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MULTI-CRITERION OPTIMIZATION OF URBAN PUBLIC ELECTRIC TRANSPORT ROUTES

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The object of this study is the public transport route network. The task addressed is to choose optimal transport routes. Existing scientific research in this field is mainly aimed at increasing its reliability and reducing economic risks. The social and environmental aspects are considered separately, not in connection with technical and economic issues. The study proposes a comprehensive approach to solving the task of urban transport operation.

To solve the problem of multi-criteria optimization of the transport network, the use of the hierarchy analysis method (HAM), which is based on expert assessments, has been proposed. A hierarchical structure of the route selection problem was constructed. Three optimization criteria were determined, as well as ten factors influencing the selected criteria. A comprehensive approach to choosing urban electric transport routes could make it possible, with minimal capital investments and operating costs, to promote the normal functioning of cities. This is especially relevant for Ukraine, which in the post-war period, due to demographic changes and changes in local infrastructure, will face the need to radically revise the operation mode of public transport.

The advantage of HAM over other expert methods is the complex hierarchical structure of cause-and-effect relationships between the choice of the optimum and alternative options, as well as the presence of a mechanism for internal control over the consistency of expert judgments.

The procedure for using HAM has been demonstrated using an example of optimizing transport communication between two districts in the city of Kharkiv (Ukraine). The existing tram route was considered, as well as alternative options. The option consisting of one tram and one trolleybus route was chosen as optimal according to technical, economic, social, and environmental criteria

Keywords: public electric transport, route, multi-criteria optimization, hierarchy analysis method, optimization criteria

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1. Introduction

Despite the high motorization of the population in European countries, the role of urban public transport (in particular electric transport) in large cities remains significant both from an economic and social point of view. At the same time, the relevance of using electric transport is also determined by the absence of dependence on the supply of hydrocarbon fuel and the environmental factor. However, the efficiency of urban public electric transport (UPET) directly depends on the rational choice of routes. The existing approach to route selection is based on Soviet approaches, which were based on the need to deliver workers and employees from their places of compact residence (large residential areas) to the place of work and back. Other tasks were of a secondary nature.

Scientific research in the field of regulation of urban public transport (in particular electric transport) is aimed mainly at increasing its reliability and reducing economic risks. The social and environmental aspects are considered separately, not in connection with technical and economic issues.

Thus, it is urgent to devise a comprehensive approach to choosing optimal UPET routes. This will make it possible, with minimal capital investments and operating costs, to contribute to the normal functioning of large cities. This is especially important for Ukraine, which in the post-war period will face the need to radically revise the public transport operating mode.

2. Literature review and problem statement

In work [1], the results of research on the problem of restructuring of land electric transport enterprises are reported; a detailed multifaceted characteristic of the modernization of transport systems – land automobile and railroad, water, air, etc. is provided. But the issues related to the study of the mutual influence of technical, economic, social, and environmental factors of the functioning of electric transport during the construction of the transport network remained unresolved.

Study [2] considers modern problems, areas of improvement of activity and prospects for the development of a separate branch of the transport system of Ukraine – urban public electric transport – taking into account military operations. The work tackles the problem of modeling the main financial indicators of the activities of urban electric transport enterprises of Ukraine in the war and post-war period. The modeling results make it possible to assess the level of profitability and predict the ability of enterprises to fulfill their obligations to transport passengers within cities, as well as to adequately respond to the variability of external and internal factors of influence. But the work did not consider the issue of a comprehensive approach to the construction of the transport network.

In [3], optimization approaches to improving the reliability of urban transport were considered, namely, two-criteria linear optimization. However, the study does not contain a methodology for selecting specific transport routes.

Work [4] considers the economic aspects of transport operations. In particular, fare payment technologies. The modern method of passenger registration in integrated public transport systems is analyzed, including current trends in passenger registration options. This work focuses on economic and social issues but does not consider technical problems. There is also no analysis of the functioning of electric transport from the perspective of its environmental safety.

In 2020, the UN Economic Commission for Europe published the Guidelines for Sustainable Urban Mobility and Spatial Planning [5]. This manual proposes that the transformation of the urban electric transport network be carried out according to the principle of "avoid – shift – improve" and which are taken as the basis for optimizing existing urban transport systems. The principle of "avoid" means the development of compact areas with complete infrastructure in order to minimize the need for movement of large masses of the population. The principle of "displacement" refers to the transition to healthier and cleaner means of transportation for trips – bicycles, micromobility, electric transport instead of transport with internal combustion engines. The principle of "improvement" refers to the development and adaptation of new technologies that improve the urban transport system. These principles, according to the conclusions in [6], should influence the construction of optimal UPET routes. However, a specific mechanism for solving the multi-criteria route optimization problem is not provided in the Manual. Classical optimization problems – the transportation problem [7] and the traveling salesman problem [8] – also cannot be a tool for optimizing UPET networks since these problems assume only one optimization criterion.

Thus, based on our review of the literature from the last decade, we can conclude that there is no comprehensive approach to optimizing UPET routes according to economic, social, and environmental criteria. This circumstance makes UPET less competitive and contradicts modern trends in sustainable development. Its solution by mathematical programming method (i.e., through the selection of variables to be optimized, the construction of the objective function, and the system of constraints) is considered inexpedient due to the practical impossibility of strict mathematical formalization of the problem with a sufficient degree of adequacy. Therefore, to solve such a problem, it is proposed to use the hierarchy analysis method (HAM), which involves the decomposition of the problem into its simpler components [9]. In this case, the problem is first structured and then represented in the form of a hierarchy of cause-and-effect relationships that directly or indirectly affect the main goal of the problem being solved. As a result of mathematical processing of a set of quantitative estimates of the influence of elements of all levels on elements of the nearest higher levels of the hierarchy, the elements of the lowest level are ranked from the position of their indirect influence on the main goal. The result of the ranking make it possible to select one or more indicators that correspond to the goal more than others and represent them as the final solution to the multi-criteria optimization problem [10].

The vast majority of the analyzed scientific works consider the application of the hierarchy analysis method for individual issues of economic and social development [11]. However, when reviewing literary sources, no work was found addressing the application of the hierarchy analysis method in relation to improving the functioning of the transport system. Therefore, it is advisable to highlight this topic and provide recommendations to interested institutions, organizations, enterprises, and decision-makers on the technique for choosing the UPET route that is optimal according to the selected criteria.

Since we are talking about automated decision-making based on the use of knowledge and experience of experts in a specific field, the software implementation of HAM can be considered an example of artificial intelligence (AI) based on an expert system [12]. Creating AI to solve this problem based on machine knowledge, neural networks, or genetic algorithms [13] is very problematic since this path requires a large amount of research work to study and formalize all aspects of the functioning of UPET. Therefore, this is a question of the future.

3. The aim and objectives of the study

The purpose of our study is to devise an approach to selecting optimal routes for urban public electric transport based on a set of criteria. An integrated approach to constructing a network of urban electric transport will make it possible, with minimal capital investment and operating costs, to contribute to the normal functioning of cities. It will ensure sustainable urban mobility when selecting routes for urban public electric transport.

To achieve the goal, the following tasks were set:

– to theoretically substantiate the use of the hierarchy analysis method for selecting optimal routes for urban public electric transport;

– to design a demonstration example of the application of the hierarchy analysis method for optimizing public transport routes.

4. The study materials and methods

The object of our study is the route network of public transport.

The subject of the study is the selection of optimal routes of urban public electric transport to meet the needs of the urban population in fast and high-quality transportation and the maximum refusal of the population from using private vehicles.

The hypothesis of the study is the contradiction of the properties of UPET routes according to various criteria. Therefore, it is necessary to choose a reasonable compromise solution when designing the transport network.

To solve the tasks related to compiling recommendations for the development of urban public transport enterprises, the study proposes a mathematical model based on the application of the hierarchy analysis method, which is a mathematical tool of a systematic approach to solving complex decision-making problems. Therefore, the main application of the method is to support decision-making through hierarchical decomposition of the task and ranking of alternative solutions.

The justification for choosing the hierarchy analysis method to solve the task of choosing the optimal route of UPET is its strictly structured methodology for setting the problem with the subsequent analysis of complex solutions. In addition, it is a reliable research method that provides a quantitative characteristic of the weight of the selected criteria for decision-making, in this case – management decisions. The advantage of the method over existing ones is to build factors that influence the adoption of a management decision as a hierarchy of cause-and-effect relationships, which allows for a comprehensive analysis of the problem; as well as the pairwise nature of comparisons of the weight of elements of each level of the hierarchy, which makes the comparison result more accurate; and the presence of internal control over the consistency of expert opinions, which makes the comparison result more objective.

The limitation on the use of the hierarchy analysis method may be caused by the presence of reversible relations in the constructed hierarchy. Therefore, in this problem, an assumption is adopted about their absence. This assumption is justified by the logic of constructing a hierarchy when solving the problem of choosing a route for UPET.

Since the hierarchy analysis method is based on expert judgments, the final assessment is influenced by the human factor. Therefore, the criteria for objectivity are the consistency of the judgments of individual experts. The probability of random consistency of the method under study assumes no more than 10%, i.e., it should not exceed 10%.

A computer program was developed in the VisualFoxpro-6 system (Microsoft, USA) to implement the method.

5. Results of devising the methodology for selecting optimal transport routes based on a set of criteria

5. 1. Theoretical justification for using the hierarchy analysis method to select optimal routes for urban public electric transport

5. 1. 1. Hierarchical structure of the UPET route selection problem

The hierarchical structure of the UPET optimal route selection problem is shown in Fig. 1.

At the top (zero) level is the main goal – choosing the optimal route. At the next (first) level are the optimization criteria. At the second – the factors influencing each of the optimization criteria. At the bottom level of the hierarchy are the UPET route options that are considered, and among them the optimal one is chosen according to the selected criteria.

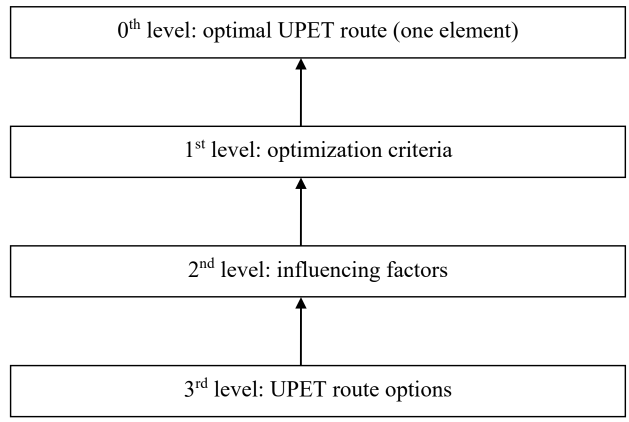

Fig. 1. Hierarchical structure of the urban public electric transport route selection problem

5. 1. 2. Selection of optimization criteria and list of influencing factors

The following were selected as optimization criteria (level 1):

1) technical and economic effect;
2) social significance;
3) environmental safety.

As factors influencing the optimization criteria of the route network (level 2), we shall consider the following ten factors:

1) coverage of housing estates;
2) proximity of social facilities to the route;
3) availability of electrical substations;
4) energy intensity;
5) value of land allotment;
6) availability of unemployed labor;
7) travel time between end points;
8) availability of transfer nodes;
9) proximity of forest park zone;
10) environmental impact.

However, we note that in the event of changes in the operating conditions of UPET, the factors may change.

5. 1. 3. Description of the sequence of actions when applying the hierarchy analysis method for selecting urban public electric transport routes

At the lower level of the hierarchy are the options for UPET routes that are being considered.

For each level of the hierarchy (except for the top one), a quantitative assessment of the elements is carried out from the point of view of their influence on the elements of the nearest higher level. In this case, the method of pairwise comparisons on a 9-point scale is used (Table 1) [9].

The result of the comparison is a square inversely symmetric matrix of judgments $A=\{a_{ij}\}$, the diagonal elements of which are equal to 1. Each element of the matrix a_{ij} is equal to the numerical characteristic of the advantage of factor i over factor j in relation to the factor under consideration of a higher level. If factor i has an advantage over factor j, then the element a_{ij} is selected from Table 1. In the opposite case, a number from 2 to 9 is assigned to the element a_{ji}, and $a_{ij}=1/a_{ji}$. Thus, the matrix of paired judgments takes the form

$$\begin{pmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ 1/a_{12} & 1 & a_{23} & \cdots & a_{2n} \\ 1/a_{13} & 1/a_{23} & 1 & \cdots & a_{3n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 1/a_{1n} & 1/a_{2n} & 1/a_{3n} & \cdots & 1 \end{pmatrix}.$$

The initial goal of pairwise element comparisons is to calculate priorities (ranks) with respect to local targets (i.e., elements of a higher level of the hierarchy). The priority vector is equal to the eigenvector of matrix A, which corresponds to the maximum eigenvalue

$$A\begin{pmatrix} w_1 \\ w_n \end{pmatrix} = \lambda_{\max}\begin{pmatrix} w_1 \\ w_n \end{pmatrix}, \quad (1)$$

where $\lambda_{\max}$ is the maximum eigenvalue of vector A; $w = (w_1, w_2, ..., w_n)^T$ is the vector of priorities relative to the local goal.

The priorities (ranks) of the elements of the hierarchical structure relative to the main goal are calculated from the recurrent formula

$$p_i^k = \sum_j^J w_i^j \cdot p_j^{k-1},\ i = 1 \div I, \quad (2)$$

where k – index of the hierarchy level (in this case, k=0.3); i, I – respectively, the index and number of elements of the hierarchy level k; j, J – respectively, the index and number of elements of the hierarchy level k–1; p_i^k – priority of element i of the hierarchy level k in relation to the main goal $\left(p_i^0 = 1\right)$.

The solution to the problem will be the vector of priorities of the lower level elements in relation to the main goal.

Any matrix of judgments is generally inconsistent since judgments are subjective opinions of the expert.

The objective value characterizing the deviation from consistency is the consistency index (CI)

$$\text{CI} = \frac{\lambda_{\max} - n}{n-1}. \quad (3)$$

To determine how accurately CI reflects the consistency of judgments, it must be compared with the random index (RI) of consistency, which corresponds to a matrix with random judgments selected from the scale

1/9, 1/8, 1/7, 1/6, 1/5, 1/4, 1/3, 1/2, 1, 2, 3, 4, 5, 6, 7, 8, 9,

provided that there is an equal probability of choosing any of the given numbers.

Table 2 gives average values of the random consistency index for random matrices of judgments of different orders.

Table 2

The value of random consistency indices

Matrix size n	Average of the random consistency index (RI)
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.48
13	1.56
14	1.57
15	1.59

Table 1

Priority scale

Intensity of relative importance	Definition	Explanation
1	Equal importance	Equal contribution of two activities to the goal
3	Moderate superiority of one over the other	Experience and judgment give an easy advantage to one type of activity over another
5	Significant or strong advantage	Experience and judgment give a significant advantage to one type of activity over another
7	Significant advantage	One of the activities is given such a great advantage that it becomes practically significant
9	A very strong advantage	The obviousness of the superiority of one type of activity over another is most strongly confirmed
2, 4, 6, 8	Intermediate solutions between two adjacent judgments	Applied in a compromise case
Inverse of the above numbers	If, when comparing one type of activity with another, one of the above numbers is obtained (for example, 3), then when comparing the second type of activity with the first, we get the inverse value (i.e., 1/3)	Applied as needed

The final conclusion about the consistency of judgments is made based on the consistency ratio (CR)

$$\text{CR} = \frac{\text{CI}}{\text{RI}}. \quad (4)$$

According to the classical theoretical hierarchy analysis method, the judgment matrix is considered consistent if $\text{CR} \le 0.1$. Otherwise, a re-examination is performed.

The UPET routes with the highest priority (rank) in relation to the main goal will be optimal according to a complex criterion that takes into account technical, economic, social, and environmental aspects.

5. 2. Demonstration example of the hierarchy analysis method application for optimizing public transport routes

The demonstration example is based on an analysis of the feasibility of preserving the existing tram route in Kharkiv (Ukraine), which connects a remote residential area with an area adjacent to a forest. This route is 28.2 km long and has been operating since 1970. At the time of its introduction, the city did not yet have a metro system, and taxis were not widespread, and the specified tram route reliably provided transport connections between a remote residential area, a transport hub, one of the markets, the city center, and the green outskirts of the city. Two large scientific and production associations and an educational center are located near the final stop. Several large industrial enterprises are located along the route.

However, over the more than 50 years of the route's existence, the city has undergone dramatic changes. In addition to the appearance of the above-mentioned transport alternatives (metro and minibus), the construction of residential complexes in relative proximity to the route took place, new social facilities appeared (schools, hospitals, cultural and entertainment complexes, etc.). There was also a general increase in the number of non-rail public and private vehicles, to which the rail track located in the middle of the roadway causes some inconvenience, and other, less significant changes took place. In addition, in recent decades, within the framework of Ukraine's European choice, more attention began to be paid to environmental factors. In particular, vibration and noise caused by a moving tram, as well as damage to the roadway that occurs around tram tracks, traffic delays due to traffic accidents involving trams have become more frequent.

While solving this task, three alternative route options were considered:

– option 1 – the existing tram route;

– option 2 – splitting the existing route into two separate tram routes in the area of the transport hub;

– option 3 – connecting the tram route from the remote residential area of the transport hub with the trolleybus route of the transport hub to the outskirts of the city.

Table 3 gives the matrix of pairwise comparisons, calculated priorities of level 2 elements (optimization criteria) in relation to the main goal, as well as the specified parameters of the consistency of judgments (λ_{max}, CI, CR).

Table 3

Matrix of pairwise comparisons of level 1 elements (optimization criteria) in relation to the main goal and the result of their ranking (λ_{max} = 3, CI = 0, CR = 0)

No.	1	2	3	Rank
1	1	2	2	0.5000
2	1/2	1	1	0.2500
3	1/2	1	1	0.2500

As is evident from Table 3, priority is given to the technical and economic factor, which is explained by the special situation in Ukraine (the difficulties of the post-war period). Tables 4–6 give matrices of pairwise comparisons of level 2 elements (impact factors) and the results of their ranking in relation to the three optimization criteria.

As is evident from Tables 4–6, in relation to the technical and economic criterion, the highest priority is given to factor 3 (availability of an electrical substation), in relation to the social criterion – factor 1 (coverage of residential areas), in relation to the environmental criterion – factor 10 (impact on the environment). It should be noted that, in addition to the direct impact of factor 10 (vibration, noise pollution, etc.), factor 9 – proximity to the forest park route – has an indirect impact on environmental safety. This is explained by the reduction in the need for motor transport in the case of laying tram or trolleybus routes, and, thus, by the reduction of atmospheric air pollution by internal combustion engines. Table 7 gives the final matrix of priorities of level 2 elements in relation to the main goal.

Table 4

Matrix of pairwise comparisons of level 2 elements (impact factors) regarding criterion 1 "technological and economic effect" (λ_{max} = 10.763, CI = 0.0848, CR = 0.0569)

No.	1	2	3	4	5	6	7	8	9	10	Rank
1	1	1	1	1/2	1	1	1/4	1/4	1	1	0.0644
2	1	1	1	1/2	1	1	1/4	1/4	1	1	0.0644
3	1	1	1	4	8	8	2	2	8	9	0.2638
4	2	2	1/4	1	2	2	1/2	1/2	2	2	0.0860
5	1	1	1/8	1/2	1	1	1/4	1/4	1	1	0.0430
6	1	1	1/8	1/2	1	1	1/4	1/4	1	1	0.0430
7	4	4	1/2	2	4	4	1	1	4	5	0.1757
8	4	4	1/2	2	4	4	1	1	4	5	0.1757
9	1	1	1/8	1/2	1	1	1/4	1/4	1	1	0.0430
10	1	1	1/9	1/2	1	1	1/5	1/5	1	1	0.0410

Table 5

Matrix of pairwise comparisons of level 2 elements (impact factors) regarding criterion 2 "social significance" (λ_{max} = 10.435, CI = 0.0483, CR = 0.0324)

No.	1	2	3	4	5	6	7	8	9	10	Rank
1	1	1	1	5	5	3	4	4	3	5	0.2512
2	1	1	1	2	2	1	1	1	1	2	0.1134
3	1	1	1	1	1	1/2	1	1	1/2	1	0.0857
4	1/5	1/2	1	1	1	1/2	1	1	1/2	1	0.0610
5	1/5	1/2	1	1	1	1/2	1	1	1/2	1	0.0610
6	1/3	1	2	2	2	1	1	1	1	2	0.1055
7	1/4	1	1	1	1	1	1	1	1	1	0.0778
8	1/4	1	1	1	1	1	1	1	1	1	0.0778
9	1/3	1	2	2	2	1	1	1	1	2	0.1055
10	1/5	1/2	1	1	1	1/2	1	1	1/2	1	0.0610

Table 6

Matrix of pairwise comparisons of level 2 elements (impact factors) in relation to criterion 1 "environmental safety" (λ_{max} = 10.077, CI = 0.0086, CR = 0.0058)

No.	1	2	3	4	5	6	7	8	9	10	Rank
1	1	1	1	1	2	2	2	1/4	1	1/4	0.0646
2	1	1	1	1/2	1	1	1	1/9	1/2	1/9	0.0385
3	1	1	1	1/2	1	1	1	1/8	1/2	1/8	0.0394
4	1	2	2	1	2	2	2	1/4	1	1/4	0.0723
5	1/2	1	1	1/2	1	1	1	1/9	1/2	1/9	0.0353
6	1/2	1	1	1/2	1	1	1	1/9	1/2	1/9	0.0353
7	1/2	1	1	1/2	1	1	1	1/9	1/2	1/9	0.0353
8	4	9	8	4	9	9	9	1	4	1	0.3035
9	1	2	2	1	2	2	2	1/4	1	1/4	0.0723
10	4	9	8	4	9	9	9	1	4	1	0.3035

Table 7

Final ranking matrix of level 2 elements (impact factors)

No.	Rank
1	0.1112
2	0.0702
3	0.1632
4	0.0763
5	0.0456
6	0.0567
7	0.1161
8	0.1832
9	0.0659
10	0.1116

As is evident from Table 7, in relation to the main goal, the highest priority is given to factor 8 (availability of interchanges).

Table 8 gives the results of pairwise comparisons and calculated priorities of level 3 elements (route options) in relation to each of the ten factors.

Table 8

Comparison matrix of level 3 elements (possible UPET routes) by criteria of level 2 elements (influence factors)

Factor 1, coverage of housing estates (3,0,0)*					Factor 2, Proximity of social facilities (3,0,0)				
No.	1	2	3	Rank	No.	1	2	3	Rank
1	1	1	4	0.4444	1	1	1	1/2	0.2500
2	1	1	4	0.4444	2	1	1	1/2	0.2500
3	1/4	1/4	1	0.1111	3	2	2	1	0.5000
Factor 3, the presence of an electrical substation (3,0,0)					Factor 4, energy intensity (3.0092, 0.0046, 0.0079)				
No.	1	2	3	Rank	No.	1	2	3	Rank
1	1	1	1	0.3333	1	1	1	1/4	0.1744
2	1	1	1	0.3333	2	1	1	1/3	0.1919
3	1	1	1	0.3333	3	4	3	1	0.6337
Factor 5, the value of land allotment (3, 0, 0)					Factor 6, availability of unemployed labor (3, 0, 0)				
No.	1	2	3	Rank	No.	1	2	3	Rank
1	1	1	1/2	0.2500	1	1	1	4	0.4444
2	1	1	1/2	0.2500	2	1	1	4	0.4444
3	2	2	1	0.5000	3	1/4	1/4	1	0.1111
Factor 7, travel time between final destinations (3.0092, 0.0046, 0.0079)					Factor 8, the presence of transition nodes (3, 0, 0)				
No.	1	2	3	Rank	No.	1	2	3	Rank
1	1	2	1/2	0.2970	1	1	1	1/4	0.1667
2	1/2	1	1/3	0.1634	2	1	1	1/4	0.1667
3	2	3	1	0.5396	3	4	4	1	0.6667
Factor 9, proximity to the forest park zone (3,0,0)					Factor 10, environmental impact (3,0,0)				
No.	1	2	3	Rank	No.	1	2	3	Rank
1	1	1	1/2	0.2500	1	1	1	4	0.4444
2	1	1	1/2	0.2500	2	1	1	4	0.4444
3	2	2	1	0.5000	3	1/4	1/4	1	0.1111

*Note: * – vector of elements: λ_{max}, CI, CR.*

When choosing quantitative indicators of the results of pairwise comparisons (according to Table 2), the following circumstances were taken into account, in particular:

– the presence of residential areas and the presence of social facilities along the routes;

– the presence of metro stations;

– the greater energy consumption of the trolleybus compared to the tram;

– the time spent by passengers on a transfer in the area of the transport hub, the greater length of the trolleybus route compared to the tram in the green area of the city, which ensures convenience for passengers heading to the educational complex and two enterprises.

Table 9 gives a summary matrix of priorities for level 3 elements in relation to the main goal.

Table 9

Summary priority matrix of level 3 elements (route options)

Route	Rank
1	0.3024
2	0.2882
3	0.4094

As can be seen from Table 9, the optimal option for connecting residential and green areas by electric transport according to technical, economic, social, and environmental criteria is Option 3, which provides for one tram (from the housing estate to the transport hub) and one trolleybus (from the transport hub to the green area) routes. Tables 3–6, 8 also show that in all cases there is good consistency of judgments (i.e., CR < 0.1). Cases of perfect consistency (CR = 0) of comparisons of elements of the 1st and in some cases of the 3rd level are explained by the equal position of two of the three elements. As a result, the comparison is essentially made between two elements, which excludes the presence of internal contradiction.

To achieve the goals of break-even operation, which is the ultimate goal of all municipal transport enterprises, it is also necessary to implement other optimization measures – to improve tariff policy, improve energy efficiency of transportation, improve transport infrastructure, etc. The results also emphasize the importance and accurate forecasting of the economic efficiency of any transport projects in the future. The results of the above studies could be used when planning the work of the industry during the post-war reconstruction of large megacities. The use of the proposed methodology makes it possible to increase the efficiency of management decisions while simultaneously improving the quality and efficiency of passenger transportation. This, in turn, should affect the increase in income and make municipal transport enterprises more competitive on the one hand, and on the other – increase urban transport mobility and have a positive impact on the well-being of citizens.

6. Discussion of research results related to devising a methodology for selecting optimal routes for urban public electric transport

The results related to devising a methodology for selecting optimal routes for urban public electric transport according to a set of criteria are attributed to the strict mathematical validity of the hierarchy analysis method. Namely, the search for priorities of factors influencing the optimum in the form of an eigenvector of the matrix of judgments according to formulas (1) and (2). The results are also explained by the following advantages of HAM over other expert methods:

1) the complex hierarchical structure of cause-and-effect relationships between the optimum and alternative options (Fig. 1);

2) the pairwise nature of comparisons of factors from the position of their influence on the optimum or on intermediate goals using a priority scale (Table 1);

3) the presence of a mechanism for internal control of the consistency of expert judgments using the consistency ratio, which is calculated by formula (4).

Our demonstration example illustrates the efficiency of the chosen conceptual approach to solving a multi-criteria optimization problem for choosing public transport routes.

A feature of the proposed approach to building a route network in comparison with existing ones described in works [1–4] is the simultaneous consideration of technical and economic, social, and environmental factors. This becomes possible due to the decomposition of the problem and the use of HAM to search for optimal routes.

The devised method for optimizing the transport network can be implemented using any programming language designed to solve engineering problems. (In addition to VisualFoxpro, these are Delphi, C++, classic Pascal, etc.). The applied method could be implemented during the post-war reconstruction of cities in Ukraine.

The limitation of the proposed method is the inadmissibility of reversible relationships when constructing a hierarchy of cause-and-effect relationships between the goal (final or intermediate) and the factors that influence it. Therefore, when using the method in practice, this must be taken into account.

The disadvantage of HAM, like all expert methods, is that it depends on the human factor. However, this objective disadvantage is minimized by statistically assessing the consistency of expert judgments by calculating the consistency ratio (4). The probability of random consistency does not exceed 10%.

Further area of our research is to take into account public transport when building an optimal electric transport network. Solving this task is complicated by the fact that motor transport routes, as a rule, change more quickly. Therefore, it will be necessary to identify the general trend in laying motor routes and take it into account when optimizing the electric transport network.

7. Conclusions

1. The feasibility of using the hierarchy analysis method for solving a multi-criteria problem of choosing optimal public transport routes has been theoretically substantiated. Three optimization criteria were selected – technical and economic, social, and environmental, as well as ten factors of influence on the specified criteria. The method, as a component, includes control over the consistency of expert judgments when assessing the importance of factors of influence on each of the optimization criteria. The probability of random consistency should not exceed 10%. The results of the above studies could be used when planning the work of UPET during the post-war restoration of megacities in Ukraine.

2. The efficiency of the method has been demonstrated on the example of an optimal transport connection of two remote residential areas in the city of Kharkiv. A tram route that has existed for more than 50 years, as well as two alternative options, was considered. The optimal option, consisting of one tram and one trolleybus route, was selected according to technical, economic, social, and environmental criteria. The efficiency of the method was confirmed by a low (less than 10%) consistency ratio, which characterizes good consistency of expert judgments.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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