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DEVISING A METHODOLOGICAL APPROACH TO PRIORITIZING ROAD SECTIONS FOR MAINTENANCE WORK

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This study examines the process that prioritizes road sections for performing operational maintenance work to ensure compliance with the predefined level of requirements.

The task addressed is to prioritize road sections in order to enable long-term network maintenance. This issue is due to objective circumstances related to the existing lack of long-term financing, poor filling of databases on the condition of roads, the need to take into account various criteria depending on the purposes of budget allocations. Unlike similar studies, in which the basis is a simple arrangement of objects by their priority, a methodological approach has been devised that is long-term-focused and includes further optimization of the road maintenance program.

Importantly, an analytical hierarchical process (AHP) method was integrated into the mathematical model whose solution has been implemented in authentic RoadRange program. In practice, it allows road organizations to determine an effective, economically justified long-term program for operational maintenance of roads under an automated mode without additional costs for expensive software.

The devised methodological approach to prioritizing sections of highways was tested using data from the Kyiv oblast (Ukraine). Based on the calculation results, 14 sections had been identified that were included in the potential long-term program and met relevant conditions and criteria. The effectiveness of program formation was proven by calculating the ratio of the consistency index to the repair index that equaled 0.002, which does not exceed the limit value of 0.10.

The prospect of this study is to test the devised methodological approach at other critical infrastructure facilities and adapt it accordingly

Keywords: analytical hierarchy process, consistency index, prioritization of road sections, long-term program

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1. Introduction

An effective road maintenance management system helps those responsible for allocating funds to make cost-effective and consistent decisions on managing the road sector as a whole. The development and functioning of the road network is a guarantee for the social, economic, and political development of any country. However, over time, road infrastructure is subject to destruction due to heavy traffic, aging processes, and insufficient maintenance. To prevent it and maintain the road network in good condition, proper management and regular maintenance are important. This helps not only minimize repair costs but also maintain the road surface in good condition, extending its service life.

The purpose of prioritizing road sections is to compile a list of the most promising sections for the further development and implementation of long-term contracts for the road network. The implementation of the most priority long-term contracts makes it possible to maximize the social and economic effect of road maintenance. This ensures rational allocation of resources, protection of roads from premature destruction, as well as increase in the efficiency of network use.

Thus, the relevance of our chosen research area implies devising an effective methodological approach to prioritizing road sections for operational maintenance of the network, which should be based on multifactor analysis and management decision-making under conditions of uncertain funding.

2. Literature review and problem statement

In study [1], the construction of a linear optimization model of road maintenance based on the road surface condition index is described. The results of the study showed that the proposed decision-making models could effectively solve the tasks of actual road maintenance. However, the authors note that the model requires simplification, as well as taking into account the priority of road sections.

In [2], a system for determining the priorities of road maintenance and their sections using multi-criteria decision-making methods in a fuzzy environment is proposed. The essence of the proposed solutions is to rank alternatives based on selected road maintenance criteria. However, for pairwise comparison of criteria in order to determine the most important ones, a simple questionnaire survey of experts was used, which may contain certain signs of impartiality of their opinions.

Optimization of the program of individual types of maintenance work using decision tree methods or Analytical Hierarchy Process (AHP) is considered in studies [3, 4]. However, they tackle individual parts of the long-term program of works on operational maintenance of the network, and the object of evaluation is only winter maintenance [3] or road landscaping [4].

The authors of [5] proposed an approach to making management decisions on network maintenance based on maximizing net present value and minimizing total costs. However, to use these research results, it is necessary to have an appropriate array of accumulated historical data to forecast budget needs and assess the impact of various investment alternatives as road quality indicators and budget allocations were used as the optimization criterion. Moreover, to forecast these indicators, it is necessary to have appropriate licensed software, which is also quite expensive, which narrows the scope of the approach for the purposes of prioritizing road sections.

Study [6] concluded that one of the most difficult issues in the field of network maintenance is determining the optimal operating times and distribution of funds in order to avoid duplication of investments and maximize resource use. The authors note that optimization of long-term maintenance should be based on the rating of road surface indicators and the priority of its maintenance. However, they admit that the gap in the validation of the results is attributed to the lack of a complete historical database on the condition of the road network.

The authors of work [7] propose optimizing the maintenance and restoration of the road surface based on a cloud decision tree. However, the scenarios of the obtained management decisions in [7] are based only on the destruction index and the International Index of Equality (IRI) and do not take into account other possible criteria. A similar approach is proposed in [8], in which the Analytical Hierarchy Process (AHP) method was used to rank the road surface sections by the condition index (PCI) in order to consistently estimate the costs of maintenance.

In an attempt to overcome the limitations of using the AHP method for prioritizing road maintenance work, study [9] examined three ways of using it for this purpose. As a result, it was found that the AHP method performs best when directly comparing all maintenance work simultaneously. Three functional classes of roads, three types of damage, and three levels of damage severity were considered for the analysis. As a result, a three-level AHP structure for prioritizing road sections was proposed. However, the limitation in using the proposed approach is the fact that section prioritization was performed only for different road maintenance tasks.

To scientifically define the weight of each factor based on its relative importance compared to other factors in prioritizing road facility maintenance, a number of authors [10–20] recommend using the AHP method. In particular, in [10], a methodology based on this method was proposed, which was successfully tested on 203 low-intensity rural roads. To determine the priority of a road for its maintenance, the following key factors were used: damage to the road surface, traffic flow intensity, type of connection and the presence of socio-economic objects in the roadside strip.

According to the results of study [11], the priorities of road maintenance according to the Analytical Hierarchy Process method were assigned based on criteria determined by surveying industry experts. In addition, the AHP method was used to determine the weight of the impact of the criteria on the priority of road maintenance. The results showed that the most important order of priority for road maintenance are the following factors: traffic intensity, road condition, maintenance policy, economic factor, and land use factor. Thus, the study focused on taking into account mainly the influence of external factors and the risks they create of non-fulfillment of the long-term road maintenance program.

In [12], it is proposed to model the network operation program in two stages:

1) define factors according to six criteria;

2) apply the AHP method to calculate the weight of criteria that influence decision-making on the construction of a general index for each road. In this case, the following criteria are considered important: road surface condition, road safety, traffic intensity level, pavement service life, road class, and construction quality. These capabilities of the built model for making maintenance decisions are used as a guideline for determining the priorities of the road network maintenance plan taking into account the annual budget. Thus, in [12], the modeling focused on annual plans for the implementation of the network maintenance.

Annual determination of road maintenance budget priorities can also be based on economic, engineering, and social factors [13], the weight of which can be calculated using the AHP method. It is noted that priority factors should be investigated so that the hierarchy of roads is consistent and the budget distribution is appropriate.

In [14], the possible subjectivity of the process of substantiating the choice of a criterion for prioritizing road sections was emphasized. That is why it is proposed to use AHP for pairwise comparison of criteria. The approbation of bla was performed using data on the condition of 28 road sections. The final list of candidate section ratings was compiled taking into account the priority weight of alternatives that reflected their qualitative condition. However, it was emphasized that in practical use, a problem may arise with the processing of large data sets; thus, there is a need to develop appropriate software, or use existing applications.

In [15], a hybrid multi-criteria decision-making method (MCDM) combining AHP, ELECTRE II, ELECTRE III, ELECTRE IV, and Copeland methods is described to determine the priorities of road maintenance. The proposed hybrid method was tested on a city's street network. The results showed that road safety is the most important criterion for road maintenance, and intensity and pavement quality index (PCI) are the second and third most important, respectively. In addition, it was determined that road capacity is the least important criterion for its maintenance. In the paper, eight main criteria were defined using previous studies and expert opinions, which were ranked in order of importance. Although the study reports more substantiated results using the method based on real data, it is currently impossible to establish whether they could be extended to other types of roads and infrastructure facilities.

In studies [16–20] it is proposed to use built-in functions of MS Excel (USA) to implement the task of optimizing a long-term maintenance program. This approach allows road organizations to significantly save money on the purchase of specialized expensive software. In particular, in [16], three steps of modeling are defined:

1) study of factors affecting road maintenance;

2) determine the ordinal priority of factors;

3) build a linear model and solve it using MS Excel. As a result of the theoretical study reported in [16], five key criteria for modeling were identified by the expert method: procurement practices, financial resources, political intervention, human factors, and road materials. The disadvantage of the proposed approach is that it does not take into account scenarios for which decision-makers have doubts about their judgments. Another disadvantage is that only five criteria were evaluated during the study, and the opinions of only three experts were taken into account.

Papers [17, 18] focus on a model for evaluating and selecting a road maintenance strategy by integrating the AHP and TOPSIS methods. The modeling task was to obtain decision-making scenarios using several criteria. The AHP method was used to determine the weights of the criteria. To work with uncertain judgments of decision-makers, the TOPSIS method was used as an evaluation tool. The model proposed in [17] was implemented in the MS Excel environment, which accelerated the processing of modeling parameters. The study showed that quality, service time, environment, production costs, and profit are the most important selection criteria. The results of the study determined that periodic maintenance had the best value of relative proximity among the considered alternatives. Paper [18] ultimately allowed prioritization to be performed only by four goals – road safety, road preservation, quality condition, comfort and aesthetics. That significantly narrows the scope of the proposed approach.

In [19], factor analysis and the AHP method were used to devise a decision-making method for managing road network maintenance. Factor analysis makes it possible to reduce the data set to a more manageable size without significant loss of original information. The AHP method was used to determine the weighting coefficients of the advantages of variables. To achieve the goal of the study, SPSS (USA) and MS Excel (USA) software were used as analysis tools. The analysis revealed that for effective network management, periodic maintenance should be based on detailed periodic monitoring of the condition of infrastructure facilities. Based on the results of the study, it was determined that the AHP method is a powerful tool for integration into MCDM in terms of maintenance management practices. However, the authors of [17, 19] did not compare it with other methods for determining the weight of criteria and prioritizing maintenance strategies.

In [20], the Analytic Hierarchy Process method was applied to the prioritization of bridges, and the expert method was used to determine the weight coefficients of the prioritization criteria. The authors proposed a rather extensive range of decision-making criteria for the operational maintenance of bridges. The proposed approach was implemented in MS Excel, but the study did not consider highways and other transport infrastructure facilities.

Our theoretical review of scientific results from similar studies [1–20] indicates significant attention to the issue of the priority of infrastructure facilities for the purposes of operational maintenance. However, most of them focus on individual factors [1, 5–13, 16–19] or fragments of the road maintenance program [3, 4, 15, 20], or do not take into account the long-term [12]. The likely reason is objective difficulties associated with the lack of an accumulated database of road condition indicators [1, 5–13, 16–19] and completed repairs [2, 3, 4, 15, 20], the existing problem of long-term budgeting [12]. A separate obstacle to the implementation of the proposed solutions may also be the need to use expensive specialized software packages to form a maintenance program, as demonstrated in [5, 14]. An option for overcoming the difficulties was proposed in [20], but the study did not take into account the priority of sections under budget constraints and the long-term nature of financing.

Thus, there is a need to devise a methodological approach to prioritizing sections of highways for performing work on a long-term network maintenance program based on multifactor analysis.

3. The aim and objectives of the study

The purpose of our study is to devise a methodological approach that makes it possible to prioritize road sections for the purposes of forming a long-term maintenance program. This will make it possible to implement a simplified procedure for prioritizing public roads in practice in order to effectively distribute funding for road maintenance.

To achieve this aim, the following objectives were accomplished:

– to state the prioritization problem and develop an algorithm for solving it;

– to integrate the analytical hierarchical process method into the mathematical model for solving the problem of prioritizing assessment objects;

– to test the devised methodological approach for assessing the priority index of a road section.

4. The study materials and methods

The object of our study is the process of prioritizing road sections for the purpose of performing operational maintenance work to ensure compliance with the predefined level of requirements.

The principal hypothesis of the study assumes that prioritizing road sections for their inclusion in the network maintenance program could lead to making informed decisions on allocating budget funds for long-term financing of operational maintenance. The methodological approach is designed to implement a simplified procedure for prioritizing roads in order to gradually transition to the use of long-term contracts for operational maintenance of roads. The approach is based on the procedure for decomposing the prioritization problem into simple components (criteria) with the subsequent adoption of informed expert decisions regarding these components by pairwise comparison of criteria.

The basic assumption of the study is that when the ratio of the compliance indices and the need for major repairs reaches a positive value, the criterion proposed by the expert can be considered justified. This could further confirm the principal hypothesis of the study by performing prioritization of sites according to reasonable criteria for the development of an effective long-term maintenance program. A simplification of the study is that only those objects that are not under an emergency condition are accepted for modeling purposes.

Underlying our research methodology is the application of the classical method of an analytical hierarchy process (AHP) [21], results from reviewing the literature related to this area, as well as previous studies [20, 22]. An expert method was used to select the prioritization criteria. For pairwise (binary) comparisons, an improved scale of relative advantages was used. While devising a methodological approach to solve the objective function, a classical simplex method of linear programming with binary decision variables was also used. For the purpose of further practical application of the methodological approach to prioritizing road sections using the Microsoft Excel spreadsheet (USA), the RoadRange software was developed.

Our study on the formation of a long-term road maintenance program based on the above methodological approach was carried out using data on 20 sections along a national highway in the Kyiv oblast (Ukraine). According to the results of simulation in the RoadRange software, an optimized long-term maintenance program for this region was compiled, which included 14 sections that satisfied the specified conditions and budget constraints according to the criteria adopted by experts.

The results were checked by the consistency index, AI = 0.001. At the same time, the ratio of the consistency index to the repair index was CR = 0.002, which does not exceed the limit value of 0.10. Thus, the defined long-term maintenance program for a national highway in the Kyiv oblast (Ukraine) was checked for adequacy and compliance with the specified conditions and constraints.

5. Devising a methodological approach to prioritizing highway sections

5. 1. Statement of the prioritization problem and development of an algorithm to solve it

Prioritization of long-term contracts is carried out to ensure compliance with the predefined level of requirements, which is determined by national regulatory legal acts regarding the satisfaction of the needs of road users. These requirements include safety, convenience, and comfort of movement; accessibility of roads; preservation of road components and road structures; minimization of the duration of defects; reduction of resource costs for eliminating defects; minimization of environmental damage from the impact of defects.

In the prioritization process, the main parameters of long-term contracts are determined [22]:

– complexity – the degree of coverage of long-term contracts of road components. In particular, in accordance with world practice, a "comprehensive long-term contract" or "specialized long-term contracts" are distinguished (separate contracts for the maintenance, for example, of the road surface, bridges, technical means of road traffic management, etc.);

– the composition and length of road sections planned to be serviced on the basis of long-term contracts, taking into account their significance (state or local), classification (international, national, etc.), and road category;

– the duration of the long-term contract;

– the levels of requirements for the operational condition of public roads;

– operational levels of service;

– operational levels of maintenance;

– the expected cost of implementing the long-term contract;

– the expected socio-economic efficiency of their implementation.

For prioritization, all available sources of data on the availability of roads and their components and on their technical and operational condition are used. These can be documented data on certification; current, targeted, and seasonal inspections and special surveys; data obtained from road users.

The result of the prioritization process is an ordered list of sections along a certain road network that are promising for the formation and subsequent implementation of a road condition management program. This approach can be carried out on the basis of taking into account budgetary, labor, technical, environmental, and other constraints.

Summarizing the world experience in prioritizing road sections and artificial structures, it is possible to distinguish the following prioritization methods of different complexity (Table 1).

Table 1

Classification of prioritization methods

Method type	Characteristics
Ranking (rating)	Ranking is based on subjective assessment, current costs, or the Analytical Hierarchy Process (AHP) to assess the technical and operational condition of road and bridge sections, taking into account their importance. Most methods are simple and easy to use but may be biased when subjective assessment is taken into account
Limited rationality	Includes marginal cost-effectiveness, multi-criteria analysis, and economic frontiers. Compares priorities based on net present value, costs, and/or efficiency measures. Considers duration of activities and deferral options. These methods are relatively simple to apply and provide better solutions, but with a limited number of options considered
Mathematical programming	Optimization methods such as linear programming, exhaustive search, dynamic programming, neural networks, genetic algorithms, and fuzzy logic. These provide solutions that are close to optimal but require complex software and are more suitable for solving problems where costs and benefits are valued in monetary terms

The objects of assessment for substantiating the priorities of road sections and road structures for inclusion in the operational maintenance program on the basis of long-term contracts may include the following:

– sections of one road according to the route or corridor principle;

– sections of several roads, including those of different importance;

– individual road components;

– individual types of activities, namely, those related to traffic safety, landscaping, road cleanliness, etc.

The technical parameters and number of component road sections – candidates for inclusion in the program, are determined according to data from road projects, certification and subsequent inspections and current inspections.

The current operational condition of the road section of an individual object of assessment is determined by identifying the presence of defects from the lists given in current regulatory documents during inspections and inspections of road sections.

It is proposed to adopt the value of the dimensionless condition index on a scale from one to one hundred points as a quantitative measure of the operational condition of the assessed road network object. In this case, 100 points corresponds to a transport and operational condition that meets all the requirements of building codes and national standards of the country in which the assessment is carried out. At the same time, it is necessary to take into account the importance of the assessed object for ensuring socio-economic needs.

In turn, the transport and operational condition of the assessed object can be assessed using the index adopted in the national regulatory and technical documentation. Our study proposes to use a 10-point ordinal scale with states designated by the index $J = 1, 2, ..., 10$. Each assessed object has one such value of the index J. If two assessment objects are assigned the same values of J, then they are equivalent, that is, they have the same transport and operational condition. However, these indicators are non-additive since it is impossible to calculate how much or how many times they differ from each other.

The assessment of the transport and operational condition indicator of a road section or a separate object of a road section should be carried out using an interval scale. In it, a certain property of the objects being assessed is manifested in the relations of equivalence, order, and additivity (Table 2).

Table 2

Scale of intervals of operational condition levels of road sections for long-term maintenance purposes

State number	State ID	Generalized characteristic	Estimated operational condition, %
1	Acceptable	The roadway is free of damage and deformation. The roadway surface is rough, even; the shoulders are reinforced. The operational condition of other objects meets regulatory requirements	≥ 90 and ≤ 100
2	Limitedly acceptable	The roadway is flat; the cross-section is not distorted. There are some cracks on the pavement. The surface is rough; the shoulders are reinforced. The operational condition of other objects is 75% in accordance with regulatory requirements	≥ 70 and < 90
3	Satisfactory	The evenness of the roadway is satisfactory. The transverse profile is not distorted. The surface of the pavement is worn. There are cracks and individual deformations on the pavement. The operational condition of other objects meets the regulatory requirements by 50%. The condition of artificial structures is serviceable	≥ 60 and < 70
4	Unacceptable	The transverse profile of the carriageway is distorted. The road surface is worn, uneven, not rough. The relative area of damage to the surface is more than 2%. Artificial structures are in limited or inoperable condition. The operational condition of other objects meets the regulatory requirements by 25%	< 60

The average number of defects of each type per year or season is determined based on data from surveys and documented inspections, defect reports from contracts of previous years, reports on work performed and services provided. And in the absence or insufficiency of information for determination, the average number of defects of each type per year or season can be determined by an expert method – a survey of experienced experts. In this case, the natural process of increasing the number of defects over time, the level of their distribution and severity is necessarily taken into account. The remaining years before the end of the standard repair period of current or major repairs or the period before the reconstruction of the assessment object are also estimated. In this case, the objective function (Z_S) is the minimized average annual level of deterioration of objects during analysis period (T)

$$Z_S = \frac{\sum_{i=1}^{N}\left(S_i \cdot \left[\sum_{t=1}^{T}\left[P_{i,t} \cdot \left(\begin{matrix} D_{i,t-1} + \Delta D_{i,t} - \\ - I_{i,t}\left(X_{i,t}\right) \end{matrix}\right)\right]\right]\right)}{\sum_{i=1}^{N}\left(S_i \cdot \sum_{t=1}^{T} P_{i,t}\right)} \Rightarrow \min, \quad (1)$$

where Z_S is the average level of deterioration of objects at the end of year t, weighted by the geometric parameter and the importance of objects for the period T; N is the number of objects under assessment; S_i is the geometric parameter of the i-th object (area, m^2; length, m); $\Delta D_{i,t}$ is the increase in the level of deterioration of the i-th object for year t; $D_{i,t}$ is the level of deterioration of the i-th object at the end of (t – 1)-th year; $X_{i,t}$ is a decision variable that takes values from the set of types of work, $X_{i,t} \in \{1,..,3\}$, where, for example, 1 is operational maintenance, 2 is current repair, 3 is major repair; $P_{i,t}$ is the priority of the i-th object at the beginning of year t; $I_{i,t}(X_{i,t})$ is the impact of the repair measure $X_{i,t}$ on reducing the level of deterioration of the i-th object in year t.

The constraints on the objective function are:

1) maximum level of deterioration

$$D_{t,i} \le D_{\max}, \quad (2)$$

where $D_{\max}$ is the maximum allowable level of deterioration (degradation). This constraint may be violated if there is insufficient funding;

2) budget constraints on the cost $C(t)$ of repairing and maintaining all facilities in year t

$$C(t) = \sum_{i=1}^{N} C_{t,i,m} \le B(t), \forall t, \quad (3)$$

where $C_{t,i,m}$ – cost of measure m for the i-th object in year t, thousand UAH; $B(t)$ – budget in year t, thousand UAH. This restriction cannot be violated.

Optimization according to the criterion of cost Z_C of repair measures for the time period T is carried out using the penalty function method

$$Z_C = \sum_{i=1}^{N}\sum_{t=1}^{T}\left(\frac{C_{i,t}}{(1+r)^t} \cdot PF_{i,t}\right) \Rightarrow \min, \quad (4)$$

where $PF_{i,t}$ is the penalty function, which is determined from the following formula

$$PF_{i,t} = \\ = \left[1 + P_{i,t} \cdot \max\left(\frac{\left(D_{i,t-1} + \Delta D_{i,t} - I_{i,t}\left(X_{i,t}\right)\right) - D_{\max}}{D_{\max}}, 0\right)\right], \quad (5)$$

where $C_{t,i}$ – cost of repair and maintenance of facility i in year t, thousand UAH; r – discount rate, adjusted for inflation;

$P_{i,t}$ – priority of facility i at the beginning of year t; $I_{i,t}(X_{i,t})$ – impact of repair and restoration measure $X_{i,t}$ on reducing the level of deterioration of facility i in year t.

Therefore, the objective function is the reduced cost of repair and maintenance of the facility, adjusted for the penalty coefficient. If the level of deterioration exceeds the specified maximum permissible value, the value of the function will increase, which serves as a barrier to unjustified reduction in repair costs. Penalties take into account the achieved condition of the facilities, and a better condition means minimizing transport costs and maximizing external positive effects.

The maximum permissible level of deterioration $D_{\max}$ is set based on economic justification, but it cannot be worse than the maximum permissible level, based on traffic safety requirements and preservation of the object element.

It is proposed to use the following algorithm for optimizing repair and maintenance programs for road sections (Fig. 1).

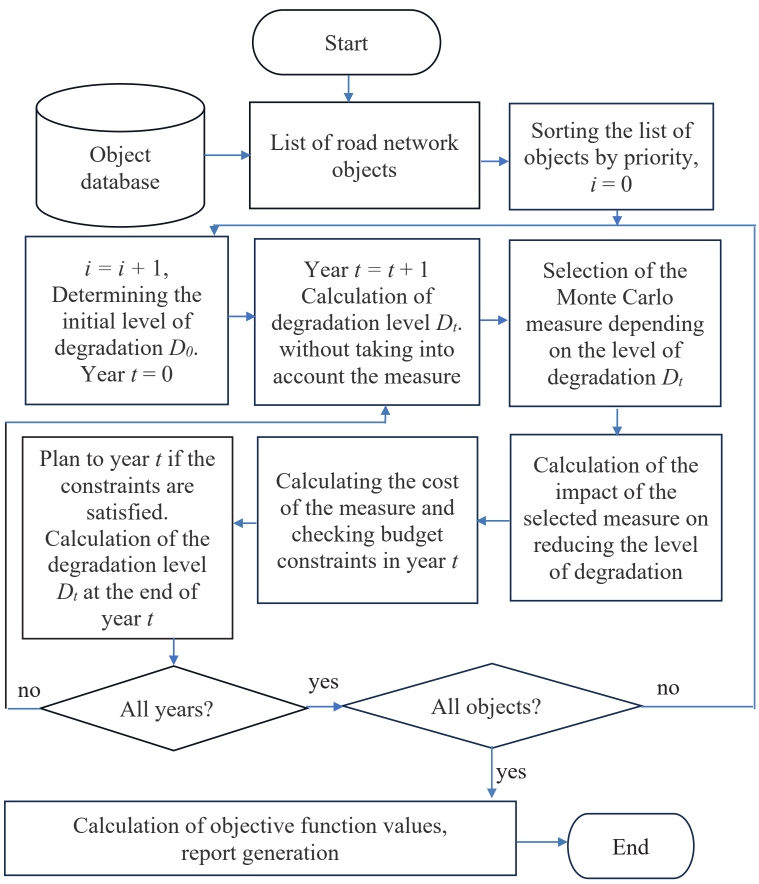

Fig. 1. Algorithm for solving the problem by priorities

There are two types of strategies for implementing long-term contracts, which are distinguished by the possibility or impossibility of including major repairs in the long-term contract. The first strategy allows for major repairs at the beginning of its implementation, which will require large current investment costs. These are the so-called "hybrid long-term contracts". The second strategy – without including major repairs in the long-term contract, will require smaller initial investments, but larger future costs for the contractor. In this case, the highest priority for implementing a long-term contract will be the objects with the lowest values of the index of the need for major repairs (RI). Thus, they must be arranged for consideration in descending order of the difference 100 – RI

$$P = 100 - RI, \tag{6}$$

where P is the priority of the road section; RI is the index of the need for major repairs.

Next, it is necessary to determine the list of road sections – potential objects of operational maintenance based on the same long-term contract (program), ss well as establish the duration of the long-term contract and for each section – the level of requirements, the level of maintenance, specifications with requirements for the operational condition of the roads.

5. 2. Application of the analytical hierarchy process method for prioritizing assessment objects

The application of the Analytical Hierarchy Process (AHP) method [21] in this case involves the procedure of decomposing the prioritization problem into simple components (criteria) with the subsequent adoption of justified expert decisions regarding these components by pairwise comparison of criteria. Based on the results of pairwise comparisons, a vector of relative advantages of criteria is formed. In this case, the purpose of the analysis is formulated, the number of levels of the hierarchy of criteria is determined, and the list of criteria at each level of the hierarchy is determined. The number of subordinate criteria (subcriteria) of a certain level for each criterion of the highest level of the hierarchy is determined by selecting no more than 9 subcriteria at the same time (Fig. 2).

At the first level of the hierarchy, the weight coefficients of each of the criteria adopted in formulating the analysis objectives are calculated. In this case, their sum must equal unity

$$\omega_1 + \omega_2 + \omega_3 = 1, \tag{7}$$

where ω_1 – weight of the index of deficiency of the operational condition; ω_2 – weight of the index of compliance with current standards; ω_3 – weight of the index of importance of the object.

The index of deficiency of the condition (EC) is determined from the following formula

$$EC = 100 - E, \tag{8}$$

where E is the estimated operational condition, %.

At the second level of the hierarchy, the weight coefficients of the criteria that are subordinate to the criteria of the first level are calculated (for example, as in Fig. 2):

$$\begin{cases} \omega_{21} + \omega_{22} = 1; \\ \omega_{31} + \omega_{32} + \omega_{33} = 1. \end{cases} \tag{9}$$

At the third level of the hierarchy, the weight coefficients of the criteria (subcriteria) that are subordinate to the criteria of the second level are calculated (for example, as in Fig. 2):

$$\begin{cases} \omega_{211} + \omega_{212} + \omega_{213} + \omega_{214} + \omega_{215} + \omega_{216} + \omega_{217} = 1; \\ \omega_{221} + \omega_{222} + \omega_{223} = 1; \\ \omega_{311} + \omega_{312} + \omega_{313} + \omega_{314} = 1; \\ \omega_{321} + \omega_{322} + \omega_{323} + \omega_{324} + \omega_{325} = 1; \\ \omega_{331} + \omega_{332} + \omega_{333} = 1. \end{cases} \tag{10}$$

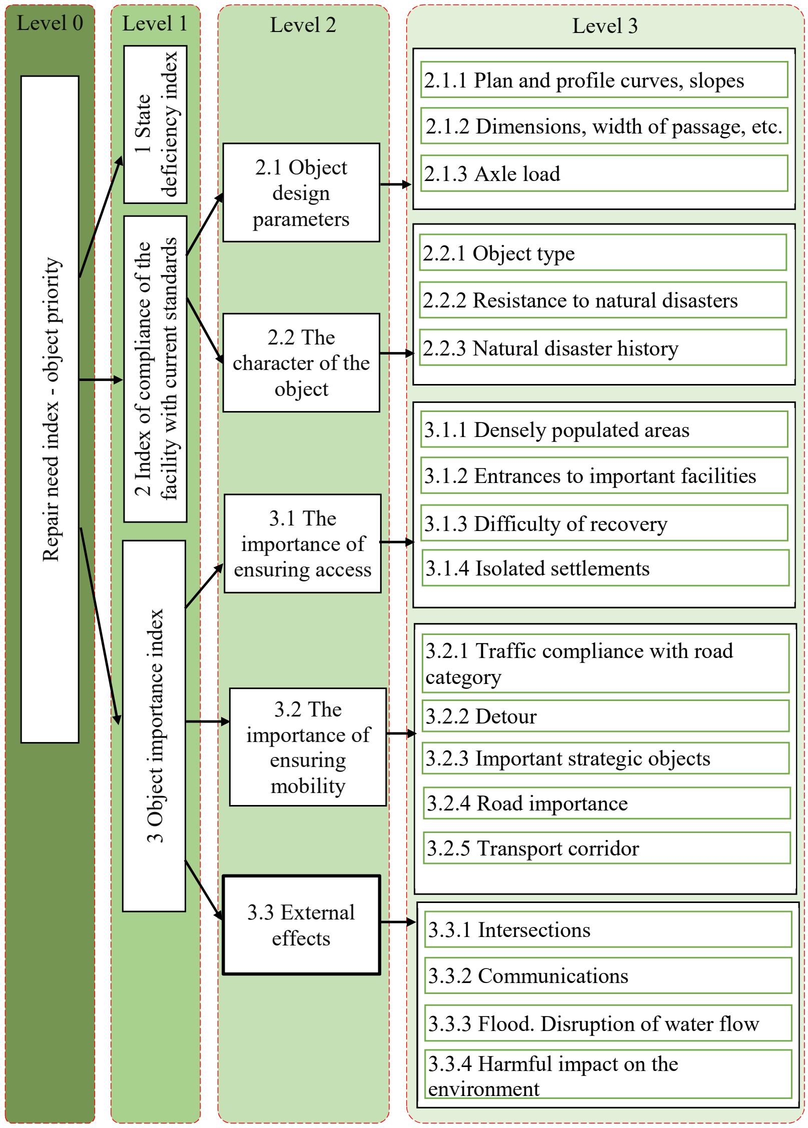

Fig. 2. Example of criteria selection in the hierarchy of road section prioritization

Next, a square matrix of criteria advantages (W) of size $N \times N$ is constructed, with the elements of the matrix being the scores w_{ij}

$$W = \begin{pmatrix} w_{11} & \dots & w_{1N} \\ \dots & w_{ij} & \dots \\ w_{N1} & \dots & w_{NN} \end{pmatrix}, \tag{11}$$

where w_{ij} is the value of the assessment of the advantage of the i-th criterion over the j-th, $i = 1, \dots, N$; $j = 1, \dots, N$; N – number of criteria accepted for analysis.

The diagonal elements of the matrix, when $i = j$, are always equal to 1. The over-diagonal elements of the preference matrix are found by pairwise comparisons. The sub-diagonal elements are taken to be inversely symmetric with respect to the over-diagonal ones (Table 3)

$$w_{ij} = \frac{1}{w_{ji}}, \quad i = 2,3,\dots,N; \quad j = 1,\dots,N. \tag{12}$$

For pairwise (binary) comparisons, the relative advantage scale is used (Table 4).

The next step is to calculate the components of the vector of priorities of compared objects (V). To do this, it is necessary to determine the geometric mean sum of each row of the matrix W

$$V = \{w_1,\dots,w_i,\dots,w_N\}, \tag{13}$$

where w_i is the geometric mean sum of each row of the matrix, which is determined from the following formula

$$w_i = \sqrt[N]{w_{i,1} \cdot w_{i,2} \cdot \dots \cdot w_{i,N}} = \left(\prod_{j=1}^{N} w_{i,j}\right)^{\frac{1}{N}}. \tag{14}$$

The resulting vector of priorities must be normalized

$$V^{\omega} = \{\omega_1,\dots,\omega_i,\dots,\omega_N\}, \tag{15}$$

where ω_i is the normalized geometric mean sum of each row of the matrix, which is determined from the following formula

$$\omega_i = \frac{w_i}{\sum_1^N w_j}, \quad i = 1,2,\dots,N. \tag{16}$$

Table 3

Example of a square matrix of criteria benefits (W)

	P1	P2	P3
P1	1,00	w_{12}	w_{13}
P2	$1/w_{12}$	1,00	w_{23}
P3	$1/w_{13}$	$1/w_{23}$	1,00

Note: P1, P2, P3 are accepted criteria.

Table 4

Scale of relative advantages

Value of preference score	Description of criteria
$w_{ij}=1$	If criterion *i* is equally important relative to criterion *j*
$w_{ij}=3$	If criterion i is more important relative to criterion *j*
$w_{ij}=5$	If criterion *i* is clearly more important relative to criterion *j*
$w_{ij}=7$	If criterion *i* is significantly more important relative to criterion *j*
$w_{ij}=9$	If criterion *i* is definitely more important relative to criterion *j*
$w_{ij}=2,4,6,8$	In intermediate cases
$w_{ij}=1/3$	If criterion *j* is more important relative to criterion *i*
$w_{ij}=1/5$	If criterion *j* is clearly more important relative to criterion *i*
$w_{ij}=1/7$	If criterion *j* is significantly more important relative to criterion *i*
$w_{ij}=1/9$	If criterion *j* is definitely more important relative to criterion *i*
$w_{ij}=1/2$; 1/4; 1/6; 1/8	In intermediate cases

The components ω_i of the priority vector are weight coefficients.

The obtained results are checked for consistency. To this end, it is necessary to calculate the $\lambda_{\max}$ value – the maximum personal number of the matrix

$$\lambda_{\max}=\sum_{j=1}^{n}\left(\sum_{i=1}^{n}w_{ij}\cdot\omega_i\right). \quad (17)$$

The measure of inconsistency is the normalized deviation $\lambda_{\max}$ from N, or the so-called "consistency index"

$$AI=\frac{\lambda_{\max}-N}{N-I}. \quad (18)$$

In order to assess whether the obtained agreement is acceptable or not, it is also compared with the Repair Need Index (*RI*). In this way, the consistency of the expert's preferences is checked

$$CR=CI/RI, \quad (19)$$

where *RI* is the index of the need for major repairs.

The value of the index of the need for major repairs is taken from Table 5 depending on the number of criteria accepted for analysis.

Table 5

Values of index of the need for major repairs depending on the number of criteria accepted for analysis

N	3	4	5	6	7	8	9	10
RI	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Similar preference matrices (Table 3) are constructed to compare all criteria (subcriteria) at all levels of the hierarchy. The size of these tables N is set equal to the number of criteria (subcriteria) at a certain level of the hierarchy, subordinate to one criterion of a higher level. For example, part of the criteria (subcriteria) of the 3rd level is subject to one criterion of the 2nd level. These matrices are checked for consistency independently of each other.

The assessment of the level of the factor of the operational condition of the object is carried out according to the aggregated estimates of the operational condition index (Table 6).

Table 6

Assessing the level of an operational condition factor of the facility

State No.	State ID	Characterization	Score
1	Excellent	$J=9$. Perform operational maintenance	100
2	Good	$J=8$. Perform operational maintenance	75
3	Satisfactory	$J=6$. Current repairs required	50
4	Unsatisfactory	$J\leq 5$. Major repairs needed	25

The final step is to calculate the cost of the measure and check the budget constraints. The mathematical model of the problem includes:

– objective function

$$E_{DC}=\sum_{i=1}^{N}\left(x_i\cdot e_i\right)\Rightarrow\max, \quad (20)$$

where E_{DC} – effect of implementing a long-term contract on the road network, monetary units; N – number of sections; x_i – integer (0 or 1) binary decision variable for the i-th section; e_i – effect of implementing a long-term contract on the i-th section, monetary units;

– constraints:

$$\sum_{i=1}^{N}\left(x_i\cdot c_{ij}\right)\leq B_j,\quad j=1,\ldots,y, \quad (21)$$

where c_{ij} is the cost of executing a long-term contract on the i-th road section, monetary units; B_j – available budget in the j-th year of program execution, monetary units; y – duration of the long-term contract, years.

The objective function is linear; therefore, to solve the problem, the simplex method of linear programming with binary decision variables is chosen (0 – not selected, 1 – selected).

To perform the procedures for prioritizing road sections and/or bridges using the Microsoft Excel spreadsheet (USA), the RoadRange software was developed. This software built templates of comparison matrices for use by an expert for prioritization purposes (Fig. 3).

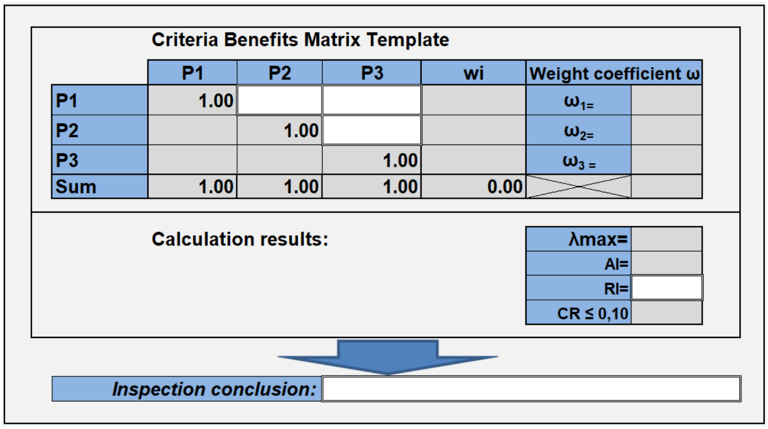

Fig. 3. Example of a 3 × 3 comparison matrix template in RoadRange

White cells in the RoadRange software are available for editing in worksheets, while others are protected from editing to prevent errors. The template sheet also contains the data preparation necessary for identifying comparison matrices. The RoadRange software provides supporting information that facilitates decision-making regarding the advantages of one criterion over another.

To select road sections for inclusion in the maintenance program, the Microsoft Excel 2016 solver and compatible versions are used, in particular the "Solution Search" function. In this case, a table of output data is formed, which includes available budget in monetary units; estimated cost of maintenance of each project; pre-calculated cost savings for the entire program execution time. Binary decision variables are also entered, which are taken equal to 1 before starting the optimization. This means that at the time of optimization all sections are included in the program (Table 7).

After starting the solver under the "Data" mode, the "Solver Parameters" window is displayed (Fig. 4), which is used to set the cell with the objective function formula, solution variables, constraint conditions (≤), and the range of available budget cells.

The new binary values will be displayed in the "YesNo" range of the "Optimization" sheet. There is also the option to generate a sheet with a report on the optimization results.

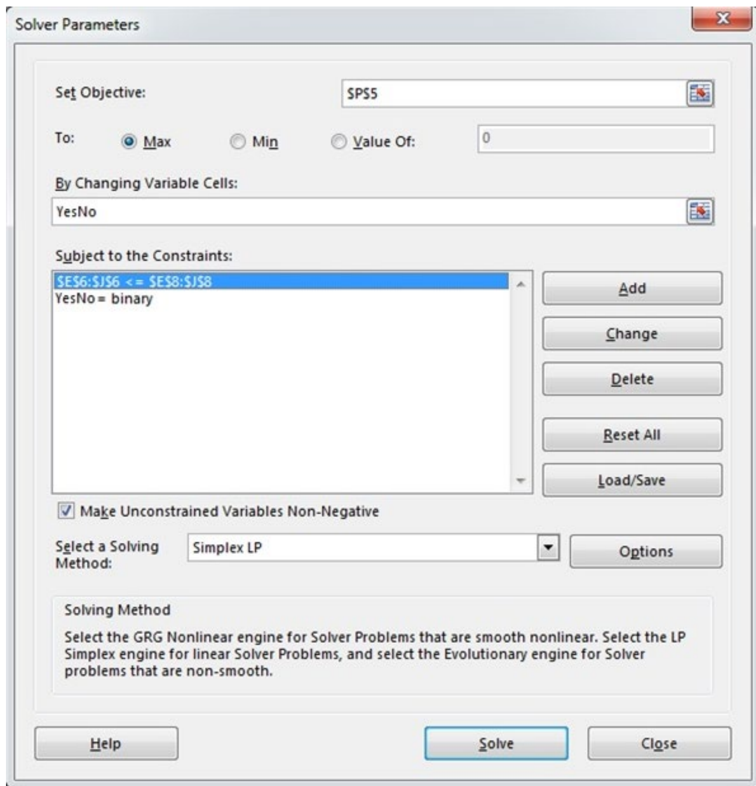

Fig. 4. Solver settings window (in the figure, "YesNo" is a named range of cells with solution variables)

Table 7

Initial data for solving the road section selection problem

Objective function	Section No.	Budget, monetary units					
		Year	1	2	3	j	y
E_{DC}		Needed	B_{r1}	B_{r2}	B_{r3}	B_{rj}	B_{ry}
		Condition	<=	<=	<=	<=	<=
		Available	B_1	B_2	B_3	B_j	B_y
Solution variable		Savings	Cost by year, monetary units				
x_1	1	e_1	c_{11}	c_{12}	c_{13}	c_{1j}	c_{1y}
x_2	2	e_2	c_{21}	c_{22}	c_{23}	c_{2j}	c_{2y}
x_i	i	e_i	c_{i1}	c_{i2}	c_{i3}	c_{ij}	c_{iy}
x_N	N	e_N	c_{N1}	c_{N2}	c_{N3}	c_{Nj}	c_{Ny}

5. 3. Testing the devised methodological approach for assessing the priority index of a road section

For the purposes of testing the devised methodological approach for assessing the priority index of a road section using the developed RoadRange software, a three-level hierarchical structure was used, which is shown in Fig. 2, as well as research data on 20 sections along a national highway in the Kyiv oblast. The goal of prioritization was set – to carry out repairs on sections according to the criteria given in Table 8.

The expert entered data regarding the criteria preferences into the template matrix for each section of the highway in the RoadRange software (Fig. 5).

Table 8

Criteria for prioritizing areas for repair purposes

ID	Criteria name
P1	Index of operational condition deficiency
P2	Index of compliance with current standards
P3	Index of importance of road section

Similar calculations were performed in the RoadRange software for other elements of the hierarchical structure (Fig. 2). The results of all worksheet matrices are collected on the "CALCULATION" sheet of the RoadRange software, a fragment of which is shown in Fig. 6.

After processing the matrices of all levels of the hierarchy, the calculation result was obtained – the index of the need for major repairs of the assessment object *RI* for each of the 20 sections of the road. At the same time, the consistency index (18) satisfied requirements (19), as evidenced by the program output (Fig. 5).

According to the algorithm (Fig. 1) using formulas (20), (21) in the RoadRange software using the "Solution Search" function based on the initial data (Table 9), the selection of road sections for inclusion in the maintenance program (Table 10) was performed.

Criteria Benefits Matrix Template

	P1	P2	P3	wi	Weight coefficient ω	
P1	1.00	3.00	7.00	2.759	ω_{1}=	0.682
P2	0.33	1.00	2.00	0.874	ω_{2}=	0.216
P3	0.14	0.50	1.00	0.415	ω_{3} =	0.103
Sum	1.48	4.50	10.00	4.05		1.000

Calculation results:

λmax=	3.00
AI=	0.001
RI=	0.58
CR ≤ 0,10	0.002

Inspection conclusion:	***Judgments are consistent***

Fig. 5. Determining the parameters for the criteria preference matrix and data consistency in RoadRange software (example for section No. 1, first level of hierarchy)

Target	1 level of hierarchy	Weight, ω	2 level of hierarchy	Weight, ω	3 level of hierarchy	Weight, ω	Factors, %	Level III and II calculatio	Level I calculation
Repair need index, RI	1 State deficiency index	0.682			Actual operational road condition	1.000	20		54.532
86.183	2 Index of compliance of the facility with current standards, OI	0.216	2.1 Object design parameters	0.750	2.1.1 Width of the carriageway	0.374	100	75.00	16.188
					2.1.2 Technical means of organizing road traffic	0.175	100		
					2.1.3 Radius of curves of the longitudinal profile	0.094	100		
					2.1.4 Radius of curves of curves in the plan	0.076	100		
					2.1.5 Longitudinal slope	0.141	100		
					2.1.6 Transverse slope	0.060	100		
					2.1.7 Design axle load	0.079	100		
			2.2 The character of the object	0.250	2.2.1 Type of road section (temporary or permanent)	0.674	100	25.000	5.396
					2.2.2 Year-round mobility. Disaster resilience	0.226	100		
					2.2.3 History of the disaster	0.101	100		
	3 Object importance index, RI	0.103	3.1 The importance of ensuring access	0.285	3.1.1 Settlements	0.550	100	28.54	2.925
					3.1.2 Access to important facilities	0.249	100		
					3.1.3 Difficulty of recovery	0.130	100		
					3.1.4 Isolated settlements	0.072	100		
			3.2 The importance of ensuring mobility	0.628	3.2.1 Traffic characteristics by road category	0.398	100	62.82	6.440
					3.2.2 Detour	0.339	100		
					3.2.3 Strategically important objects	0.151	100		
					3.2.4 Road significance	0.084	100		
					3.2.5 Transport corridor	0.028	100		
			3.3 External effects	0.086	3.3.1 Crossings	0.731	100	6.85	0.702
					3.3.2 Environmental impact (ecology)	0.188	33		
					3.3.3 Disruption of water flow during floods	0.081	0		
								Σ=	86.183

Fig. 6. "Calculation" sheet in RoadRange (example for section No. 1)

Table 9

Initial data for solving the road section selection problem

Objective function	Section No.	Budget, monetary units						
		Year	1	2	3	4	5	6
177		Need	477.2	482.2	452.2	645.0	1004.3	1081.3
		Condition	<=	<=	<=	<=	<=	<=
		Available	500.0	300.0	300.0	350.0	700.0	800.0
Solution variable		Economy	Cost by year. monetary units					
1	1	11.0	30.0	30.0	32.0	11.0	10.0	12.0
1	2	10.0	30.0	30.0	30.0	12.9	8.6	8.3
1	3	8.0	12.9	12.9	12.9	5.6	61.0	23.0
1	4	6.0	27.5	27.5	27.5	5.4	58.0	59.0
1	5	12.0	29.1	29.1	29.1	12.0	14.1	78.0
1	6	7.0	8.0	8.0	8.0	11.9	44.0	37.0
1	7	8.0	26.3	26.3	26.3	5.4	44.0	42.0
1	8	6.0	15.0	15.0	15.0	6.7	10.1	43.0
1	9	9.0	28.2	28.2	28.2	3.8	55.0	64.0
1	10	9.0	21.4	21.4	21.4	13.3	72.0	62.0
1	11	7.0	22.4	22.4	22.4	51.0	79.0	58.0
1	12	9.0	22.5	22.5	22.5	35.0	10.7	63.0
1	13	7.0	18.1	18.1	18.1	43.0	9.8	71.0
1	14	9.0	25.5	25.5	25.5	3.0	75.0	83.0
1	15	12.0	22.8	22.8	22.8	60.0	93.0	80.0
1	16	10.0	38.3	38.3	38.3	60.0	90.0	41.0
1	17	9.0	13.3	13.3	13.3	59.0	40.0	39.0
1	18	7.0	15.7	15.7	15.7	95.0	96.0	74.0
1	19	14.0	55.0	60.0	28.0	66.0	75.0	74.0
1	20	7.0	15.2	15.2	15.2	85.0	59.0	70.0

Table 10

Results of solving the road section selection problem

Objective function	Section No.	Budget, monetary units						
		Year	1	2	3	4	5	6
124		Need	296.3	296.3	298.3	342.6	632.6	716.3
		Condition	<=	<=	<=	<=	<=	<=
		Available	500.0	300.0	300.0	350.0	700.0	800.0
Solution variable		Economy	Cost by year. monetary units					
1	1	11.0	30.0	30.0	32.0	11.0	10.0	12.0
1	2	10.0	30.0	30.0	30.0	12.9	8.6	8.3
1	3	8.0	12.9	12.9	12.9	5.6	61.0	23.0
0	4	6.0	27.5	27.5	27.5	5.4	58.0	59.0
1	5	12.0	29.1	29.1	29.1	12.0	14.1	78.0
1	6	7.0	8.0	8.0	8.0	11.9	44.0	37.0
1	7	8.0	26.3	26.3	26.3	5.4	44.0	42.0
1	8	6.0	15.0	15.0	15.0	6.7	10.1	43.0
1	9	9.0	28.2	28.2	28.2	3.8	55.0	64.0
1	10	9.0	21.4	21.4	21.4	13.3	72.0	62.0
0	11	7.0	22.4	22.4	22.4	51.0	79.0	58.0
0	12	9.0	22.5	22.5	22.5	35.0	10.7	63.0
1	13	7.0	18.1	18.1	18.1	43.0	9.8	71.0
1	14	9.0	25.5	25.5	25.5	3.0	75.0	83.0
1	15	12.0	22.8	22.8	22.8	60.0	93.0	80.0
0	16	10.0	38.3	38.3	38.3	60.0	90.0	41.0
1	17	9.0	13.3	13.3	13.3	59.0	40.0	39.0
1	18	7.0	15.7	15.7	15.7	95.0	96.0	74.0
0	19	14.0	55.0	60.0	28.0	66.0	75.0	74.0
0	20	7.0	15.2	15.2	15.2	85.0	59.0	70.0

In Table 10, the areas that were not included in the long-term road maintenance program after modeling using the developed approach in the RoadRange software are highlighted in color. This means that they do not meet conditions (21) for the objective function (20). Thus, the optimized long-term road maintenance program is formed for this example and consists of 14 areas that satisfied the initial conditions, with the exception of 6 selected road sections.

6. Results of testing the devised methodological approach to prioritizing road sections: discussion

The devised methodological approach to prioritizing road sections for maintenance work is based on the application of the AHP method to establish the relative advantages of the criteria. This makes it possible to determine the optimal list of road sections – potential objects for financing a long-term program (contract). At the initial stage, a scale of intervals of operational state levels of road sections for long-term maintenance purposes was proposed (Table 2). At the same time, the objective function of minimizing the average annual level of deterioration of objects for analysis period (1) was established with restrictions on the maximum level of degradation (2) and the level of financing (3). The function of penalties for non-performance (4), (5) was adopted as the criterion for optimizing the cost of repair measures. An algorithm for optimizing repair and operational maintenance programs for road sections is proposed (Fig. 1, (6)), which takes into account the strategies for implementing long-term programs (contracts). To form a vector of relative advantages for the criteria for including sections in the maintenance program, the method of the analytical hierarchical process (AHP) was applied (Fig. 2, (7) to (19), Tables 3, 4). It is proposed to assess the level of the operational condition factor of the object using aggregated estimates of the operational condition index (Table 6).

Unlike [5–13, 16–19], in which the basis is a simple ordering of objects by their priority, the devised methodological approach is focused on long term and includes further optimization of the road maintenance program. Unlike [3, 4, 15, 20], in which studies are focused on prioritizing fragments of the road maintenance program, our approach allows for the evaluation of any components of the program both separately and the program as a whole. Study [12] does not take into account long terms, and the emphasis is mainly on replacing defective objects in the program, ignoring the possibility of their preservation under a good or satisfactory condition in the long term.

The devised methodological approach, unlike [12], takes into account the fact that making such decisions to manage the condition of objects can also give negative results since this allows objects in good condition to move to worse categories, which are usually associated with higher costs. Therefore, at the last stage, the built approach calculates the cost of the repair measure, which is optimized by the function of minimizing budget costs (20) under constraints (21).

In order to effectively use the devised methodological approach in practice, the corresponding RoadRange software was developed on its basis (Fig. 3, 4, Table 7). The development was tested on the basis of data on 20 sections along a national highway (Tables 8, 9, Fig. 5, 6) in the Kyiv oblast (Ukraine). As a result of modeling using the devised approach in the RoadRange software, an optimized long-term maintenance program for this region was obtained, which included 14 sections that satisfied conditions (21) for objective function (20) according to the adopted criteria (Table 8). The results were checked for consistency with the value of the index $AI = 0.001$. This meets requirements (19) regarding the ratio with the repair index RI, which was $CR = 0.002$ and does not exceed the limit value of 0.10, as evidenced by the conclusion of the calculations in the program (Fig. 5).

The limitations for using the devised methodological approach for prioritizing road sections are that it is currently impossible to carry out large-scale testing on its basis, due to the lack of filling in databases on the qualitative condition of roads. The disadvantages of this approach are that it does not take into account the case when all objects are in a state of emergency, require major repairs, and cannot be included in the long-term program.

In the future, it is planned to test the devised methodological approach at other critical infrastructure objects (in particular, bridges, overpasses, hydraulic structures, etc.). This will make it possible to expand the list of criteria for including objects in long-term maintenance programs under limited budget funding.

7. Conclusions

1. The prioritization problem has been stated, which involves minimizing the average annual level of deterioration of road facilities for the analysis period with restrictions on the maximum level of degradation and the established level of funding. An algorithm for solving the prioritization problem has been developed, which takes into account the implementation of long-term programs (contracts) for the maintenance of the road network. It was taken into account that the maximum permissible level of deterioration of road sections is set based on economic justification. However, it cannot be worse than the maximum permissible level, which is set based on the requirements of traffic safety and preservation of the operational condition of the facility.

2. A method of the analytical hierarchical process was integrated into the mathematical model for solving the problem of prioritization of assessment facilities. At the same time, it was proposed to use an expert method with subsequent pairwise comparison of their relative advantages to select the prioritization criteria. The objective function of the problem is taken to be the minimization of budget funds allocated for the long-term program of operational maintenance of the road network. At the same time, the simplex method of linear programming with binary decision variables was used to solve this objective function. The corresponding software RoadRange has been developed based on the Microsoft Excel spreadsheet (USA), which makes it possible to automate the process of using a methodical approach to prioritizing road sections.

3. We have validated the devised methodological approach to assessing the priority index of a road section using data on 20 sections of a national highway in the Kyiv oblast (Ukraine). Based on the test results, a long-term operational maintenance program for this road was compiled. In accordance with the assigned level of funding and the three defined criteria, 14 sections out of 20 were included in the long-term program. The adequacy of the results from mathematical modeling was assessed by the ratio of the consistency index to the repair index, which was CR = 0.002, which does not exceed the accepted limit value of 0.10. Thus, this approach is a practical tool for decision-makers in managing long-term maintenance of road facilities.

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

The data will be provided upon reasonable request.

Use of artificial intelligence

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

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