TRANSPORT PROBLEMS 2020 Volume 15 Issue 2
PROBLEMY TRANSPORTU DOI: 10.21307/tp-2020-028

Keywords: scheduling; crews of vehicles; trucks fleet; disjunctive graph

Myroslav OLISKEVYCH*
National Transport University
1, M. Omelianovycha-Pavlenka Str., Kyiv, Ukraine 01010
Stepan KOVALYSHYN, Myron MAGATS, Viktor SHEVCHUK, Oleh SUKACH
L'viv National Agrarian University
1, Volodymyr Velykij Str., Dublyany, L'viv Region, 30831, Ukraine
**Corresponding author*. E-mail: myroslav@3g.ua

THE OPTIMIZATION OF TRUCKS FLEET SCHEDULE IN VIEW OF THEIR INTERACTION AND RESTRICTIONS OF THE EUROPEAN AGREEMENT OF WORK OF CREWS

Summary. The importance of compliance with the schedule of work of road trains on the highway transport network of the European Union is shown. The possible options for work and rest modes for truck drivers on international routes have been analyzed. A model for optimizing the truck fleet operation plan has been developed. This model has two levels, that is, the general graph contains subgraphs designed with incompatible vertices to determine the active and shortest schedule. Each of the subgraphs reflects alternative routes and schedules of a truck. The model also includes restrictions on the total cycle time and active period duration of available unloading points. To find the shortest schedule, integer programming with a guaranteed optimal solution was applied. Testing of the proposed algorithm was performed for the example of serving orders for international freight transportation between the cities of Ukraine, Poland, and the Czech Republic. The active schedule is based on the criterion of the minimum of the total duration of drivers' work. The results obtained are valid, consistent with the rules of the European Agreement. They indicate that the choice of the best schedule for a single car on a unitary route is not the best solution for the entire truck fleet and the entire flow of orders.

1. INTRODUCTION

Long-distance and international freight transportation in Europe is difficult because of the severe restrictions imposed on working hours and rest of vehicle crews. Doing these trips, drivers are required to comply with the European agreement on the work of crews of vehicles engaged in international road transportation (AETR) [1]. This leads to safety on the freeways, on the one hand, but complicates the efficient use of fixed assets, on the other. Use of trucks for rest or breaks by drivers reduce the productivity of vehicles and increases delays in the delivery of goods. The route parameters for delivery are not the same as the time constraints of the traffic schedules, very often. It also happens that drivers cannot rest due to the lack of parking spaces or deliver the goods within the short time of service of loading points, so-called time windows. All this leads to penal sanctions or to the loss of vehicle efficiency.

If one considers the use of a fleet of vehicles, which are linked by organizational and technological interactions, and have a unitary information support, then the above problem is easier to solve. In this case, the total time reserve of drivers of the aggregate of vehicles can be evenly distributed between the routes, which allows to reduce unproductive idle time. In this respect, it is relevant to harmonize the AETR requirements and and freight transport processes performed by the fleet of freight road trains.

2. ANALYSIS OF THE MODERN STATE OF PROBLEMS

The problem of coordinating the work of vehicles with other service units while ensuring timely and qualitative delivery of goods to their destination is mentioned in many modern publications, including articles [1, 4-7]. Researches describe various ways to solve the problem. In particular, paper [2, 6] states that harmonization of rolling stock and, for example, loading and unloading facilities is possible if one uses so-called "floating" timetables of vehicles. These allow to change the traffic time in a certain range (2-5%), due to transport delays or improper timing of the operation of cargo vehicles. From here, it follows that one can change the intervals of drivers' breaks and their rest over a period of 3.5 hours. For many customers of motor transport services, as well as carriers, the fact that it is possible to work on a "floating" schedule of vehicles' submission without probable financial risks for payment of penalty for late work can be extremely important. But most known studies show only the possibility to arrange schedules of drivers of different vehicles at terminals and warehouses. No real adjustment algorithms that would guarantee optimal ways to achieve this goal have been offered as yet [2].

Many studies have been devoted to the problem of vehicles routing for long distances. Some authors consider it the primary stage in the design of schedules [1, 4, 8]. In this case, known and modified algorithms are used: Dijkstra's [9], Ant [10], Annealing [11], etc. Most researchers tend to focus on complex solutions for the routing and scheduling problems [2, 4], especially passenger transport [5, 12]. However, the application of the labor rules of drivers of international crews significantly complicates the formalization of this problem. A review of some attempts to implement these rules is given in [11]. Mixed integer linear programming formulations of the time dependent vehicle routing problem (TDVRP) and the time-dependent traveling salesman problem TDTSP are presented as a sample that treats the travel time value as step functions. But the characteristics and properties of the TDVRP preclude modification of most of the algorithms that have been developed for the vehicle routing problem. Several simple heuristic algorithms are given for the TDTSP and TDVRP without time windows based on the nearest-neighbor heuristic. A mathematical-programming-based heuristic for the TDTSP without time windows using cutting planes is also briefly discussed before [12]. However, routing problems were discussed without selecting operating modes of drivers in these and other famous studies.

A unitary model for a single time-dependent truck routing problem, formulated in accordance with "Hours of Service" (HOS) rules, with several delivery points, and time windows is described in thesis [12]. The goal was to minimize the total time needed to service a certain number of customers. The greedy heuristic was used to generate appropriate initial solutions to problems that have been further enhanced by meta-heuristic simulation anomalies. These studies do not take into account the interaction of vehicles of fleet, and do not consider possible alternatives to schedules, because of the possibility of applying rules options.

Paper [13] presents a review of existing models of VRP, planner behavior models in the VRP context and driver behavior models, and provides a motivation to integrate these models in a stochastic traffic environment to produce practical, economic and driver-friendly logistics solutions. The paper provides valuable insights into the relevance of behavioral issues in logistics and highlights the modeling implications of incorporating planner and driver behavior in the framework of routing problems.

Work [4] explores the problem of truck driving scheduling a minimum length (MD-TDSP). This is a problem in determining a timetable consistent with current legislation, in which all work begins within one of the relevant time windows and has a minimum duration. However, the truck driver can only take rest periods in designated resting areas. Therefore, routing should be considered in conjunction with accessible highway locations where such rest is permitted. Therefore, routing should be "tied" to the geography of the highway region.

Assigning and scheduling vehicle routes are crucial management problems. It was considered in such a way with dynamic travel times due to potential traffic congestion in paper [14]. The approach developed introduces mainly the traffic congestion component based on the queuing theory. This is an innovative modeling scheme to capture travel times. The queuing approach is compared with other approaches and its potential benefits are described and quantified. Moreover, the optimization of the starting times of a route at the distribution center is evaluated. Finally, the trade-off between solution quality and calculation time is discussed. But time-independent solutions are often unrealistic within a congested traffic environment, which is usually the case on European road networks [15].

The problem of routing through countries borders and trucks queues at customs has an organizational and legal origin. However, some of its technical aspects have been studied in detail. The effect of customs procedures' duration on delivery time, taking into account the requirements of AETR, was investigated by N. Shramenko [16]. Customs procedures are a very significant constraint and an accidental factor that is difficult to predict, on the one hand, and that impedes the timely arrival to the destination. This is especially the case with the entry of vehicles and the importation of goods into the EU territory from Ukraine. However, there are subjective factors, which have no scientific interest here. Therefore, the timing of the customs procedures execution can be considered predictable if they are under proper control. A simulation applied in the mentioned above work requires a considerable amount of initial data and a long period of observations. Consequently, these research tools are not quite suitable for the synthesis of optimal scheduling of trucks. Paper [11] empirically demonstrated that reactive dispatching strategies based on some tolerance to deviations to the current planned routes (due to dynamic events) leads to better overall results. It is clear that more sophisticated optimization methods, such as meta-heuristics, can be considered to create even better solutions. But finding the exact solution to a formulated problem loses its meaning partially if one considers the availability of time windows in schedules, as well as a small number of mode choices, and narrow constraints on finding the optimum. It is enough to find an approximate solution using deterministic methods in this case.

Many scheduling models are based on the use of Petri-object modeling technology. Modern transport systems have a high level of complexity, namely, a large number of interconnected elements, heterogeneous processes of operation of elements and subsystems. Discrete-event modeling methods are most suitable for describing such systems. Each method has its own simulation advantages; thus, it is important to have such a formalization of the system that would allow both approaches to be applied. [17].

Exploring freight transportation over long distances, we can confidently say that the length of rest and break periods affects the overall time required for their implementation. Regulation of EC No 561/2006 defines rules regarding the quantity, duration and time intervals in the European Union. Well-known studies have proposed two mixed-purpose linear programming models and optimization strategies that, together with the conversion algorithm, allow one to plan the driver's activity in accordance with this rule for the sequence of customer locations and other stops that need to be made [1]. The first of the models takes into account all rules, including the advanced part, and the other takes into account regular requirements. Each client location has one or more time windows, among which a choice must be made. The peculiarity is the consideration of "soft" time windows that have not yet been studied in this context. If time windows cannot be completed, the resulting graph provides the controller with the important information needed to establish a better schedule. In online re-scheduling, the delay may be detected early. Therefore, it is possible to reorganize the schedule or discuss the time of arrival with clients, before costs increase. But, in any case, further delays or cancellations are inevitable. In addition, all mathematical models and algorithms can only "see" the route before the next termination of the client order, and this reflects the client's timeline and plans the driver's activity in advance, respectively. The main weakness of the described formalization methodology is the graph structure, the vertices of which are transport points. It is not consistent with the dynamic scheduling, where the main subjects of research are events, since the vehicle routes are selected earlier [6].

A hybrid genetic search with advanced diversity control is often used for solving the combined vehicle routing, and truck drivers' scheduling problem. Truck driver schedule planning is done for route evaluations with "soft" adjustment, which forwards labeling algorithms developed for the rules applied in different countries of the European Union. Considering Directive 2002/15/EC, researchers include multiple time windows and allow penalized lateness with respect to the time window constraints. However, lateness is only allowed to facilitate transition between structurally different solutions during the searching and there, where any voluntary increase of lateness at a customer location for the purpose of reducing lateness at subsequent customers is forbidden. Furthermore, Goel and Vidal present an international comparison of the economic impact of different hours of service regulations [18].

The results of another study demonstrate the crucial effect of time-varying of speeds on a real goods delivery. Ignoring this issue can lead to delays on the routes, producing unacceptably long duties for drivers. In this case, there were no time-window constraints on delivery service. But where these are important, ignoring time-varying speeds can lead to missing delivery time windows as well. The next step in this research should be to modify the algorithm to find the set of routes that will produce these routes that directly minimize the delays, still taking account of the time-varying speeds due to patterns of congestion and queues. [19].

3. METHODICAL APPROACH

The common disadvantage of all the works discussed above is that they have attempted to formalize transportation processes, which are difficult. Therefore, a large number of variables were used, and the algorithms were complex and did not provide an exact solution. The purpose of our research was to clarify the formulation of the problem, but at the same time to take into account that the routing of several vehicles will be applied simultaneously, and their effective interaction is taken into account. We proceeded from the fact that to fulfill most of the orders for international carriage, the carrier may choose one of the alternative routes, which may differ in length, the presence of congestion and obstacles, and therefore, the speed of movement. Each alternate route may also have a different number of transport points, where rest, break, refueling, loading or unloading of the vehicle can be set.

The following assumptions are applied:

1) drivers are assigned to vehicles, and do not change until the end of the planning horizon;
2) duration of loading/unloading operations, customs control and movement along a given highway at a certain time are values that can be predicted with sufficient accuracy;
3) drivers' rest may only be provided in predefined places such as a fixed parking, a motel or a gas station; and
4) since the considered routes do not exceed 500 km, each vehicle is operated by one driver.

Alternate routes can be diversified by developing options for acceptable driving times and rest schedules. They are obtained by applying the allowable options as it is done in [1]:

- split of required breaks;
- split of time of daily rest;
- reduction of daily rest time; and
- increase in daily driving time.

Note that the last two options reduce the driver's running time for subsequent cycles; thus, the scheduling options differ in their advantages and disadvantages. For example, we will show the variants of cargo transportation on the route L'viv (Ukraine) - Bydgoszcz (Poland). Figure 1 shows a map of the route from Google Map, which presents three alternative routes, respectively, along the highways E40, E371 and E372. Each of the highways is characterized by the level of traffic intensity, and the time of its passage, as well as the presence of temporary obstacles in the form of repairs, or other congestion. The execution of the order includes the preparation operations at the departure of the truck, a drive to the place of loading in L'viv city, movement on separate sections of the highway, customs procedures, fueling and unloading at the destination.

Fig. 2 shows variants of schedules for the execution of an order in the presence of one driver.

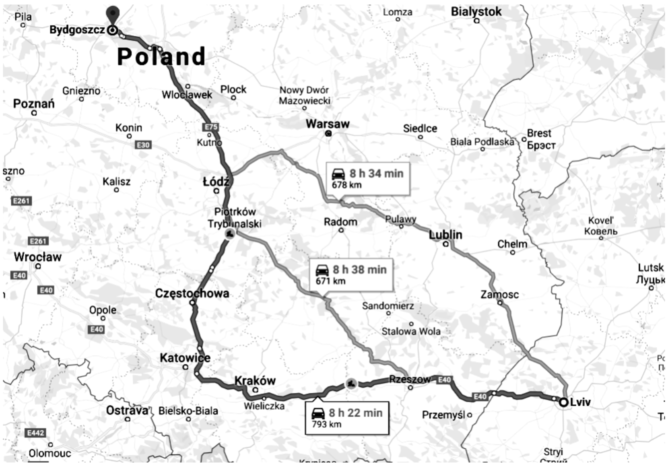

Fig. 1. Route map L'viv (Ukraine) - Bydgoszcz

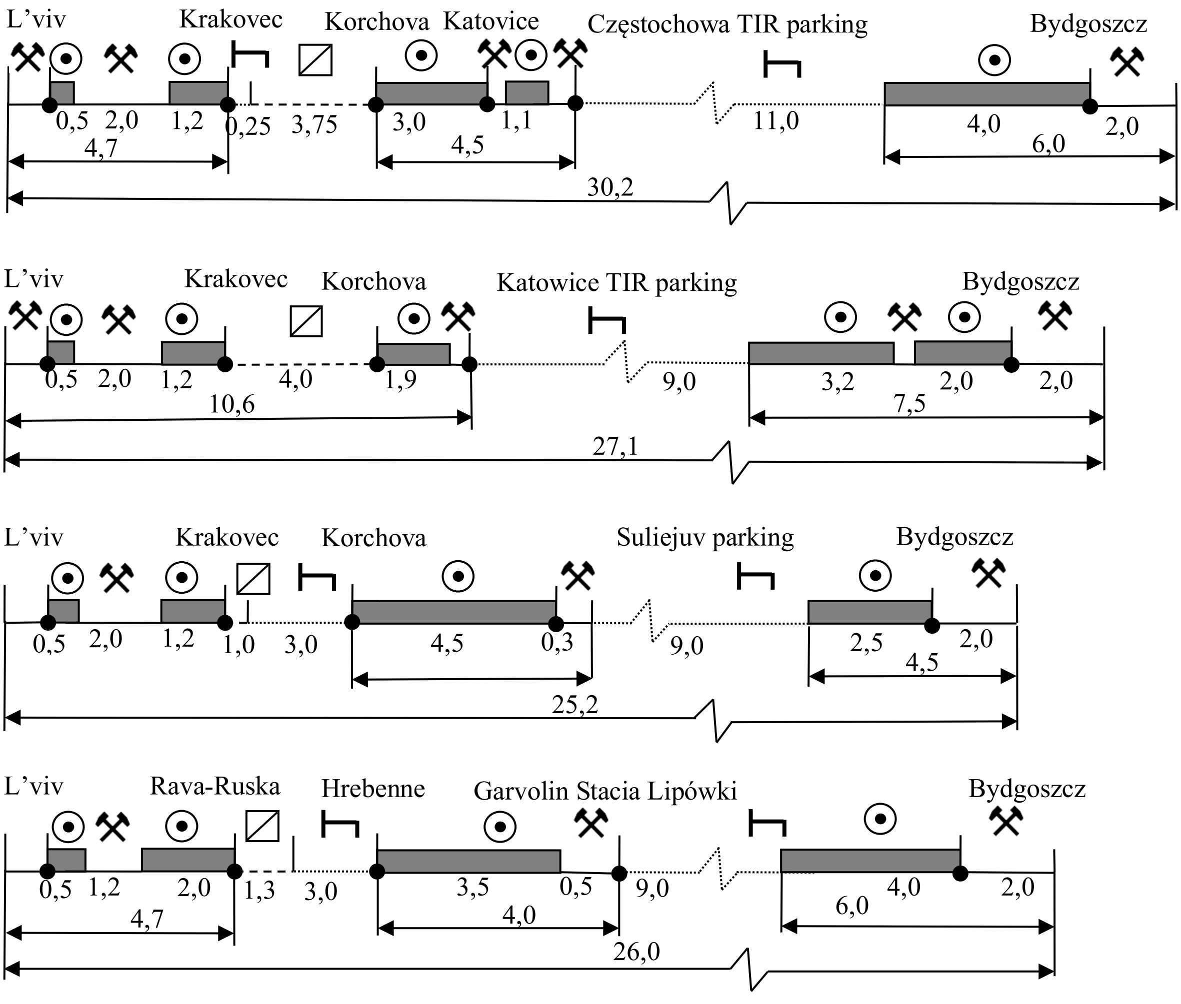

Fig. 2. Process scheduling options

The version in Fig. 2a focuses on movement through highways E40 and E75, through Krakow, Katowice, Częstochowa and Lodz. The duration of loading in all variants is 2 hours. The average duration of idle time at the section Krakovets-Korchova is 4 hours.

Due to the fact that most of the custom control time at this section is the expectation of the beginning of customs procedures, then, the schedule in Fig. 2a includes the first part of the split break of 15 min to reduce unproductive downtime. The daily rest time is not reduced here. The duration of driving is increased up to 10.2 hours. The total cycle time is 30,2 hours. After this cycle, the driver can perform the next unplanned duty cycle.

The same route, but carried out after an extended working shift, leads to a reduction of cycle duration by 2,5 hours – 27,1 hours. (Fig. 2.b). But in this case, the execution time of the subsequent orders, or the movement to the next stop point may be longer due to the need to apply the requirement of Art. 6, pp. 2 and 3 of the AETR. Other schedules are also created on the basis of the requirements and regulations (Figures 2.c-d). If the driver of this vehicle receives other orders after completing the order A) L'viv-Bydgoszcz, he will perform them with varying success, which depends on:

a) the chosen option of the schedule A and

b) the chosen version of the next schedule B.

This provides grounds for formulating and solving the problem, which is to combine possible alternatives, taking into account the following conditions:

a) available free vehicles;

b) acceptable planning horizon; and

c) available orders.

The problem of vehicle fleet scheduling on long-distance and international routes is complex and has a much larger field of variables. The variability of the problem is due to the fact that the choice is made not only among alternative routes but also among the sets of schedules of work of transport crews. Unlike the known methods, this task is complicated by the variable sequence of tasks. This takes into account time windows, as well as the presence of several vehicles, which can be applied with different efficiencies to perform the same transportation task.

4. FORMULATION OF THE PROBLEM AND DEVELOPING A SOLUTION

4.1. Terms, variables and restrictions

The problem is formulated as follows: the set of orders $P=\{1, 2, ... , p\}$ for the period T is given. Each p order can be made by k_p alternative routes. The minimum value of k_p is 1. There are $k_{p.i}$ schedules for each route that are created in advance. Therefore, there are k options for order fulfillment. Alternative options for each of the orders are incompatible over time. Among all alternative routes and corresponding schedules for the same order, at most one must be selected.

The set of trucks $M=\{1, 2, ... , m\}$ is given. All trucks of set M belong to one fleet. This means that each of them may be used to fulfill the order of P. But the location of M vehicles at the transportation network differs. Therefore, schedules of the same order fulfilled by different trucks differ too.

Each i-th order may have the following characteristics:

a) $\left[t_{b.i}, t_{e.i}\right]$ − time windows, where $t_{b.i}$ − the earliest time of shipment of point p and $t_{e.i}$ − the time up to which it must be completed; each order may have several time windows during the planning horizon;

b) $t_{o.i}$ − the actual starting moment of the i-th order execution;

c) $t_{f.i}$ − the actual completion moment at the final point of delivery; and

d) T_i^k − the mathematical expectation of the duration of the order for the alternative schedule k, k=1..m, calculated with the assumption that the driver who performed it pre-completed the weekly cycle of driving and had the appropriate period of rest, that is, it does not depend on the pre-completed work.

Overall, it is necessary to find an optimal sequence of fulfillment of orders with a given set of vehicles M. We call this sequence a project. The goal of reseach is to design a project of minimal duration within the framework of the planning horizon *T*. All restrictions on the modes of work and rest of drivers, as well as the timeliness of orders must be met. In fact, this task requires a comprehensive implementation of the following actions:

a) distribute existing vehicles to the tasks, with the condition of obligatory engagement of all *m* of them;
b) choose the rational sequence of execution of orders by each of the involved trucks; execution of all known orders is not required; and
c) choose the most suitable route and scheme of work and rest of drivers for this order.

Each truck may execute several orders during the planning horizon. It is not contrary to international transportation conventions such as the prohibition of cabotage without a corresponding license. To start the first of these, one must submit the vehicle to the point where the order is formed no later than the directive moment $t_{e.i}$. The time required by the driver to comply with the rules of the AETR is spent to execute orders. The choice of schedule options depends on the duration of movement and idle time. Consequently, it is necessary to take into account the duration of zero mileage, as well as the time of travel and breaks on a trip between points *i, j* of the transportation network:

$$T^k_{i.j} = T^k_{i.j.mov} + T^k_{i.j.br} + T^k_{i.j.rest} + T^k_{i.j.serv}, \tag{1}$$

where $T^k_{i.j.mov}$ - the time of the truck movement between points *i* and *j* for the *k* schedule option; $T^k_{i.j.br}$ - the duration of the driver's break; $T^k_{i.j.res}$ - the duration of the driver's daily rest; and $T^k_{i.j.serv}$ - the duration of other jobs, such as fueling, loading/unloading, customs control, repair and maintenance of the vehicle, and other operations, which are part of the driver's working time.

To fulfill the *j* order, which is next after the *i,* the vehicle must be driven in for loading to the adjacent transport facility, where there is a corresponding request, or download at the same place where the pre-unloading has taken place. This means that the timing of freight order fulfillment processes should be considered.

4.2. Time sequence modeling of the transportation processes

Orders *i, j* may be linked by time links, due to the necessity to adhere to the allowable schedule. This can be generalized using such a magnitude that shows the ratio of the moments of the start of the corresponding *i*-th and *j*-th transport processes (order fulfillment) for the *k* variant of the schedule:

$$a^k_{i.j} = t_{o.j} - t_{o.i} + T^k_{i.j}, \tag{2}$$

or for the inverse sequence of execution:

$$a^k_{j.i} = t_{o.i} - t_{o.j} + T^k_{j.i},\ i, j = \overline{1, P}. \tag{3}$$

The whole set *P* of known orders can be reflected using a mixed graph $A(G,U,V)$, where *G* is the set of vertices, $\{g_1, g_2, \dots, g_{p-1}, g_p\}$, where $g_2 \dots g_{p-1}$ symbolizes the starting moments of orders execution. The vertex g_1 is fictitious, representing the formal moment of the beginning of the whole project. The vertex g_p is fictitious too, symbolizing the end of the scheduled cycle of duration *T*. *U* is the set of arcs; each of them represents the time communication between the starting moments of the execution of the *i*-th and *j*-th orders for the *k*-th route option, by the same vehicle. The arches *U* of graph *A* are weighted. If an order arrives, it is reflected in the graph with the arc of the weight $a_{i.j} > 0$. Requirement (2) or (3) must be satisfied for any condition. In addition, the time constraints of the project are set by other kind of arcs. For a sample, arcs $a_{1.i}$ are the earliest moments of the possible start of the execution of each and every order. Each arc $a_{i.R}$ is a time communication, a "pure" duration of the execution of the *i*-th order. Each arc $a_{i.R}$ is a time communication, a "pure" duration of the execution of the *i*-th order. It was used to begin the vehicle loading before it arrived at the *i*-th point already with idling or zero mileage, as well as for a driver who will not waste time for rest. Obviously:

$$a_{i.P} \le a_{i.j}\,. \tag{4}$$

Condition (4) will be fulfilled for any i and j.

The arc with a negative weight, $-a_{i.1}$ displays the time limit for the execution of the i-th order. For example, $-A_{P.1}$ is the time allowed to execute all known orders (as a rule, it coincides with the T period). All arcs $-a_{P.i}$ reflect the policy moments of the most recent late-end orders. All other non-existent or insignificant connections are represented by arcs with weight $-\infty$.

A set of V ribs (links without arrows, or with reciprocal arrows) is given in the model of the disjunctive (mixed) graph A (Fig. 3); each of them corresponds to the pair of weights $a_{i.j}$, $a_{j.i}$. If a rib connects vertices $i, j,$ it indicates their temporal interdependence. The corresponding i and j orders will be executed in an arbitrary order.

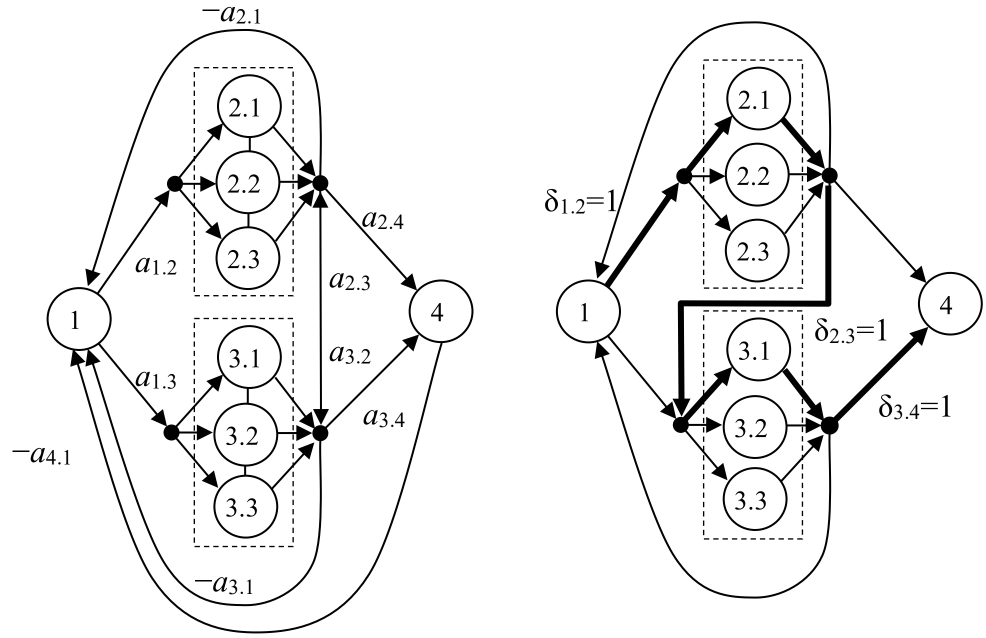

Fig. 3. Model for scheduling the execution of orders for the carriage of goods: a) a mixed graph with the corresponding arcs and ribs marked on it by the weights $a_{i.j}$; b) oriented graph without cycles and contours of positive weight with marked variables

The path in the graph is a sequence of arcs where all vertices are different, and the initial and final ones coincide. Contour is a closed path in the graph A. The weight of the path is the sum of the weights of the arcs entering it. The weight of the path is expressed numerically in the interval $(-\infty,+\infty)$, that is, it is a valid number. According to this, the term contour, or the path of a positive (or negative) weight is used. The path of the greatest positive weight in the graph A connecting i, j to the vertex is denoted by ϑ_{ij}. If there is no path from vertex i to vertex j in the graph by eliminating some edges, then $\vartheta_{ij}=-\infty$.

M transport vehicles may be involved in the transportation process. They should work synchronously, executing several orders sequentially. This means that in A, we need to find m chains starting at the vertex g_1, passing through some vertices of the graph, which relate to existing orders and ending at the vertex g_p. The wanted chains must pass through those vertices for which $q_{x.y}>0$. If the chain reaches the vertex y, and then there is no path in the graph A with an integral or nonzero weight, then the chain goes to the vertex g_p. The transport cycle for this truck will be considered complete, despite the fact that there is a spare time to fulfill other, not yet executed orders. The task has similar features to the known task of the multi-salesmen-problem [19]. The period T is not a predetermined value. We do not need to look for its numerical value as soon as possible. The number of given vehicles may not be equal to the number of actually involved ones in transportation. Besides, to formalize the shortage of transport capabilities of a fleet of vehicles at a given flow of orders, fictitious vehicles are set; thus, from all the found formal paths in *A*, the best ones are chosen. Others are less favorably attributed to fictitious vehicles.

4.3. Mathematical method of constructing the active schedule of a fleet of vehicles

The formal content of the problem of scheduling is that we need to find ways ϑ_{ij} for all, *i, j*=1…*P*. The weights of these paths determine the moments of the earliest start of the execution of each and every *i*-th order [20]. One must comply with the following conditions to create the desired unambiguous (there was no time mismatch) timetable $\{t_{o.1}, t_{o.2}, \dots t_{o.p}\}$:

$$a_{i.j} \geq t_{o.j} - t_{o.i}\,. \tag{5}$$

The moment of the start of any *i*-th order can be found from the ratio [18]:

$$t_{o.i} = \max_{j}\left\{0, \vartheta_{i.j}\right\}, \quad 1 < j < p\,, \tag{6}$$

We can find the moment of any *i*-th order completion from the expression:

$$t_{f.i} = t_{o.i} + a_{i.p} < t_{e.i}\,. \tag{7}$$

The schedule for which condition (5) is fulfilled for all orders and for all trucks is called *active*. The value calculated according to (6) 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 contours of positive weight [20, 22]. Consequently, we consider as unequivocal the decomposition that is generated by the graph and does not contain contours of positive weight, and hence edges of set *V*.

A consistent analysis of variants with overlapping of all graphs from a plural is used, and the search among them is optimal in criterion (4). To organize such a search, the procedure of sequential subdivision is used to avoid the unproductive selection of non-optimal variants. Ribs are established between vertices of graph *A*, which belong to one subset *k*, which means their independence. However, these vertices represent mutually exclusive alternatives of the same order, in fact, although they have different time links. Such a relationship cannot be represented in the graphic model with the help of arcs or edges. For example, there are vertices rounded up by a dotted line in Fig. 3, which means different routes, or different schedules. There are arcs between them. However, a rigid mutually exclusive connection must be present. This means that the schedule of execution of orders should be built on the path in the graph, which goes only through one of the three vertices 2.1 / 2.2 / 2.3 and, accordingly, 3.1 / 3.2 / 3.3. To implement this, additional variables $\delta_{i.j.k} \in \{0,1\}$ have been introduced. If the path exists in the graph passing the vertex $g_{i.k}$, then all the other vertices of the subset *k* must be isolated using the variable $\delta_{i.j}$ as follows:

$$\sum_{j=1}^{P}\sum_{k=1}^{s}\delta_{1.j.k} = 1, \tag{8}$$

where *s* is the number of alternative ways of executing the *j*-th order.

The algorithm for solving the problem is as follows: the set of orders is also divided into non-negative subsets; each of them represents a unitary order. One needs to construct a schedule of execution of the specified orders, that is, to indicate the starting point and the ending point for each cargo transportation as well as the number of M_k carriages [21]. An optimal schedule fulfills the following conditions:

$$F\left(t_{o.1}, t_{o.2}, \dots, t_{o.p}\right) \to \min \tag{9}$$

where *F* is a goal function, that is, in this case, the total duration of the project. Given the introduced variables (8), the calculation of the criterion will be as follows:

$$T_{pr} = \sum_{i=1}^{P}\sum_{j=1}^{P}\sum_{k=1}^{s}\delta_{i.j.k}\cdot a_{i.j.k} \to \min\,. \tag{10}$$

The content of the operations with the graph is as follows:

1. Identify all vertices that are included in each subset $k = 1...s$ as a single one. The vertices of any set k are merged. All vertices that do not belong to this set must be eliminated, except for the vertex for which identification is performed. For example, subset 2 of the graph of the initial model, shown in Fig. 3a, contains 3 vertices: 2.1, 2.2 and 2.3. As a result of the identification in the subset, vertices 2.2 and 2.3 are eliminated. They become isolated, since the variables $\delta_{i.2.2}$ and $\delta_{i.2.3}$ acquire zero values, that is, all the connections of these vertices are also destroyed. Vertex 2.1 becomes a plural representative one, whose connections with other vertices of the graph remain.
2. Remove contours of the positive weight of graph A. To do this, one must ensure that the following restrictions are fulfilled:

$$\sum_{j=1}^{n} \delta_{i.j} - \sum_{i=1}^{n} \delta_{i.j} = 0, \tag{11}$$

means the number of arcs entering any i-th vertex of graph A, except finite, which must be equal to the number of arcs that come out of it;

$$\sum_{j=1}^{P} \delta_{1.j.k} = M, \tag{12}$$

means that the number of arcs coming from the original fictitious vertex must be equal to the number of available vehicles that can carry the carriage;

$$\sum_{i=1}^{P} \delta_{i.P.k} = -M, \tag{13}$$

means that the number of arcs entering the final fictitious vertex must be equal to the number of available vehicles M.

Constraints (11) - (13) lead to the fact that when they are performed in graph A, then all contours of positive weight are eliminated. Operations 1 and 2 with a graph are performed simultaneously, that is, the simultaneous programming of all variables $\delta_{i.j.k}$ is performed.

4.4. Remarks on the solution of the problem

On the other hand, this problem leads to the timing of the ordering of works (orders) and their distribution between available vehicles. Therefore, it can be attributed to known classification features to the tasks of compiling cyclic unitary schedules for project operations by several operators [11]. It is necessary to develop the shortest idle run for each vehicle that will be involved in the process, when planning the execution of transportation. Also, we must find the best schedule for executing orders with a combination of trucks with minimal downtime in the presence of time constraints, i.e. without delays. Such a task should be attributed as optimization [10]. The algorithm for finding the optimal solution refers to polynomial problems in terms of complexity, that is, there is a deterministic algorithm for finding a successful exact solution for polynomial time [9]. Given that such tasks can be formulated only for a small number of orders on the horizon of international transportation, the size of the task and, accordingly, its complexity will not be significant. The result of the applied ordering of the initial graph is an oriented graph without cycles. Separate optimization results for the developed algorithm are shown in Fig. 3 b. The thickened arrows show the resulting graphs that are part of the critical path; the early completion times of each order are calculated.

5. APPLICATION

The proposed algorithm was applied for such a case study. The orders for international transportation of packed cargoes by road transport on the routes were considered: A) L'viv (Ukraine) - Bydgoszcz (Poland); B) L'viv-Wroclaw (Poland), C) Brno (Czech Republic) - L'viv; D) Katowice

(Poland) - L'viv; E) Krakow (Poland) - L'viv; and F) Brno-Krakow. To carry out these transportations, five freight trains can be used, which are located on the production base near the city of L'viv. Execution of each order can be done using different schemes of work and rest of the driver, as well as different routes. Indicators of the duration of the various options for these orders are given in Table 1. The planning horizon is 56 hours, corresponding to one week of work. Each vehicle is driven by one operator. Rest and a break for the driver can happen only at fixed transport points. The duration of idle time at the customs control at the border crossing points Ukraine-Poland is 4 hours. The loading/unloading time of the car trailer for all orders is the same: 2 hours. The route parameters listed in the table are computed.

The duration of the journey is in direct proportion to the duration of the driver, as can be seen from table 1. The duration of the journey here is calculated with the assumption that the transportation cycle is carried out at the beginning of the week and a driver did not reduce the weekly rest time previously. If several tasks (orders) are assigned to one vehicle, then the duration of each of these is different from those presented in Table 1.

Therefore, a matrix of transitions from the execution of one transport task to another was compiled for the simulation of the process. The time required to start the new order execution consists of the following elements:

a) zero run time to the place of first loading;
b) idle time associated with the daily rest of the driver;
c) idle times associated with breaks in driving; and
d) waiting time for starting the time windows.

Table 1

Parameters of execution of orders and compliance with the rules AETR

Appellation	Initial – end points	Time windows, hours	Runtime, hours
A	L'viv-Bydgoszcz	[24; 32]; [48; 56]	1) 25,2; 2) 26; 3) 27,1; 4) 30,2
B	L'viv-Wroclaw	[12; 20]; [29; 38]	1) 19,52; 2) 20,31; 3) 23,1; 4) 29,2
C	Brno-L'viv	[32; 42]	1) 16,7; 2) 21; 3) 25; 4) 31,4
D	Katowice-L'viv	[0; 12]; [25; 37]; [49; 61]	1) 11; 2) 14; 3) 16
E	Krakow- L'viv	[10; 22]; [32; 44]	1) 9,5; 2) 12,5; 3) 14
F	Brno-Krakow	[0; 12]; [20; 32]; [46; 58]	1) 10; 2) 11; 3) 12,5

For example, to find the transitional time from the order A1 (L'viv-Bydgoszcz) to order E1 (Krakow-L'viv), we will determine the remaining working time of the driver after executing the order A1 according to the tab. 1. The duration of this cycle is 25.2 hours, including the driver's work - 13 hours, split rest 3 + 9 = 12 hours. The driving time is 8.2 hours. Since the driver did not exceed the allowed normative length of working time, he had spare time to reach Krakow to download. The time window in Krakow is [32, 44]. In addition, 4.5 hours of working time was used after the last daily rest on the route A1, L'viv-Bydgoszcz, with 2 hours of unloading in Bydgoszcz. The travel time along the route Bydgoszcz-Krakow is 5.2 hours at the route A1. This means that during the current change, a driver will be able to make a trip to Krakow. The vehicle driver has a choice: to start an 11-hour vacation and load, or to stay around 40 minutes before unloading, and load within 2 hours and to go for daily rest in Krakow. It takes extra time to idle in the first case. Thus, it is advisable to choose the second option, according to the duration of the transient process before loading, which is 5.2 + 11 = 16.2 hours. After starting the cycle A1 to the beginning of cycle E1, 41.4 hours passes, which is included in the second time window. Note that the transition time sufficiently depends on the alternative of the transport cycle chosen. This is shown in the example of the transition from order A to order E in figure 4.

This dependence follows for the majority of transient processes. It can be concluded from this that the choice of a shorter duration of the transportation cycle is accompanied by an increase in the cost of transients. Therefore, the task of selecting a sequence of orders of execution is optimization. Since the formalization of the procedure for calculating the transitional duration is rather complicated at this stage of the research, taking into account the purpose of this article, all these processes were calculated pre-manually. The resulting matrix of transient durations is asymmetric with respect to its diagonal. The size of the matrix depends on the number of alternative scheduling orders.

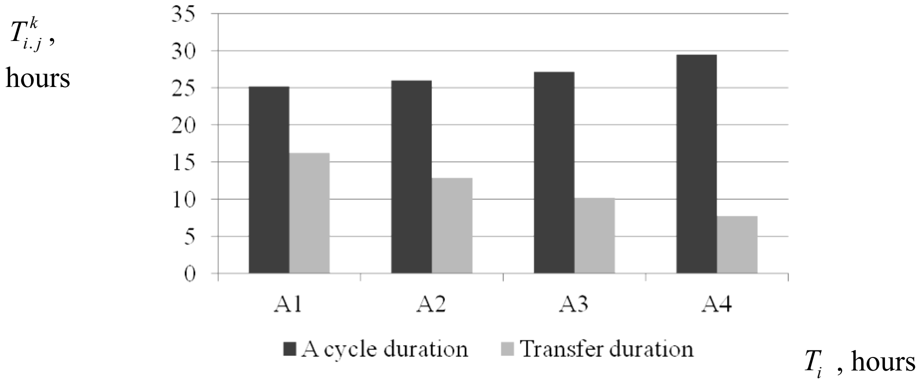

Fig. 4. Dependence of the duration of the transition process on the duration of the previous cycle A, hours

The described algorithm was used to optimize the joint schedule of a group of *m* trucks, when performing the specified order in the table. 1. It was programmed in Delphi language. The results of the optimization are presented as a set of routes (Fig. 5).

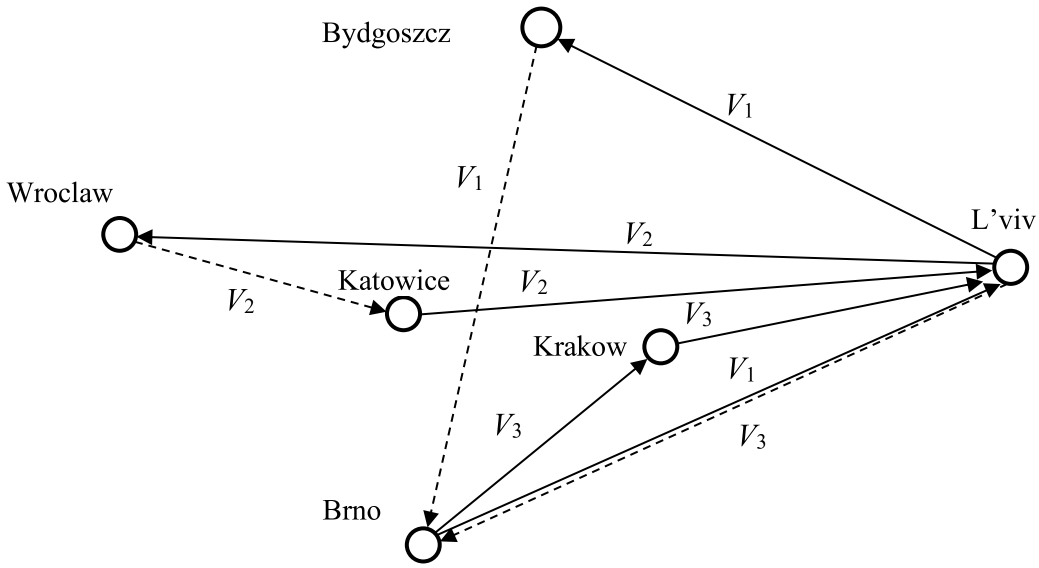

Fig. 5. Resulting model of international transportation cycles' optimization: V_k – vehicle number

The variable in this case was the number of cars involved in the project. Their total number is 6. The figure shows the version of the project, which involves 3 cars. Route parameters are described in Table 2.

Table 2

Parameters of the optimal project of execution of 6 orders

Vehicle No	Route	Duration of, hours				
		cycle	driver work	daily rest	brake	driving
1	L'viv- Bydgoszcz - Brno - L'viv	52,5	34,7	20	3,8	23
2	L'viv- Wroclaw- Katowice- L'viv	40	29,5	9	1,5	19
3	Brno - L'viv	50	36,8	11	2,2	27,5

The total duration of all orders is 148,5 hours. Cycle No 1 has the highest duration. It's a critical way of the project and its maximum duration is 52,5 hours. This is slightly less than the planning horizon. Increasing the number of cars to 4 does not significantly reduce the overall duration of the project – 142 hours. 5 and 6 cars carry out orders with almost equal success.

6. CONCLUSIONS

AETR terms significantly complicate the development and implementation of the shortest vehicle timetables, despite the positive functions that they perform. However, if problems of selecting routes, distribution of vehicles on routes and assembly sequence of orders and optimization of schedules are combined as a single complex task, it extends the search for effective solutions.

Increasing the scheduling task variables complicates the process of finding a guaranteed exact solution. Dynamic programming that was applied recently in such cases reduces the accuracy of decisions. Instead, the use of mixed graphs and binary variables states the problem of schedule development of truck drivers for a fleet of vehicles in such a way as to provide a guaranteed accurate solution.

The parameters of optimal transport projects show that the use of more trucks does not always shorten the duration of transportation orders, and the shortest routes do not always "fit" effectively into the structure of the optimal project.

References

1. *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.
2. Marius, M. Solomon Algorithms for the Vehicle Routing and Scheduling Problems with Time Window Constraints. *Operations Research*. 2006. Vol. 35. No. 2. P. 254-265.
3. Bernhardt, A. & Melo, T. & Bousonville, T. & Kopfer, H. Scheduling of driver activities with multiple soft time windows considering European regulations on rest periods and breaks. Fakultät für Wirtschaftswissenschaften der htw saar, Saarbrücken. 2016. *Schriftenreihe Logistik der Fakultät für Wirtschaftswissenschaften der htw saar*. No. 12. 143 p.
4. Goel, A. The minimum duration truck driver scheduling problem. *EURO Journal Transportation and Logistic*. 2012. Vol. 1. No. 4. P. 285-306 Available at: http://intranet.paluno.uni-due.de/bibliography/aigaion2/index.php/attachments/single/283.
5. Taran, I. & Litvin, V. Determination of rational parameters for urban bus route with combined operating mode. *Transport Poblems*. 2018. Vol. 13. No. 4. P. 157-171.
6. Бондарєв, С.І. Обґрунтування математичної моделі розрахунку тривалості оборотного рейсу при виконанні міжнародних автоперевезеннях. *Scientific Journal «ScienceRise»*. 2014. No. 3/2(3). P. 7-10. [In Ukrainian: Bondarev S.I. Substantiation of a mathematical model for calculating the duration of a working trip when performing international road transport. *Scientific Journal «ScienceRise»*].
7. Turpak, S.M. & Taran, I.O. & Fomin, O.V. & Tretiak, O.O. Logistic technology to deliver raw material for metallurgical production. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*. 2018. Vol. 1. P. 162-169.
8. Hokey, Min. *Combined Truck Routing and Driver Scheduling Problems under Hours of Service* Regulations Final Report. 2009. Bowling Green State University. 47 p.
9. 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.
10. Данчук, В.Д. & Сватко В.В. Оптимізації пошуку шляхів по графу в динамічній задачі комівояжера методом модифікованого мурашиного алгоритму. *System Research & Information Technologies*. 2012. No 2. P. 78-86. [In Ukrainian: Danchuk, V.D. & Cvatko V.V.

Optimization of the search of paths by the graph in the dynamic task of salesman by the method of the modified ant algorithm. *System Research & Information Technologies*].
11. Jean-Yves, P. & Ying, X. & Benyahiac, I. Vehicle routing and scheduling with dynamic travel times. *Computers & Operations Research*. 2006. No. 33. P. 1129-1137.
12. Vidit, D.S. *Time Dependent Truck Routing and Driver Scheduling Problem with Hours of Service Regulations.* PhD thesis. Northeastern University Boston, Massachusetts. 2008. 126 p.
13. Srivatsa Srinivas, S. & Gajanand, M.S. Vehicle routing problem and driver behaviour: a review and framework for analysis. *Transport Reviews.* 2017. No. 37(5). P. 590-611.
14. Chryssi, M. Time Dependent Vehicle Routing Problems: Formulations, Properties and Heuristic Algorithms. *Transportation Science*. 1992. Vol. 26. No. 3. P. 161-260.
15. Van Woensela, T. & Kerbacheb, L. & Peremansc H. & et al. Vehicle routing with dynamic travel times: a queueing approach. *European Journal of Operational Research*. 2008. Available at: https://www.researchgate.net/publication/220288626_Vehicle_routing_with_dynamic_travel_times_A_queueing_approach?enrichId=rgreq-35b16f04ac323c3ce1d30773a74=publicationCoverPdf.
16. Шраменко, Н.Ю. Вплив тривалості митного оформлення на строк доставки вантажів у міжнародному сполученні. *Вісник Академії митної служби України*. 2012. No 1. P. 69-75. [In Ukrainian: Shramenko N. The influence of the duration of customs clearance for the term of delivery of goods in international route. *Bulletin of the Academy of Customs Service of Ukraine*].
17. Stetsenko, I.V. State equations of stokhastic timed Petri Nets with Informational relations. *Cybernetics and Systems Analysis*. 2012. Vol. 48. No. 5. P. 784-797.
18. 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.
19. 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.
20. Танаев, В.С. & Сотсков, Ю.Н. & Струсевич В.А. *Теория расписаний. Многостадийные системы*. Москва: Наука. 1989. 328 p. [In Russian: Tanaev, V.S. & Sotskov, Y.N. & Strusevich, V.A. *Theory of schedules. Multistage systems*. Moscow: Science].
21. Pinedo, M. *Scheduling: theory, algorithms, and systems*. Springer. 2018. 674 p.
22. D'Ariano, A. & Pacciarelli, D. & Pranzo M. A branch and bound algorithm for scheduling trains in a railway network. *European Journal of Operational Research*, Vol. 183. No. 2. P. 643-657. Available at: https://doi.org/10.1016/j.ejor.2006.10.034.

Received 16.12.2018; accepted in revised form 11.06.2020