

# Formation of alternative routes for passenger trains in the event of non-standard situations

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**Abstract.** Railway passenger transportation has always had a significant place in the economic, material and technical development of Ukraine. The current conditions are no exception, when in connection with the beginning of a full-scale military invasion of our country, passenger transport assumed responsibility for the timely evacuation of people and their safe relocation to other regions of the country or abroad. Due to the fact that railway transport is of strategic importance for Ukraine, its infrastructure has increased risks of destruction. Each destruction of the railway infrastructure has serious consequences for the organization of the movement of passenger trains, in particular high-speed trains. Therefore, with the aim of reducing the possible costs of organizing the movement of high-speed passenger trains in the event of the destruction of the railway infrastructure and increasing the reliability of the functioning of the high-speed railway passenger transport system in Ukraine, an automated technology for providing an alternative route for the trains of the branch "Ukrainian Railway High-Speed Company" (UZShK) is proposed. The formation of this technology is considered on the example of the most popular passenger direction, namely - Kyiv-Lviv, the topology of which is represented by a weighted graph, where the vertices are railway stations, and the edges are railway sections with a weight in the form of a tuple (time to overcome each section, presence of electrification, bandwidth). The proposed technology also provides for the possibility of attracting additional "shuttle" trains or road transport, in cases where it is necessary to significantly reduce the travel time by an alternative route or the possibility of the arrival of railway transport to the station where it is necessary to board/disembark passengers is excluded. The formalization of this process was carried out by forming an optimization mathematical model according to the criterion of minimum operating costs. The formation of a set of alternative routes was carried out using the adjacency matrix of the graph representing the Kyiv-Lviv transportation direction. The developed technology is proposed to be integrated in the form of a software product for automated workplaces (AWP) of operative personnel in the form of a decision support system (DSP), the algorithm of which is also given in this publication.

## 1 Introduction

The reliable transportation of passengers is one of the most important tasks of any type of transport, among which railway is no exception. Its relevance did not decrease even after the introduction of martial law on the territory of Ukraine on February 24, 2022. Thus, it was passenger rail transport that took on a huge responsibility for the transportation of wounded soldiers and civilians, the evacuation of the civilian population from those areas where hostilities are most active, the transportation of high-ranking Ukrainian and foreign representatives, etc. Therefore, when organizing any type of passenger rail transportation (high-speed, long-distance, regional, etc.), the possible impact of external and internal factors that can directly affect reliability, transportation, final cost and total travel time must be evaluated.

Unfortunately, in today's military realities, the destruction of railway infrastructure is not uncommon. Evidence of this is the missile attack on Khmelnytskyi

on May 13, 2023, which resulted in significant damage to the railway infrastructure, and the movement of trains along one of the sections was completely stopped for more than 72 hours [1]. Each such or similar destruction of the railway infrastructure, the consequence of which is the complete closure of the section for a certain period, requires the creation of an alternative route for passenger trains, the route of which was supposed to pass through this section. Since it is important for every passenger, after boarding, to reach the final station of destination in complete safety and with minimal deviation from the planned time, and for the carrier, even before that, it is important to organize this trip with the minimum cost, there is a need for the formation of a decision support system, the basis of which is an optimization mathematical model, which would be able to form an alternative route in operational mode with the maximum satisfaction of the needs of the parties mentioned above. Therefore, the purpose of this study is to develop an automated technology for providing an

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alternative route based on an optimization mathematical model for high-speed passenger trains in the event of non-standard situations with the possible involvement of additional "shuttle" trains or road transport.

Many scientific works of foreign and Ukrainian scientists were devoted to the study of alternative routes for various types of transport. One such work is the publication [2], in which Chinese colleagues considered the methodology of prioritizing such "permanent" alternative routes through the main traffic "generators" for routing strategies and traffic forwarding in the corresponding local network, and also demonstrated the management and operation scenario in emergency situations, in real time, city traffic with identification of existing traffic jams and alternative routes in the city of Xi'an Ming.

In publication [3], an innovative agent model was developed, based on a heuristic algorithm, which is able to simulate the process of rational decision-making by passengers based on material costs and costs and the cost of time spent on the road for the transport system of Denmark.

In research [4] presents the public transport trip planning parameters procedure of the calculated walking route directions, integrated with the calculation results of public transit routes, as well as combining visualization in digital maps. The result of this study is developed VINTRA system, a comprehensive solution to a fully developed public transit system in Lithuania, and it is very important in encouraging travelers to use public transport.

In [5], a model was proposed that provides an assessment of the vulnerability of the Dutch railway system by finding the critical combination of circuits that cause the most adverse consequences for passengers and trains. The value of vulnerability was formed on the basis of the total cost of transporting passengers, the number of passengers who will not be able to reach their destination, as well as the costs of adjusting train traffic. After that, options for alternative routes with minimum time were formed for the most vulnerable precincts.

In the scientific publication [6], a procedure for providing an alternative route in the direction of transportation of Ukrainian high-speed trains was proposed. The formalization of this process was carried out using the technology of risk management by forming an optimization mathematical model according to the criterion of minimal excess of operating costs when transporting by an alternative route compared to regular scheduled transportation.

Based on the analysis of previous studies and the development of the technology presented in the publication [6], the possibility of involving additional "shuttle" trains or road transport in the construction of alternative tracking routes was considered in order to reduce the travel time and the amount of operating costs.

## 2 The main part

As you know, high-speed trains of the Intercity category + UZShK branches are the most popular among passengers on the network of Ukrainian railways, in particular during wartime. Therefore, it is their routes that will be the object of this study. The operating fleet of trains of this category consists of 3 models (Hyundai Rotem, Skoda, Tarpan), which can develop a speed of up to 160 km/h and are powered by both direct and alternating current. As you know, UZShK has a monocentric topology. All trains of this branch are assigned to the Darnytsia depot, which is the only one in Ukraine that has equipment for maintenance and ongoing repair of trains of this category, and all routes of these trains are laid from Kyiv. Therefore, the authors of this report, when analyzing the intensity of passenger traffic by direction, divided it into two parts. The first one is an analysis of passenger traffic going in a direct direction (from Kyiv). The second part represents the number of transported passengers heading in the return direction (to Kyiv). All data were taken from the ASK PP UZ system, and the results were summarized in Table 1.

**Table 1.** Analysis of passenger flows by UZShK trains for 2021-2022 years.

Years	Directions	Lviv	Kharkiv	Donetsk	Dnipro	Odesa
2021	There (from Kyiv)	933472	820954	590699	483021	395901
	Return (to Kyiv)	552213	269671	310694	243921	195462
2022	There (from Kyiv)	628819	544387	123634	285059	40882
	Return (to Kyiv)	248851	267922	66168	149716	17395
Percentage share from 2022 to 2021 year	There (from Kyiv)	67,36%	66,31%	20,93%	59,02%	10,33%
	Return (to Kyiv)	45,06%	99,35%	21,30%	61,38%	8,90%

In the given table, the direction Kyiv - Lviv, both in 2021 and in 2022, is the most popular among passengers. In addition, this direction is used by all international diplomatic delegations when visiting our country on working visits. Based on this, in the subsequent studies, this direction was taken as the main one. The chosen direction, as in the publication [6], was depicted in the form of a weighted graph  $G(I,J)$  (Fig. 1). The vertices of this graph are proposed to take the main railway stations in the given direction, and to present the edges in the form of a tuple (time to overcome each section, availability of electrification, carrying capacity).

In real conditions, each section (edge of the graph) consists of a certain number of elements (stages and intermediate stations), each of which has its own maximum permitted speed for the movement of passenger trains, approved by the head of the regional branch, within which the route of the passenger train passes. It is from the value of this speed that the travel time of the train depends, and, accordingly, the operating costs. Therefore, in order for the procedure of forming alternative routes to be more accurate, it is necessary to start from the distance between junctions (as proposed in the publication [6]), but from the time required to

overcome these distances and the value of operating costs per train hour for each type of traction. The value of this time will be equal to the sum of the ratios of the distance of each element of the site to its maximum speed. A formal description of the graph  $G(I,J)$  looks like this, where  $I = I(i)$  – set of graph vertices (railway stations);  $J = J(j)$  – set of graph edges (railway sections) with weight in the form of a tuple.

$$j(i_k, i_{k+1}) = (t_j, h_j, N_j) \quad (1)$$

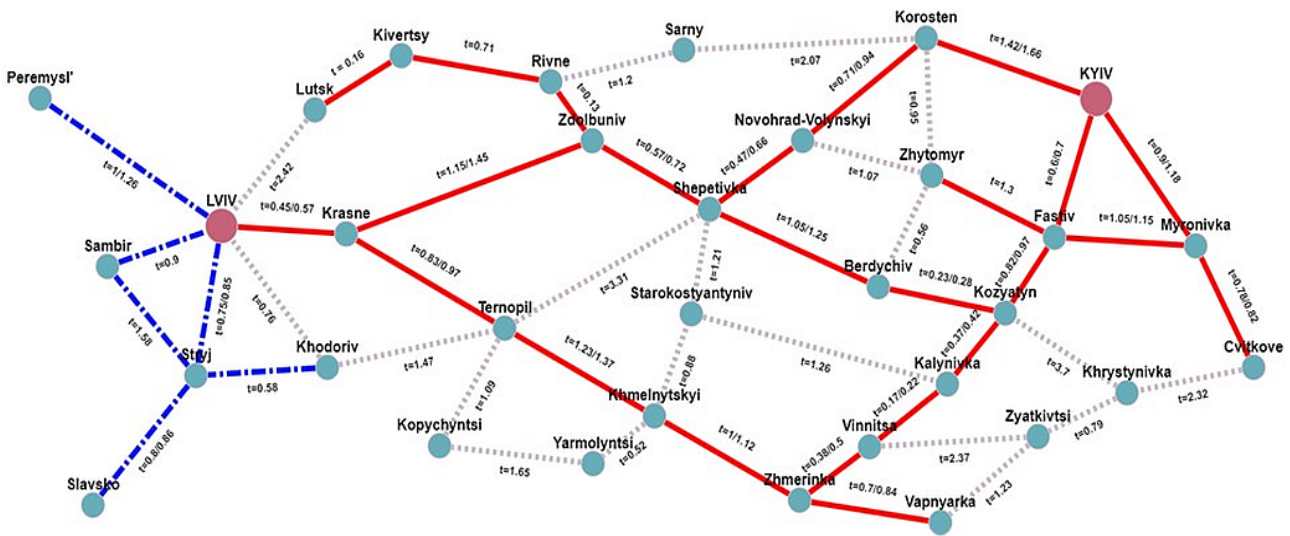
Where,  $t_j$  - time to follow a certain area;

$h_j$  – boolean variable:

$$\begin{cases} h_j = 1 \rightarrow \text{precinct is electrified} \\ h_j = 0 \rightarrow \text{precinct is not electrified} \end{cases} \quad (2)$$

$N_j$  – throughput capacity of the  $j$ -th precinct;

$k \in I(i)$  – vertex (station) number.



**Fig. 1.** Weighted graph of the Kyiv-Lviv precinct (the precincts marked with a solid line are electrified with alternating current, dash-dotted - direct, dotted - non-electrified)

According to the provisions of graph theory, a route is defined as a sequence of edges, not necessarily different, but such that every vertex of two adjacent edges coincides. The graph shown in fig. 1, is three-connected, while the number of possible routes connecting the top of Kyiv and the top of Lviv is more than 80. According to the graph (Fig. 1), a weighted adjacency matrix (Fig. 2) is constructed, which fully and unambiguously reproduces this count. A fragment of this matrix is shown in (Fig. 2). The weight of the  $j$ -th edge reflects the required time to follow this section  $t_j$ .

Also, in order to reduce the time of traveling by train on an alternative route and operating costs, the work took into account the possible use of special "shuttle" trains, which would provide transportation of passengers from the stations where their boarding is planned to the stations through which the most profitable alternative route passes, and vice versa for disembarking passengers. Since the "shuttle" trains will not be formed by high-speed trains, but by locomotive traction, or with the help of rail buses, according to the design features of the locomotives, their maximum speed cannot exceed 100 km/h. This value of speed will be accepted on the speed of more than 100 km/h. The time of departure of "shuttle" trains along such sections is entered through a fraction into the composite adjacency matrix, a fragment of which is shown in (Fig. 2).

In other cases, this time will coincide with the departure time of high-speed trains. In addition, for some cases, for example, when an intermediate station is

destroyed, which makes it impossible to use all the railway sections approaching it, the authors took into account the use of road transport (buses) to pick up passengers. The speed for such buses was set to 90 km/h, and a fragment of the adjacency matrix for them in time is shown in Figure 3.

	KYIV	Korosten	Myronivka	Fastiv	Kozyatyn	Zhytomyr	...	Sambir	Lutsk	LVIV
KYIV	X	1,42/ 1,66	0,9/ 1,18	0,6/ 0,7			...			
Korosten	1,42/ 1,66	X				0,95	...			
Myronivka	0,9/ 1,18		X	1,05/ 1,15			...			
Fastiv	0,6/ 0,7		1,05/ 1,15	X	0,82/ 0,97	1,3	...			
Kozyatyn				0,87/ 0,97	X		...			
Zhytomyr		0,95		1,3		X	...			
...	...	...	...	...	...	...	...	...	...	...
Sambir							...	X		0,9
Lutsk							...		X	2,42
LVIV							...	0,9	2,42	X

**Fig. 2** Fragment of the time contiguity matrix for railway transport (the fraction indicates the time for "shuttle" trains at stations with a maximum speed of more than 100 km/h) elements of precincts with a maximum permitted

	KYIV	Korosten	Myronivk	Fastiv	Kozyatyn	Zhytomy	...	Sambir	Lutsk	LVIV
KYIV	X	1,73	1,20	0,70			...			
Korosten	1,73	X				0,92	...			
Myronivka	1,20		X	1,12			...			
Fastiv	0,70		1,12	X	1,05	1,12	...			
Kozyatyn				1,05	X		...			
...	...	...	...	...	...	...	...	...	...	...
Sambir							...	X		0,85
Lutsk							...		X	1,63
LVIV							...	0,85	1,63	X

**Fig. 3** Fragment of the time adjacency matrix for a bus at a conditional speed of 90 km/h.

Thus, the formation of an alternative route in the event of a failure in the system can be according to three options: **1st option**. Changing the main route of the passenger train with a stop at each station where it is necessary to board and disembark passengers.

**2nd option**. Changing the main route of a passenger train without this train stopping at a station where it is necessary to board/disembark passengers. Transportation of passengers to/from this station will be organized by special "Shuttle" trains.

**3rd option**. Changing the main route of a passenger train without this train stopping at a station where it is necessary to board/disembark passengers. The organization of the delivery of passengers to/from this station will be organized with the help of road transport.

Also, in order to obtain the most economically advantageous solution, it is possible to combine these 3 options.

In order to determine the optimal alternative route, an optimization mathematical model was formed according to the criterion of the minimum increase in operating costs compared to the operating costs of regular scheduled transportation  $\Delta E(t)$

The objective function has the following form:

$$\Delta E(t_q) = E_{alt}(t) + E_{shuttle}(t) + E_{auto}(t) + E_{pr}(t) \rightarrow \min_{t_q \forall \{t_q\}} \quad (3)$$

Where,  $q$  – is the index, number of the alternative route;

$E_{alt}(t)$  – expenses when going directly on an alternative route under own traction or with the help of an auxiliary locomotive.

$$E_{alt}(t) = \sum_{i=1}^n (b_1 \cdot t_{el i} \cdot C_{el} + b_2 \cdot t_{diesel i} \cdot C_{diesel}) + b_3 \cdot t_{pr} \cdot C_{pr} + b_2 \cdot C_{org diesel} \quad (4)$$

Where,  $b_{1-3}$  - boolean variable.

$$\begin{cases} b_{1-3} = 1 - \text{a certain category of expenses is present} \\ b_{1-3} = 0 - \text{a certain category of expenses is not present} \end{cases} \quad (5)$$

$i = [1; n];$

$n$  – the number of involved precincts;

$t_{el i}$  – The time that the specified train (UZShK) traveled on an alternative route on a certain section without using an auxiliary locomotive, hours;

$C_{el}$  – The cost of a train hour when traveling by electric train UAH/hour;

$t_{pr}$  – The time the train stood still waiting for the auxiliary locomotive, hour;

$C_{pr}$  – The cost of one hour of downtime, UAH/hour;

$C_{org diesel}$  – Organizational costs for attracting a diesel locomotive, UAH;

$T_{diesel i}$  – The time that the given train traveled with an auxiliary locomotive (thermal locomotive) at a certain section, hours;

$C_{diesel}$  – The cost of one hour of train travel by thermal train, UAH/hour;

$E_{shuttle}(t)$  - Costs when using the "shuttle" train.

$$E_{shuttle}(t) = \sum_{h=1}^p \left[ (c_1 + C_{org diesel h} + c_2 \cdot C_{org el h}) + 2 \sum_{r=1}^l (c_2 \cdot t_{el l} \cdot C_{el} + c_1 \cdot t_{diesel l} \cdot C_{diesel l}) \right] \quad (6)$$

Where,  $c_{1-2}$  boolean variable;

$$\begin{cases} c_{1-2} = 1 - \text{a certain category of expenses is present} \\ c_{1-2} = 0 - \text{a certain category of expenses is not present} \end{cases} \quad (7)$$

$p = [1; h];$

$p$  – the number of "shuttle" train routes;

$r = [1; l];$

$r$  – the number of involved precincts;

$C_{org el}$  – Organizational costs for the use of an electric locomotive for an additional "shuttle" train, UAH.

$E_{auto}(t)$  - Expenses when using road transport (buses), UAH.

$$E_{auto}(t) = d \sum_{s=1}^k \{ [P / 55] \cdot (C_{org auto s} + 2 \sum_{j=1}^m (t_{auto j} \cdot C_{auto})) \} \quad (8)$$

Where,  $d$ - boolean variable;

$$\begin{cases} d = 1 - \text{a certain category of expenses is present} \\ d = 0 - \text{a certain category of expenses is not present} \end{cases} \quad (9)$$

$s = [1; k];$

$k$  – number of bus routes used ( $k=k+1$  for those cases when bus service is used at  $k+1$  non-adjacent stations);

$P$  - the number of passengers who need to be taken to the boarding/disembarking station (calculated using a mathematical model for predicting passenger flows based on neural networks [7]);

$j = [1; m]$

$m$  – the number of involved precincts;

$C_{org auto}$  – organizational costs for the use of road transport, UAH;

$T_{auto j}$  – travel time by road transport along the  $j$ -th precinct, UAH;

$C_{auto}$  – cost of one hour of bus use, UAH/hour.;

$E_{pr}$  – expenses for an additional train with which the given train has a connection (if any) UAH.;

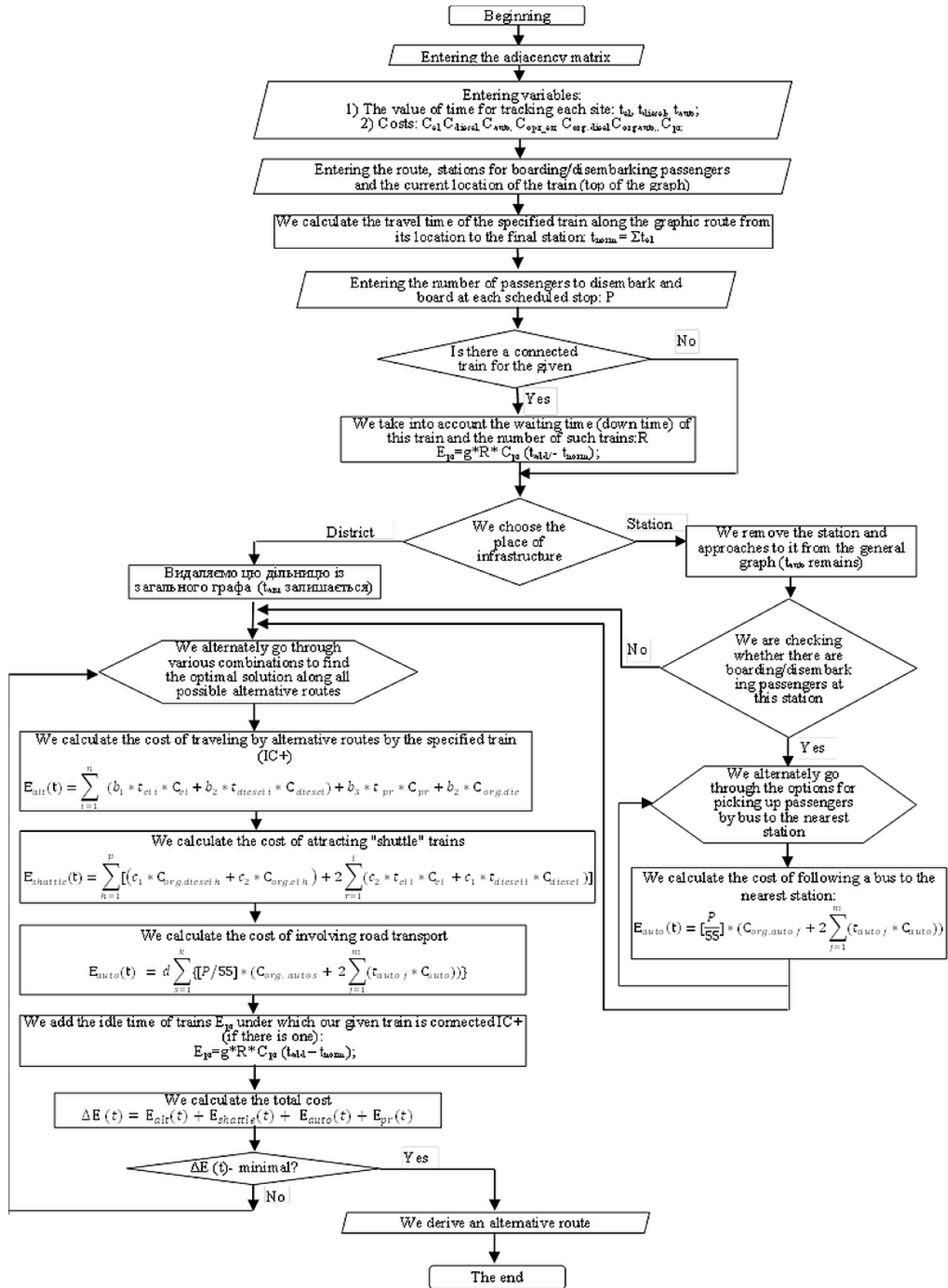


Figure 4. Algorithm of the software product for finding the most optimal alternative route

$$E_{pr} = g * R * C_{pr} (t_{add} - t_{nom}) \quad (10)$$

Where, R- the number of trains to which the target is connected;  
 g – boolean variable;

$$\begin{cases} g = 1 - \text{a given train is connected to another} \\ g = 0 - \text{a given train is not connected to another} \end{cases} \quad (11)$$

$t_{add}$  – travel time via an alternative route to the final station, hours.;

$t_{nom.}$  – travel time of the specified train along the scheduled route from its location to the final station, hours.

The system of restrictions to the objective function (3) reflects the technical and technological conditions of transportation:

$$\begin{cases} V_{max} \leq 160 \text{ km / h} \\ V_{shuttle} \leq 100 \text{ km / h} \\ V_{auto} = 90 \text{ km / h} \\ P \leq 579 \\ N \leq N_{available} \end{cases} \quad (12)$$

To form an automated technology for providing an alternative route, an algorithm for the software product was developed in Figure 4.

The developed automated technology for providing an alternative route is proposed to be integrated in the form of a software product into the automated workplaces (AUW) of the operational staff in the form of a decision support system (DSPR). The main advantage of the proposed technology is that, regardless of the number of destroyed elements of a given direction of passenger transportation presented in the form of a weighted graph, there will always be a solution for organizing the transportation of passengers from the initial destination to the final destination. The introduction of such technology will provide an opportunity to significantly increase the reliability of transportation and, as a result, the level of competitiveness of railway transport in the general transport system.

### 3 Conclusions

Thus, in order to reduce the possible costs of organizing the movement of high-speed passenger trains in the event of the destruction of the railway infrastructure and increase the reliability of the functioning of the high-speed railway passenger transport system in Ukraine, an automated technology for providing an alternative route to the trains of the UZShK branch was formed. The formation of this technology was considered on the example of the most popular passenger direction, namely - Kyiv-Lviv, the topology of which is represented by a weighted graph, where the vertices are railway stations, and the edges are railway sections with a weight in the form of a tuple (time to overcome each section, presence of electrification, bandwidth). The proposed technology also provides for the possibility of involving additional "shuttle" trains or road transport in cases where it is

necessary to significantly reduce the travel time by an alternative route, or the possibility of railway transport arriving at the station where it is necessary to board/disembark passengers is excluded, or if, in the event of destruction, the connecting the transport direction graph is transformed into disjoint subgraphs. The developed technology was proposed to be integrated in the form of a software product for automated workplaces (AWP) of operational personnel in the form of a decision support system (DSP), the algorithm of which was also formed in this work. The main advantage of the proposed technology is that, regardless of the number of destroyed elements of a given direction of passenger transportation, there will always be a solution for organizing the transportation of passengers from the initial destination to the final destination. The introduction of such technology will provide an opportunity to significantly increase the reliability of transportation and, as a result, the level of competitiveness of railway transport in the general transport system.

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