i.j}\right), \quad 1 < j < N. \tag{6}$$

The moment of the end of execution of any i-th order is searched together with:

$$t_{i.F} = t_{s.i} + a_{i.F} < t_{e.i}. \tag{7}$$

A schedule for which condition (5) is satisfied for all orders and all trucks is called active, and the value $t_{i.F}$, calculated by (7), will be the earliest completion of the i-th order. There is a one-to-one correspondence between the set of all active schedules constructed from graph A and the set of all graphs that do not contain positive weight contours. Therefore, we consider the schedule generated by graph A, which does not contain positive weight contours, and hence edges V, to be unique [18]. A sequential analysis of variants is applied with an enumeration of all graphs from the set of admissible graphs, and the search among them for the optimal one according to the criterion of minimum project duration for a given number of drivers.

Considering the requirements of EU regulations 561/2006, arcs with negative weights $-a_{i.j}$ were used to impose restrictions on the schedule of drivers involved in the transportation process, which reflect the restrictions on the time of order fulfilment (Fig. 2). The time of movement of a truck between any two points of the transport network was determined based on information on the average operating speed for past periods.

Then, for example, if $t_{S.1.e} = 0$, $a_{S.1} = 2.5$ hours, $a_{1.2} = 3.0$ hours, $a_{2.F} = 2.5$ hours, $a_{2.S} = 4.5$ hours (maximum permitted 561/2006 duration of continuous vehicle movement), and $a_{F.S} = 9$ hours (maximum permitted duration of driver shift), then constraint (5) for path S–1–2–F is not satisfied by the duration of continuous run, but is satisfied by the maximum duration of shift for path S–1–F. If condition (4) is not satisfied for any edge or arc, then such edge and arc are

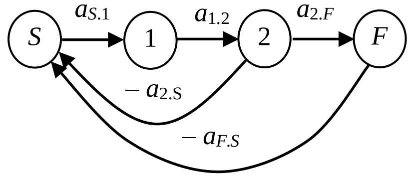

Fig. 2. Graphical modelling of operation duration constraints

called conflicting, and measures are taken to resolve the conflict. Therefore, in this example, it is necessary to use some intermediate point between points n_1 and n_2 for a short-term driver rest or to apply driver replacement. The interacting links, marked as $-\infty$, are actually absent or not considered.

The algorithm was programmed for computer problem-solving in the Delphi environment.

4.3. Example of solving a test problem

Let us consider one of the results of applying the proposed algorithm for compiling an optimal schedule for the execution of 13 orders on the transport network (see Fig. 1) for cargo delivery: 1) fictitious *S*; 2) 1–*D*; 3) 2–5; 4) 2–6; 5) 3–6; 6) 3–4; 7) 4–1; 8) 4–3; 9) 5–3; 10) 5–1; 11) 6–3; 12) 6–2; 13) fictitious *F*. The durations of transportation between the specified points of the specified orders constitute a vector of values (0, 2.5, 5, 4.5, 6, 5.5, 3, 4, 3, 4.5, 4.5, 5.5, 6.0). The total, net labour intensity of drivers to fulfil these orders is 53 hours. The allowed project execution time is 24 hours. Under such conditions, at least 10 drivers are required, which the carrier does not have.

A graph of the initial conditions of the problem was constructed. When applying the algorithm, the following solution was obtained with eight drivers (Fig. 3).

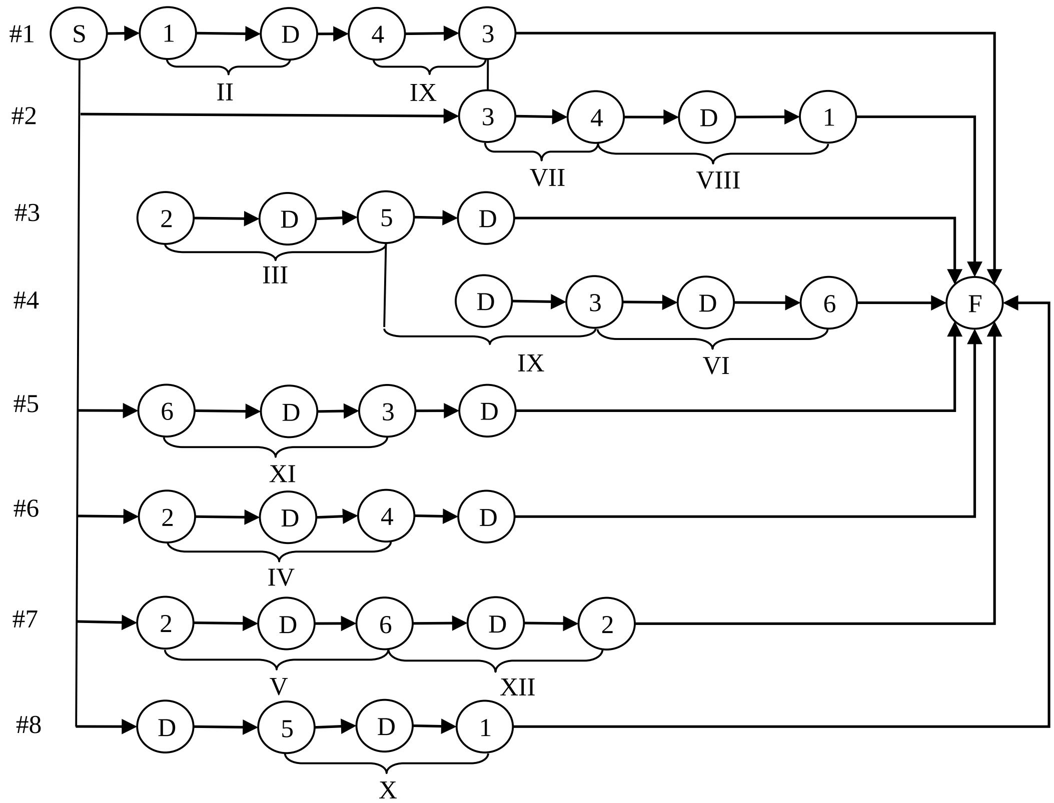

Fig. 3. Solution to the scheduling problem: #1–8 – driver number;
II–XIII – orders being executed; S, F – fictitious orders

The project duration is 17.5 hours. This duration is the time from the start of execution of all orders $t_{S.1.e} = 0$ to the completion of the last scheduled order (in Fig. 3, order VI, which ends at point 6). The maximum duration of the driver shift does not exceed 11 hours for driver No. 7, while the duration of driving the truck does not exceed 8.5 hours. For all other drivers, the duration of the shift does not exceed 9 hours, with an allowable duration of continuous driving of 4.5 hours each. The duration of useless runs does not exceed 7.5 hours for all drivers. The project deadlines are met. The algorithm is designed so to allow for changes to the maximum number of drivers involved and the maximum duration of the project. If these initial data are contradictory, an error is issued about the possibility of achieving positive results.

4.4. Research into the impact of the number of drivers involved on the duration of a set of orders

The algorithm was applied for three initial conditions: 1) drivers are not assigned to vehicles or to the departure point *D*; 2) drivers are not assigned to vehicles, but each of them must start and end the shift at point *D*; 3) drivers are assigned to trucks individually, and must also leave for the route and return from the trip only from point *D*. In each of the three options, the initial number of drivers varied from 12 to 6. Such limits were adopted for the following reasons. The maximum required number of drivers cannot exceed the number of orders. The minimum required number of drivers depends on: the total labour intensity of fulfilling all orders (53 hours, excluding unloaded trips); the maximum allowed duration of fulfilling all known orders (19.5 hours, or two driver shifts); and the nominal driver time fund considering the requirements of EU 561/2006 (9 h., 45 min.). If the number of drivers is entered into the schedule optimization algorithm as 5, then the corresponding computer program cannot find an acceptable schedule. It means that the minimum required number of drivers has been achieved according to the adopted heuristic. The obtained simulation results are presented in Table 1. The maximum duration of driving a vehicle by one driver is 4.5 h, according to Article 7 of the regulations 561/2006.

Table 1

Simulation results

Variant of initial conditions	Number of drivers	Minimum project duration achieved, hours	Maximum duration of driver shift, hours	Total duration of idle run, hours
1	6	22.5	10.5	12
	7	19	10	12
	8	**17.5**	**8.5**	**7.5**
	9	10	8.5	4.5
	10	8	9	4.5
	11	6.5	11	4.5
	12	6.5	11	2
2	6	56	11	24
	7	56	8	18
	8	**38**	**8,5**	**18**
	9	28	11	11
	10	22.5	11	10
	11	16	9	8
	12	12.5	9	8
3	6	175	10	35
	7	105	10	22
	8	**55**	**9**	**17**
	9	36	11	17.5
	10	26.5	9	12.5
	11	24	8	11
	12	22.5	11	11

The simulation results were obtained when applying the algorithm within the allowable time. The results enable one to select the optimal option based on the availability of human resources. The enterprise, for which the methodology and algorithm were used, has eight drivers as staff members. When applying three different options for the initial conditions to a staff of this number of drivers, the results, presented in Table 1 in bold, were obtained.

5. CONCLUSIONS AND PERSPECTIVES FOR FURTHER RESEARCH

The work schedule of a group of drivers is of primary importance in planning their employment. After all, the number of hired drivers depends on the planned duration of transportation and the work and rest regime of drivers in accordance with EU regulations 561/2006, on the other. The coordination of these conditions and restrictions can be achieved through schedule optimization. In this study, optimization was carried out according to the criterion of minimizing unproductive downtime and drivers waiting time, as well as unloaded truck runs. The optimal options differ significantly depending on the choice of initial conditions and restrictions. The best of all the above indicators is option 1, which confirms our assumption about the effectiveness of the variable method of driver work and the detachment of drivers from point *D*. With any number of hired drivers from the interval 12–6, the option of initial conditions 1 gives from 59.86 % to 48 % reduction in the minimum duration of the project compared to option 2. Compared to option 3, these ratios increase, respectively, by 78–71 %.

The maximum duration of the driver shift is a value that depends on the choice of the nominal work and rest modes for drivers and the constructed schedule. So, for the example shown in Fig. 3, the maximum duration of the driver shift No. 7 does not exceed 11 hours, and at the same time, he performs two orders, V and XII, and the duration of the driver shift No. 2 is 9.5 hours, while he also performs two orders, VI and VIII. The option of the initial conditions of the schedule does not affect the maximum duration of the shift for these reasons.

The total duration of the useless mileage of trucks depends on the sequence of order execution. Changing the initial conditions option can reduce this duration by 2 to 4 times if only the drivers are untied from the vehicles, and by 3 to 6 times if the trucks are untied from their long-term storage location.

For example, if the drivers are attached to the trucks and to the start and end points of the routes, then a team of 8 such drivers will be able to complete the transport task no earlier than a week later, taking into account the necessary inter-shift rest. Reducing the number of restrictions on the organization of drivers' work reduces their shortage when it is necessary to fulfil the order promptly. The optimal schedule is advisable for the first option under the initial conditions. If we compare the duration of the project for the first and second options with the same number of drivers, then in the first option is at least half as long as the second and three times shorter than the second option.

Thus, it can be argued that the developed algorithm for scheduling a team of drivers who work in shifts and are not tied to a specific place of inter-shift rest is an effective way to reduce the duration of cargo delivery, increase the driver productivity, and reduce the required number of drivers. Unlike known methods and corresponding algorithms, the schedule is compiled for a team of drivers, taking into account EU Regulations 561/2006, and allows one to reduce the duration of route runs.

The use of a parametric series of active schedules allows for an optimal decision regarding the number of drivers involved. An increase in the number of drivers results in a significant reduction in the project’s duration. However, this reduction is not linear. Thus, under the first variant of the initial conditions and the presence of 6 drivers, increasing number of drivers to 7 will lead to a 15.5 % reduction in the project duration, while increasing the number of drivers by one more will result in a 7.9 % reduction in the duration. In the second variant, increasing the number of drivers from 6 to 7 does not yield any positive results, and increasing to 8 drivers results in a 32 % reduction in the project duration. For the third variant, the change in the number of drivers is of cardinal importance. The duration of the project here changes from 40 to 105 % with an increase in the number of drivers. For the first variant of the conditions, the duration of all orders can be reduced threefold by increasing the number of drivers. However, at the same time, the driver’s productivity decreases, each team member becomes more autonomous in their work, so the integrative effect of their labour productivity decreases.

Thus, the developed methodology is an affordable way to improve the organization of drivers’ work and achieve the desired logistics indicators.

At the same time, it becomes clear that the proposed scheduling methodology can have a greater effect if applied to a much larger volume of initial data. It is the prospect of future research.

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ОПТИМІЗАЦІЯ РОЗКЛАДУ РОБОТИ ВОДІЇВ ДЛЯ ВИКОНАННЯ ЗАДАНОГО ОБСЯГУ МІЖМІСЬКИХ ВАНТАЖНИХ ПЕРЕВЕЗЕНЬ

Анотація. *Розглянуто глобальну проблему дефіциту водіїв для автомобільних перевезень вантажів. Один з перспективних напрямів уникнення цього браку трудових ресурсів – удосконалення логістики виконання замовлень для сукупності вантажівок і водіїв, які ними керують. У дослідженні запропоновано відкинути усі обмеження на організацію роботи водіїв, крім тих, які встановлені регламентом Європейського Союзу 561/2006, що впливають на втому і безпеку дорожнього руху. Об'єктом дослідження є розклад роботи водіїв під час виконання заданого обсягу міжміських перевезень вантажів. Предметом дослідження є вплив методів організації праці та взаємодії водіїв на досягнення мінімальної необхідної їх чисельності за умови вчасного виконання заданого обсягу замовлень і дотримання регламентів ЄС 561/2006. Запропоновано, зокрема, відмовитись від закріплення водіїв за транспортними засобами, запровадити змінний метод, а початок і завершення зміни кожного водія призначити в пунктах завантаження і розвантаження вантажів. У такому випадку зростає складність методики розроблення активного розкладу, адже потрібно врахувати організаційну взаємодію водіїв на маршрутах. Водії отримують можливість передавати один одному транспортні засоби, виконувати комбіновані завдання, але відпочивати лише після завершення зміни без порушення регламентів 561/2006. Так робочий час водіїв використовується ефективніше. Задача побудови розкладів є, в такому разі, NP складною і її точний та гарантований розв'язок не завжди доступний. Однак для пошуку такого розв'язку в дослідженні застосовано модифікований метод впорядкування змішаних диз'юнктивних графів. Одна із модифікацій полягає у тому, що поле можливих розв'язків обмежене операціями на допоміжному графі, який використовується в методиці. Структура допоміжного графа залежить від кількості водіїв, яких можна залучити до перевезень. Хроматичне число допоміжного графа не повинно бути більшим, ніж задана максимальна кількість водіїв. Ще одна модифікація стосується підготовки змісту й переліку* *дуг основного графа. Дуги сформовані з урахуванням ранніх можливих початків і пізніх завершень перевезень. Із цими змінами вдалось розробити евристичний алгоритм упорядкування графа й отримати гарантований оптимум. Алгоритм застосовано для тестової моделі виконання перевезень за різної кількості водіїв і різних варіантів обмежень їхньої роботи. Показано, що за різних умов можна досягти різної ефективності виконання замовлень, застосувати мінімальну кількість персоналу. Завдяки запропонованому методу можна скоротити необхідну кількість водіїв, щонайменше на 7 % порівняно з чинною організацією їхньої праці, тобто без змінного методу, закріплених пунктів перебування водіїв. Практична цінність запропонованої методики і відповідного алгоритму полягає у тому, що їх можна успішно застосовувати в діяльності автомобільних вантажних перевізників для часткового вирішення проблеми браку трудових ресурсів. Результати демонструють можливість так організувати працю і відпочинок обмеженої кількості найманих водіїв, що вони зможуть виконати на 24 % замовлень більше за той самий фонд часу, і при цьому їм буде забезпечена дозволена максимальна тривалість керування вантажівками і мінімальна тривалість змінного і міжзмінного відпочинку.*

Ключові слова: *розклад роботи водіїв, змінний метод, взаємодія водіїв, впорядкування змішаних графів, оптимізація логістики перевезень.*