This paper considers the processes of cost management and the duration of road maintenance projects. A conceptual model is proposed to describe the relationship between time, cost, and quality of projects, which is based on the theory of the «silver triangle». Based on the results of studying the influence of factors, a model has been built for determining the cost and duration of road maintenance projects. Multiple optimization approaches to the components of the «silver triangle» of projects were used. The model constructed at the stage of initiating projects for the maintenance of roads, in contrast to the previous ones, is based on the pre-project level of quality indicators.

Owing to the introduction of additional parameters and coefficients, the proposed model of cost management, quality, and duration of road projects was calibrated. The model graph was constructed and optimization was carried out on the example of a long-term road operation project. The algorithm of application of cost and duration management model of highway projects under conditions of uncertainty has been developed, which was checked for adequacy at an estimated error of about 3 %. This makes it possible to assert the effectiveness of the devised model for solving tasks related to project management for maintenance.

The model was used to perform calculations based on a real example of the project, which showed that the optimization of the parameters of long-term contracts for the maintenance of highways produces a multiplier effect. This is expressed by reducing the administrative costs of the customer, reducing the responsibility of road services, creating prerequisites for stable financing of road works, the satisfaction of road users, and building strong partnerships between the customer and contractor

Keywords: cost and duration management, maintenance project, long-term maintenance, management model, silver triangle

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BUILDING A MODEL FOR MANAGING THE COST AND DURATION OF MOTOR ROAD PROJECTS

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1. Introduction

The key to the successful implementation of road maintenance projects is preventive consideration of possible factors of influence on this process. Important parameters of projects in the road industry are the time of their implementation, the cost of future contracts, and quality indicators that will be achieved as a result. Thus, there is a so-called «silver triangle», which reflects the ratio of «time-cost-quality» of projects. The interdependence of the components of this relationship is complex, and rather uncertain since each of them is influenced by various factors at different stages of the project implementation. Unfortunately, the consideration of cost management processes and the duration of road maintenance projects, as well as the impact of a set of factors on them, are given insufficient attention in the scientific environment.

The use of modeling processes to determine the cost and duration of the road organization in accordance with the level of complexity and quality of maintenance work makes it possible to adequately substantiate the production capacity of the contractor's organization. This will contribute to creating a free competitive market environment and ensuring the quality of work and services for the future. However, the main problem in the process of determining the cost and duration of projects is the difficulty of determining the impact of factors on the project implementation process. Thus, the relevance of consideration of this issue is due to the need to build an effective model for managing the cost and duration of road projects under conditions of uncertainty.

2. Literature review and problem statement

The classic way of determining the cost of a road maintenance project is absolutely not suitable for determining the cost of long-term contracts that require taking into consideration quality indicators (service levels). In the scientific community, the latter conducted research in the direction of determining the cost and duration of road maintenance projects based on road maintenance levels. In particular, [1] proposed a model that was tested to determine the cost of guarantees for the project of operation of the road network. However, the process of maintaining highways has several cycles of repair and wear of the coating during the warranty period, which was not taken into consideration in this model [1].

In study [2], to estimate the cost of a short-term guarantee on the project of road operation, a structural method based on reliability was applied. To determine the quantitative value of the cost of guarantees, a methodology for system analysis was devised. However, as the approbation of the results of the study has shown [2], the proposed method is ineffective when planning for the long term.

Several authors [3] emphasize that in order to stimulate contractors in the framework of long-term road operation projects, it is advisable to use the «cost+time» and «incentive/containment» scheme.

In particular, in [3], the researchers draw attention to the fact that the scheme of «incentive/containment» contributes to the development of the project and encourages contractors to complete the tasks assigned to it, indicated by the contract, earlier.

Study [4] draws attention to the problem of overspending of road agencies for the maintenance of highways, especially taking into consideration the need for a higher level of traffic comfort and the problem of underfunding of this sector. However, the cited study does not specify how the term of the contract affects overruns and how to optimize the cost in order to avoid overspending.

Studying costs based on the approach of public-private partnership in road maintenance projects [5] can make it possible to more accurately predict the probability and volume of overspending and thus determine the optimal cost of the project. However, one of the limitations of the cited research [5] is the assumption (usually due to lack of data) that cost overruns, along with other cost characteristics, behave equally under different methodical approaches.

According to the results reported in [6], it is determined that the process of implementing road maintenance projects depends on such three main components as time, cost, and quality. Thus, there is a so-called «silver triangle», whose components are directly related. However, the cited study does not give an unambiguous assessment of how to optimize these characteristics of the project.

Study [7] determined that focusing or solving one goal of a triangle affects the other two tricks. However, the cited study was not used for road maintenance projects.

Somebody's analysis of scientific research [1–6] reveals insufficient validity of mechanisms for managing the cost and time of road maintenance projects.

3. The aim and objectives of the study

The aim of this study is to build a model for managing the cost and duration of road projects, which makes it possible to optimize the cost-time ratio in long-term road maintenance contracts.

To achieve the set aim, the following tasks have been solved:

– to build a conceptual model for managing the cost and duration of maintenance projects, which will include groups of factors influencing each component;

– to construct a mathematical model for determining the cost and duration of road maintenance projects;

– to test the devised model on the example of the long-term maintenance project of the highway.

4. The study materials and methods

The object of our research is the processes of cost management and the duration of projects for the maintenance of highways.

The model of cost management and duration of road projects is based on the main provisions of graph theory, structural method, and theoretical aspects of determining the interaction of the components of the «silver triangle». The main hypothesis of the study assumes that with long-term operational maintenance of highways, it becomes necessary to justify the main parameters of the project, such as time and cost with the quality of work. The main assumption of our study is to take into consideration the uniqueness of each individual project by determining the likely impact of different groups of factors on cost, duration, and quality. This makes it possible to perform modeling on the principle of pairwise comparison. The devised model was implemented in the Excel (USA) environment in the form of a separate optimization module. The proposed model makes it possible to compile individual tables of interdependence of the components of the «silver triangle» of the project for making managerial decisions. Testing of the model is carried out on the example of a long-term maintenance project of the highway. The completed calculations on the real example according to the model were tested for adequacy using the Fisher criterion with a level of significance of 0.05. At the same time, the estimated error according to the model was about 3 %.

5. Results of building a cost and duration management model for highway projects

5. 1. Constructing a conceptual model for managing the cost and duration of road maintenance projects

According to somebody's research, it is determined that the process of implementing road maintenance projects depends on such three main components as time, cost, and quality, which, in turn, constitute the so-called «silver triangle» (Fig. 1) [6]. Given the complexity of determining the relationship of these components, it becomes necessary to identify and take into consideration the main groups of factors that influence the implementation of projects in the contract phase.

The main aspects of managing the components of the «silver triangle» according to [6, 8] are:

1. Time management (T) is a multi-stage process that is necessary for the timely fulfillment of contractual obligations.

2. Cost management (C) – a process that ensures monitoring and control of the contract budget and consists of many successive inalienable stages (determining the necessary resources, determining the cost, budget planning, analyzing resource deviations, etc.).

3. Quality management (Q) – the process of checking compliance with the quality levels specified in the contract.

Thus, the conceptual model of cost management and duration of the project of long-term maintenance of the highway, taking into consideration the quality of the triangle TCQ will include a number of factors that affect its components (Fig. 2).

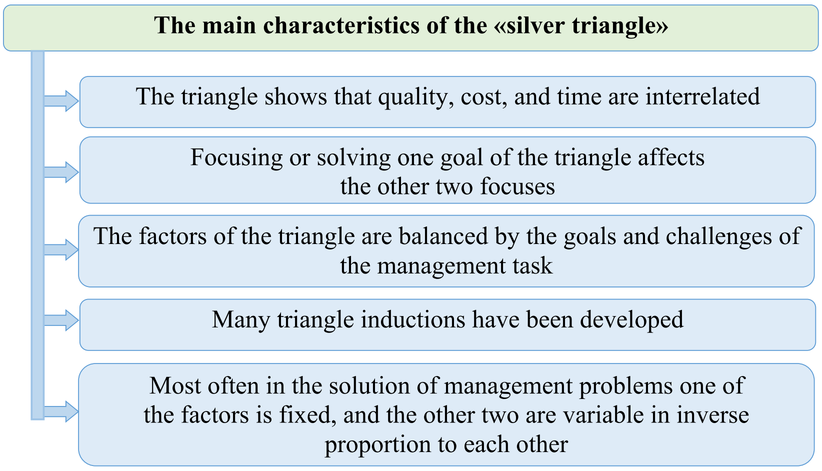

Fig. 1. The basic characteristics of the «silver triangle»

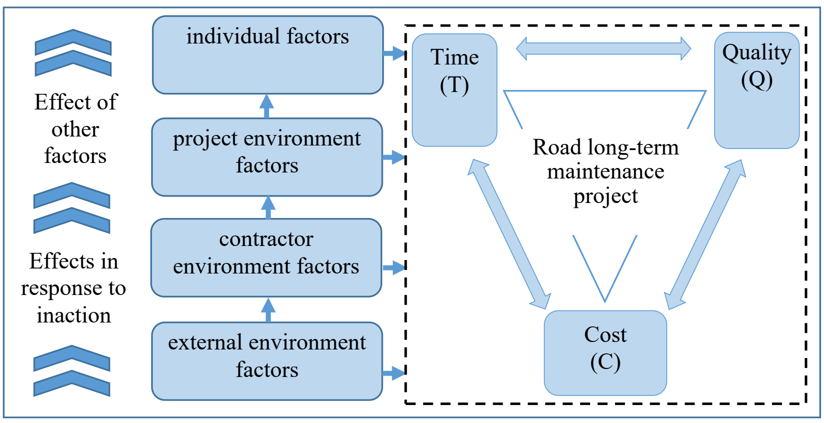

Fig. 2. Conceptual model of cost management and duration of the long-term maintenance project of the highway

The relationship of the components of the triangle *TCQ* is very complex and ambiguous, this is due to the presence of various kinds of factors that under different circumstances can affect one or more components at the same time. Certain groups of factors have a variable character, which depends on the uniqueness and environment of the project, the activities of the organization-performer, and the external environment. Thus, there is a need to take them into consideration in the mathematical model of determining the cost and duration of road maintenance projects.

5. 2. Constructing a mathematical model for determining the cost and duration of road maintenance projects

When constructing a mathematical model for determining the cost and duration of road maintenance projects for each project resource, it is necessary to determine the most important indicators (factors).

To solve the problem of optimizing the components of the *TCQ* triangle, it is advisable to describe the long-term maintenance of roads with a network model activity-on-node:

$$G=(A,P),\ A\in\{0,\ldots,n+1\},$$

$$P\in\{P_l\}, \qquad (1)$$

where n is the number of nodes (actions, assets); P is the sum of all paths in the activity-on-node network, ranging from activity 0 to n+1; P_l is the sum of actions (works, assets) that are along the way l.

The components of the triangle can be represented as a model using the structural method (Table 1).

According to Table 1, the influence of the interaction of certain factors on the labor force can be described by the formula:

$$L_{PRD(i)}=$$

$$=L_{PRDi}^{\max}-K_{LQ(i)}\cdot\left(Q_{L(i)}-Q_{Li}^{\min}\right), \qquad (2)$$

where L_{PRD} is productivity; $Q_{L(i)}$ is the actual level of quality of work (i) $Q_{L(i)}\in\left(Q_{Li}^{\min},Q_{Li}^{\max}\right)$; $Q_{Li}^{\min}$, $Q_{Li}^{\max}$ – minimum and maximum level of quality of work (i) involved in activities (i); $K_{LQ(i)}$ is the coefficient of the ratio of factors affecting the labor force, which is determined from the formula:

$$K_{LQ(i)}=\left(L_{PRDi}^{\max}-L_{PRDi}^{\min}\right)/\left(Q_{Li}^{\max}-Q_{Li}^{\min}\right), \qquad (3)$$

where $L_{PRDi}^{\min}$, $L_{PRDi}^{\max}$ is the minimum and maximum level of productivity involved in the activities (i).

Table 1

Model structure (adapted from [9])

Project (Contract)						Total Σ
Activities						
Activity (1)	Activity (i)				Activity (n)	
Resources						
.....	Human resources (L_i)	Building materials and products (M_i)	Construction machinery and equipment (E_i)	Administration of works (A_i)	.....	Σ
Main indicators (factors) of resources						
.....	Productivity; cost; labor intensity of works; quality of work	Cost; quality	Productivity of equipment; cost; number; quality	Cost; quality	.....	Σ
Time-Cost-Quality						
.....	Time (i)				.....	Σ
.....	Cost L_i	Cost M_i	Cost E_i	Cost A_i	.....	Σ
.....	Quality L_i	Quality M_i	Quality E_i	Quality A_i	.....	Σ

The relationship between the quality of materials and their cost can be described by the formula:

$$C_{M(i)} = C_{Mi}^{\min} - K_{MQi} \cdot \left(Q_{M(i)} - Q_{Mi}^{\min}\right), \quad (4)$$

where $Q_{M(i)}$ is the actual level of quality of materials (i); $Q_{Mi}^{\min}$, $Q_{Mi}^{\max}$ are the minimum and maximum level of quality of materials (i); $K_{MQ(i)}$ – the ratio of factors affecting the quality of materials, which is determined from the formula:

$$K_{MQ(i)} = \left(C_{Mi}^{\max} - C_{Mi}^{\min}\right) / \left(Q_{Mi}^{\max} - Q_{Mi}^{\min}\right), \quad (5)$$

where $C_{Mi}^{\min}$, $C_{Mi}^{\max}$ are the minimum and maximum cost of materials in activities (i); $C_{M(i)}$ – the actual cost of materials involved in the activities (i), $C_{M(i)} \in \left(C_{Mi}^{\min}, C_{Mi}^{\max}\right)$.

Since construction equipment is a factor that exerts a significant influence on the *TSQ* triangle, it is necessary to introduce a modification coefficient taking into consideration the impact of this equipment on the duration of the project:

$$P_{RD(i)} = L_{PRD(i)} \cdot D_{EK(i)}, \quad (6)$$

where $P_{RD(i)}$ is the actual performance of the activity (i); $D_{EK(i)}$ is a modification factor in productivity (i) that takes into consideration the parameters of machinery and equipment.

The modification coefficient can be derived from the relationship between the quality of construction equipment and labor productivity:

$$D_{EK(i)} = D_{EKi}^{\min} + K_{DQ(i)} \cdot \left(Q_{E(i)} - Q_{Ei}^{\min}\right), \quad (7)$$

where $D_{EK(i)}$ is a modification factor in performance (i); $Q_{E(i)}$ – the actual level of quality of construction machinery and equipment (i) in the activities (i), $Q_{E(i)} \in \left(Q_{Ei}^{\min}, Q_{Ei}^{\max}\right)$; $K_{DQ(i)}$ – the ratio of factors affecting the performance of construction equipment:

$$K_{DQ(i)} = \left(D_{EKi}^{\max} - D_{EKi}^{\min}\right) / \left(Q_{Ei}^{\max} - Q_{Ei}^{\min}\right), \quad (8)$$

where $Q_{Ei}^{\min}$, $Q_{Ei}^{\max}$ – the minimum and maximum quality of construction machinery and equipment (i) in activities (i).

To determine the relationship between the quality of equipment and its cost, it is worth using the same linear dependence as for materials and products:

$$C_{E(i)} = C_{Ei}^{\min} - K_{EQ(i)} \cdot \left(Q_{E(i)} - Q_{Ei}^{\min}\right), \quad (9)$$

$K_{EQ(i)}$ is the coefficient of the ratio of factors affecting the quality of construction equipment:

$$K_{EQ(i)} = \left(C_{Ei}^{\max} - C_{Ei}^{\min}\right) / \left(Q_{Ei}^{\max} - Q_{Ei}^{\min}\right), \quad (10)$$

where $C_{Ei}^{\min}$, $C_{Ei}^{\max}$ are the minimum and maximum costs of construction machinery and equipment (i) in activities (i); $C_{E(i)}$ – the actual cost of construction machinery and equipment involved in the activities (i), $C_{E(i)} \in \left(C_{Ei}^{\min}, C_{Ei}^{\max}\right)$.

To objectively determine the cost of overtime work, it is necessary to use the coefficient of change in the cost of construction equipment and equipment for overtime work:

$$C_{E(i)} = \left(C_{Ei}^{\min} - K_{EQ(i)} \cdot \left(Q_{E(i)} - Q_{E(i)}^{\min}\right)\right) \cdot \alpha_i, \quad (11)$$

where α_i is the coefficient of change in the cost of construction equipment and equipment for overtime work (associated with an increase in the number of used construction equipment and machinery):

$$\alpha_i = \left[1 + \left(K_{DP(i)} - 1\right) \cdot K_{EO(i)}\right], \quad (12)$$

$K_{EO(i)}$ is the coefficient of decrease in productivity of work (we take equal to 20 %).

The relationship between the quality and cost of work management can be described by the formula:

$$C_{A(i)} = C_{Ai}^{\min} - K_{AQ(i)} \cdot \left(Q_{A(i)} - Q_{Ai}^{\min}\right), \quad (13)$$

where $Q_{A(i)}$ is the actual level of quality of work administration (i) in activities (i), $Q_{A(i)} \in \left(Q_{Ai}^{\min}, Q_{Ai}^{\max}\right)$; $Q_{Ai}^{\min}$, $Q_{Ai}^{\max}$ are the minimum and maximum level of quality of work (i) administration in activities (i); $K_{AQ(i)}$ is the coefficient of the ratio of factors influencing management:

$$K_{AQ(i)} = \left(C_{Ai}^{\max} - C_{Ai}^{\min}\right) / \left(Q_{Ai}^{\max} - Q_{Ai}^{\min}\right), \quad (14)$$

$C_{Ai}^{\min}$, $C_{Ai}^{\max}$ are the minimum and maximum cost of administration of work (i) in activities (i); $C_{A(i)}$ – the actual cost of administering work (i) in activities (i), $C_{A(i)} \in \left(C_{Ai}^{\min}, C_{Ai}^{\max}\right)$.

It is determined that during overtime work the cost of operation of construction equipment and machinery for relevant works increases. The cost of administering works, in this case, will also increase. Therefore, to objectively determine the cost of administering work overtime, it is necessary to introduce an appropriate coefficient of increase in the cost β_i:

$$C_{A(i)} = \left(C_{Ai}^{\min} - K_{AQ(i)} \cdot \left(Q_{A(i)} - Q_{Ai}^{\min}\right)\right) \cdot \beta_i, \quad (15)$$

where β_i is the coefficient of change in the cost of administration for overtime work (associated with an increase in the number of used construction equipment and machinery):

$$\beta_i = \left(K_{ACR(i)} + 1 - \frac{K_{ACR(i)}}{K_{DP(i)}}\right), \quad (16)$$

where $K_{ACR(i)}$ is the hourly coefficient of administration of overtime work (we accept equal to 2.0).

The time required for the implementation of certain activities is determined based on the volume of work, actual productivity, and factors that determine overtime:

$$D_{UR(i)} = Q_{NT(i)} / P_{RD(i)} \cdot K_{DP(i)}, \quad (17)$$

where $D_{UR(i)}$ is the time of activity (i); $Q_{NT(i)}$ is the scope of activity (i); $P_{RD(i)}$ is the actual performance in activities (i); $K_{DP(i)}$ is the overtime rate, $K_{DP(i)} \in [1,0;\ 1,5]$ if overtime work is performed from 0 to 4 hours per day (since the working day is 8 hours per day), $K_{DP(i)}=1$ if there is no overtime work.

The cost of labor is determined according to the cost of the activity (i) and overtime (if any):

$$\begin{aligned} C_{L(i)} &= C_{LDi}^{S} \cdot D_{UR(i)} + \left(K_{DP(i)} - 1\right)\left(K_{LCR(i)} \cdot C_{LDi}^{S}\right) \cdot D_{UR(i)} = \\ &= C_{LDi}^{S} \cdot D_{UR(i)} \cdot \left[1 + \left(K_{DP(i)} - 1\right) \cdot K_{CR(i)}\right] = \left(C_{LDi}^{S} \cdot D_{UR(i)}\right) \times \\ &\times \left(\begin{bmatrix} L_{PRDi}^{\max} - \\ -K_{LQ(i)} \cdot \left(Q_{L(i)} - Q_{Li}^{\min}\right) \end{bmatrix} \times \\ \times \begin{bmatrix} K_{DEi}^{\min} + \\ +K_{DQ(i)} \cdot \left(Q_{E(i)} - Q_{Ei}^{\min}\right) \end{bmatrix} \right)^{-1} \cdot \begin{pmatrix} K_{LCR(i)} + 1 - \\ -K_{LCR(i)} / K_{DP(i)} \end{pmatrix}, \end{aligned} \quad (18)$$

where $C_{L(i)}$ is the cost of labor in activities (i); C^{S}_{LDi} – the cost of work per unit of time (example, day) of activity (i); $K_{LCR(i)}$ is the coefficient of consideration of the cost of work (i) activities in overtime (we take equal to 2.0).

Having determined the main relationships of indicators (factors) of resources, it is possible to definitively describe the model proposed in [9]. In this case, the total time (T_W) is determined from the formula:

$$T_W = \max_{i=1,n}\left(EST_{(i)} + D_{UR(i)}\right), \tag{19}$$

where $EST_{(i)}$ is the early commencement of activity (i), which corresponds to the end of the previous work.

The total cost (C_W):

$$C_W = \sum\nolimits_{i=1}^{n}\left(C_{L(i)} + C_{M(i)} + C_{E(i)} + C_{A(i)}\right), \tag{20}$$

where n is the volume of operations. The overall quality (Q_W):

$$Q_W = \sum\nolimits_{i=1}^{n}\left(WT_i \cdot Q_{P(i)}\right), \tag{21}$$

where WT_i is an indicator of the quality of each activity (i), $\sum\nolimits_{i=1}^{n} = WT_i = 1.0$; $Q_{P(i)}$ is the quality of activity (i), calculated taking into consideration the quality of work, materials, products, construction machinery and equipment, administration:

$$\begin{aligned} Q_{P(i)} &= LWT_i \cdot Q_{L(i)} + MWT_i \cdot Q_{M(i)} + \\ &+ EWT_i \cdot Q_{E(i)} + AWT_i \cdot Q_{A(i)}, \end{aligned} \tag{22}$$

LWT_i, MWT_i, EWT_i, AWT_i – the indicators of quality of works, materials, and products, construction machinery and equipment, administration of activities (i); $Q_{L(i)}$, $Q_{M(i)}$, $Q_{E(i)}$, $Q_{A(i)}$ – the quality of works, materials, and products, construction machinery and equipment, administration of activities (i).

The project can be considered successfully implemented only when it is executed in the shortest possible time in accordance with the requirements for the quality of work and without cost overruns, that is, within the framework of the budget specified in the contract [10, 11].

Thus, the proposed model of cost management, the quality and duration of road projects, formulated on the basis of graph theory, can be calibrated by introducing additional parameters and coefficients [12, 13]:

$$(X', Y', Z') = \begin{cases} X' \in f\left(T_{W(i)}; T_{AW(i)}; k_{cc(i)}; k_{pw(i)}; k_{of(i)}\right), \\ Y' \in f\begin{pmatrix} C_{W(i)}; C_P; C_{FS(i)}; C_T; \\ k_r; k_{ir(i)}; k_{cw(i)}; k_{fp(i)} \end{pmatrix}, \\ Z' \in f\left(Q_{L(i)}; Q_{M(i)}; Q_{E(i)}; Q_{A(i)}\right), \end{cases} \tag{23}$$

where X' is an optimized time value (T); Y' is the optimized cost value (C); Z' is the optimized quality value (Q); $T_{W(i)}$ is the duration of the main (planned) work; $T_{AW(i)}$ is the duration of unplanned and auxiliary work; $k_{cc(i)}$ – a coefficient that takes into consideration delays due to the peculiarity of climatic conditions; $k_{pw(i)}$ – a coefficient that takes into consideration the productivity of working personnel; $k_{cc(i)}$ – a coefficient that takes into consideration other factors that affect the time of work; $C_{W(i)}$ is the cost of work ($C_{L(i)}$, $C_{M(i)}$, $C_{E(i)}$, $C_{A\,(i)}$); C_P is the profit; C_T – the general production costs; $C_{FS(i)}$ is the amount (cost) of fines and incentive payments; k_r – a coefficient that takes into consideration the risks of all parties to the contract; $k_{ir(i)}$ – a coefficient that takes into consideration the level of inflation; $k_{cw(i)}$ – a coefficient that takes into consideration the level of complexity of work; $k_{fp(i)}$ – a coefficient that takes into consideration the priority of financing the contract; $Q_{L(i)}$ – the level of quality of work; $Q_{M(i)}$ – the level of quality of materials and products; $Q_{E(i)}$ – the level of quality of equipment and machinery; $Q_{A(i)}$ – is the level of administration quality.

The model graph is described by formula (24) with the structure of the nodes from Table 2 [14]:

$$G(K) = \begin{Bmatrix} \left\{T_{W(1)} \ldots T_{W(i)} \ldots T_{W(n)}\right\} \\ \begin{bmatrix} C_{L(1)}; C_{M(1)}; C_{E(1)} \ldots C_{L(i)}; C_{M(i)}; \\ C_{E(i)}; C_P; C_A \ldots C_{L(n)}; C_{M(n)}; C_{E(n)}; \end{bmatrix} \\ \begin{bmatrix} Q_{L(1)}; Q_{M(1)}; Q_{E(1)} \ldots Q_{L(i)}; \\ Q_{M(i)}; Q_{E(i)} \ldots Q_{L(n)}; Q_{M(n)}; Q_{E(n)} \end{bmatrix} \end{Bmatrix}, \tag{24}$$

where $K = \{0, \ldots, n+1\}$ is the number of nodes (activities, assets).

Table 2

Characteristics of the nodes of the graph of the built model [14]

<table>
<tr><td colspan="9">Project (Contract)</td><td rowspan="6">Σ</td></tr>
<tr><td colspan="6">Work (W)</td><td rowspan="5">Σ</td><td rowspan="5">C_P</td><td rowspan="5">C_A</td></tr>
<tr><td>$W_{(1)}$</td><td colspan="3">$W_{(i)}$</td><td>$W_{(n)}$</td><td rowspan="4">C_T</td></tr>
<tr><td colspan="5">Work resources (R_W)</td></tr>
<tr><td>$R_{WL(1)}$
$R_{WM(1)}$
$R_{WE(1)}$</td><td>$R_{WL(i)}$</td><td>$R_{WM(i)}$</td><td>$R_{WE(i)}$</td><td>$R_{WL(n)}$
$R_{WM(n)}$
$R_{WE(n)}$</td></tr>
<tr><td>$F_{RW(1)}$</td><td colspan="3">Main indicators (factors) of resources ($F_{RW(i)}$)</td><td>$F_{RW\,(n)}$</td></tr>
<tr><td colspan="10">Time-Cost-Quality</td></tr>
<tr><td>$T_{W(1)}$</td><td colspan="3">Time $T_{W(i)}$</td><td>$T_{W(n)}$</td><td>n/e</td><td>ΣT_W</td><td colspan="2">n/e</td><td>ΣT</td></tr>
<tr><td>$C_{L(1)}$
$C_{M(1)}$
$C_{E(1)}$</td><td>Cost $C_{L(i)}$</td><td>Cost $C_{M(i)}$</td><td>Cost $C_{E(i)}$</td><td>$C_{L(n)}$
$C_{M(n)}$
$C_{E(n)}$</td><td>C_T</td><td>ΣC_W</td><td colspan="2">C_P; C_A</td><td>ΣC</td></tr>
<tr><td>$Q_{L(1)}$
$Q_{M(1)}$
$Q_{E(1)}$</td><td>Quality $Q_{L(i)}$</td><td>Quality $Q_{M(i)}$</td><td>Quality $Q_{E(i)}$</td><td>$Q_{L(n)}$
$Q_{M(n)}$
$Q_{E(n)}$</td><td>n/e</td><td>ΣQ_W</td><td colspan="2">n/e</td><td>ΣQ</td></tr>
</table>

Note: n/e – the indicator is not taken into consideration; C_T – general production costs; C_A – administrative expenses of road services; C_P – profit; $R_{WL(i)}$, $R_{WM(i)}$, $R_{WE(i)}$ – human, material, machinery, and equipment resources, respectively

Based on research, an algorithm for applying the cost and duration management model of highway projects in conditions of uncertainty has been constructed (Fig. 3).

Optimization of model parameters is performed using a hybrid (multi-object) genetic algorithm, based on the approach reported in [15]. At the same time, the objective optimization functions were determined, taking into consideration the approach of multipurpose optimization of this problem by two methods [13]:

– by the method of constants:

$$Z=\begin{bmatrix}\omega_t\left[\dfrac{T-T_{\min}+\gamma}{T_{\max}-T_{\min}+\gamma}\right]+\\+\omega_C\left[\dfrac{C-C_{\min}+\gamma}{C_{\max}-C_{\min}+\gamma}\right]+\\+\omega_q\left[\dfrac{Q_{\max}-Q+\gamma}{Q_{\max}-Q_{\min}+\gamma}\right]\end{bmatrix}\rightarrow\min, \quad (25)$$

where ω_t, ω_c, and ω_q are coefficients (adaptive values, respectively, of time, cost, and quality); γ is a constant (determined empirically according to the statistical data of such projects, that is, by the method of analogs);

– by the method of a sum of squares of deviation:

$$U=\frac{1}{2}\begin{bmatrix}\omega_t\left[\dfrac{T-T_{\min}}{T_{\max}-T_{\min}}\right]^2+\\+\omega_C\left[\dfrac{C-C_{\min}}{C_{\max}-C_{\min}}\right]^2+\\+\omega_q\left[\dfrac{Q_{\max}-Q}{Q_{\max}-Q_{\min}}\right]^2\end{bmatrix}\rightarrow\min; \quad (26)$$

where T, C, Q are, respectively, the total time, cost, and quality of the project, which are determined taking into consideration formulas (19)–(21), graph (24), and the algorithm for applying the cost and duration management model of road projects (Fig. 3):

$$\begin{cases}T=T_W\cdot\left(1+\sum\limits_{i=1}^{n}\left(k_{cc(i)}+k_{pw(i)}+k_{of(i)}\right)\right)+T_{AW};\\C=C_W\cdot\left(1+\sum\limits_{i=1}^{n}\left(k_r+k_{ir(i)}+k_{cw(i)}+k_{fp(i)}\right)\right)+\\+\sum\limits_{i=1}^{n}C_{FS(i)}+C_p+C_T;\\Q=Q_W.\end{cases} \quad (27)$$

The main conditions (boundaries) of the model are formulated for objective functions (25), (26):

$$\begin{cases}Z_1=T\rightarrow\min; T\neq 0;\\C\cdot X\leq C_{\max};\Sigma C\geq\left(C-C_p\right);C\rightarrow\min;C\neq 0;\\Q\cdot X\geq Q_N;Q\rightarrow\max;Q\neq 0,\end{cases} \quad (28)$$

where $C_{\max}$ is the maximum cost indicator; Q_N – the minimum quality requirements in the project (service levels);

$$X=\begin{bmatrix}K_{DP(1)}\ldots K_{DP(n)}Q_{L(1)}\ldots Q_{L(n)}Q_{M(1)}\ldots\\\ldots Q_{M(n)}Q_{E(1)}\ldots Q_{E(n)}Q_{A(1)}\ldots Q_{A(n)}\end{bmatrix}^T_{1\times 5n}$$

is the vector of all variables of the model.

Having determined all the initial parameters and specifying constraints and assumptions, a genetic algorithm is chosen as a method by which a multipurpose problem of optimizing time, cost, and quality can be solved.

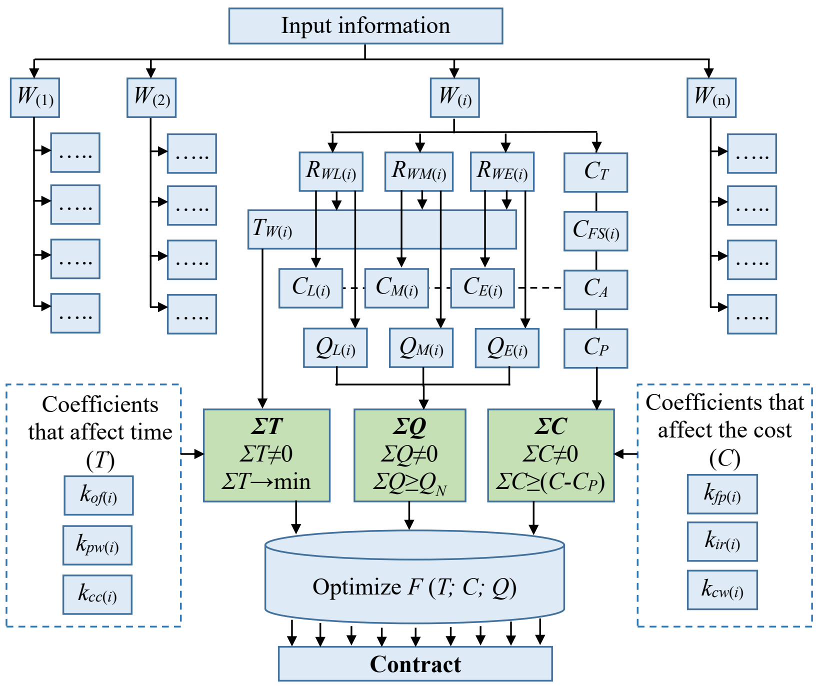

Fig. 3. Algorithm of application of cost management model and duration of highway projects [14].
Note: Q_N – minimum quality requirements in the project (service levels)

Based on the results of this study, the author's software module DCtcq (Ukraine) was born to run the model on the Eclipse Java platform (USA) with further integration into MS Excel (USA). The process of running the model occurs until the required response is obtained, that is, compliance with the objective function, and includes the following main stages:

1. Creating a random solution for a parameter (the first generation of the genetic algorithm $G=1$):

$$d^0_{i,j}=d^{(L)}_j+r^G_{i,j}\left(d^{(U)}_j-d^{(L)}_j\right),\ \forall i=1\ldots s,\ \forall j=1\ldots n, \quad (29)$$

where $r^G_{i,j}$ is the evenly distributed random values in the range from 0.0 to 1.0; $d^{(U)}_j$ and $d^{(L)}_j$ are the upper and lower limits of the variable d_j (symbol of the parameters that change in the TCQ model).

2. The stage of determining the mutated (weighted) vector (w_j), which is determined by the product of the mutation coefficient F and the differential vector, determined by the difference from the two randomly selected vectors from the set:

$$w^G_j=F\left(d^G_{a,j}-d^G_{b,j}\right),\ \forall j=1\ldots n, a\neq b, \quad (30)$$

where F is the mutation coefficient, which is usually accepted in the range from 0.4 to 1.0; a, b is the variable number, aε[1; p], bε[1, p]; p is the population size.

3. Build population $p(G+1)$:

$$d_{i,j}^{G+1}=\begin{cases} d_{\varepsilon,j}^{(G)}+w_j^G \text{ if } r_{i,j}\le \varepsilon_r ;\forall_j=1\ldots n, \\ d_{\varepsilon,j}^{(G)} \quad \text{other wise,} \end{cases} \tag{31}$$

where ε_r is the cross-crossing constant that contributes to the creation of a new generation, $\varepsilon_r \varepsilon[0;1]$, $\varepsilon\varepsilon[1;p]$, $r\varepsilon[0;1]$.

4. Create a new generation $p(G+1)$ population that meets conditions (28) of objective function (25) or (26):

$$x_{i,j}^{G+1}=\begin{cases} d_{\varepsilon,j}^{(G+1)} \text{ if } f\left(d_i^{(G+1)}\right)\in Z \text{ or } f\left(d_i^{(G+1)}\right)\in U, \\ d_{\varepsilon,j}^{(G)} \text{ other wise.} \end{cases} \tag{32}$$

The use of the mathematical model and the algorithm (Fig. 3), which were the basis for the development of the relevant DCtcq software (Ukraine), will in practice make it possible to simplify the process of determining the duration and cost of road maintenance projects at a given limitation, at a certain level of quality.

5. 3. Testing the built model on the example of the long-term maintenance project of a highway

The implementation of the project of maintenance of the highway is preceded by a visual examination of its elements. In particular, as a result of the survey of the experimental section of a highway, the destruction and deformation of the existing road surface are registered. These are potholes of crumbling, track, a grid of cracks, common transverse cracks, destruction of the edges of roadbeds, and subsidence of roadbeds (Fig. 4).

The next step is to evaluate the indicators and optimize by using the model built. The data for optimizing the operational maintenance project are given in Table 3. The cost indicators of the initial data ($C_{L(i)}$, $C_{M(i)}$, $C_{E(i)}$, $C_{A(i)}$,) were calculated on the basis of the estimated cost of the work performed (A–F) per unit of the specified amount of damage elimination work ($Q_{NT(i)}$). Quality indicators (Q) are set in the form of dimensionless value (coefficient) according to the standards of road maintenance.

a *b*

Fig. 4. Results of visual inspection of the road section (example): *a* — a grid of cracks with pit repairs; *b* — transverse cracks

Table 3

Data to optimize the cost and duration of the maintenance project (example)

N	ID	$Q_{NT(i)}$	L_{PRD}, min-max	Workforce (L)		Materials and products (M)		Construction machinery and equipment (E)			Administration (A)	
				$C_{L(i)}$, monetary units	$Q_{L(i)}$, min-max	$C_{M(i)}$, monetary units min-max	$Q_{M(i)}$, min-max	$C_{E(i)}$, monetary units min-max	$Q_{E(i)}$, min-max	L_{PRDE}, min-max	$C_{A(i)}$, monetary units min-max	$Q_{A(i)}$, min-max
A	1	260 m^3	110–160 m^3/day	770	0.8–1.0	3520–4900	0.7–1.0	660–720	0.8–1.0	0.8–1.2	90–150	0.7–1.0
B	2	120 m^2	11–13 m^2/day	330	0.8–1.0	880–1220		122–132	0.8–1.0	0.98–1.02		
	3	18 t	0.7–0.9 t/day	660	0.7–1.0	6100–7950		141–158	0.8–1.0	0.9–1.1		
	4	57 m^3	17–22 m^3/day	825	0.9–1.0	20100–25600		165–198	0.9–1.0	0.95–1.05		
	5	83 m^3	9–13 m^3/day	1870	0.8–1.0	17100–22000		1650–1980	0.8–1.0	0.98–1.02		
	6	66 m^3	22–27 m^3/day	473	0.8–1.0	7100–9400		132–165	0.8–1.0	0.9–1.1		
C	7	132 m^2	9–12 m^2/day	495	0.7–1.0	1320–1870		230–255	0.9–1.0	0.98–1.02		
	8	3.5 t	0.9–1.3 t/day	880	0.7–1.0	12300–15800		282–310	0.8–1.0	0.9–1.1		
	9	53 m^3	8–11 m^3/day	1100	0.7–1.0	18600–24200		220–264	0.9–1.0	0.95–1.05		
	10	68 m^3	5–7 m^3/day	825	0.8–1.0	14400–18200		1380–1638	0.8–1.0	0.98–1.02		
D	11	115 m^2	9–12 m^2/day	500	0.7–1.0	1210–1760		198–220	0.8–1.0	0.98–1.02		
	12	3.1 t	0.9–1.3 t/day	890	0.7–1.0	11500–13800		246–277	0.8–1.0	0.9–1.1		
	13	47 m^3	8–11 m^3/day	1150	0.7–1.0	16550–21350		198–230	0.9–1.0	0.95–1.05		
	14	60 m^3	4.5–7 m^3/day	830	0.8–1.0	12800–16100		1210–1450	0.8–1.0	0.95–1.05		
E	15	105 m^2	9–12 m^2/day	520	0.7–1.0	1210–1760		198–230	0.8–1.0	0.95–1.05		
	16	2.4 t	0.9–1.3 t/day	890	0.7–1.0	8500–11900		192–220	0.8–1.0	0.9–1.1		
	17	41 m^3	8–11 m^3/day	1130	0.7–1.0	14600–18800		193–210	0.9–1.0	0.95–1.05		
	18	55 m^3	4.5–7 m^3/day	830	0.8–1.0	11900–14600		1100–1320	0.8–1.0	0.9–1.1		
F	19	146 m^2	19.5–26 m^2/day	340	0.7–1.0	3550–4200		44–55	0.8–1.0	0.98–1.02		
	20	66 m^2	44–55 m^2/day	830	0.7–1.0	7700–9400		110–132	0.8–1.0	0.98–1.02		

Note: N – groups of works; ID – works (activities) $Q_{NT(i)}$ – volume of work; A – elimination of blockage; B – restoration of signs; C – work on the elimination of effusion of binders; D – elimination of cracks; E – elimination of pits; F – markup

To determine the quality of work, indicators of groups of works were used (Table 4).

Table 4

Quality indicators of the road maintenance project (example)

<table>
<tr><th>N</th><th>GWT_j</th><th>ID</th><th>WT_i</th><th>$LWT_{(i)}$</th><th>$MWT_{(i)}$</th><th>$EWT_{(i)}$</th><th>$AWT_{(i)}$</th></tr>
<tr><td>A</td><td>0.06</td><td>1</td><td>0.04</td><td rowspan="20">0.1</td><td rowspan="20">0.7</td><td rowspan="20">0.15</td><td rowspan="20">0.05</td></tr>
<tr><td rowspan="5">B</td><td rowspan="5">0.24</td><td>2</td><td>0.06</td></tr>
<tr><td>3</td><td>0.06</td></tr>
<tr><td>4</td><td>0.06</td></tr>
<tr><td>5</td><td>0.05</td></tr>
<tr><td>6</td><td>0.03</td></tr>
<tr><td rowspan="4">C</td><td rowspan="4">0.18</td><td>7</td><td>0.04</td></tr>
<tr><td>8</td><td>0.05</td></tr>
<tr><td>9</td><td>0.06</td></tr>
<tr><td>10</td><td>0.05</td></tr>
<tr><td rowspan="4">D</td><td rowspan="4">0.22</td><td>11</td><td>0.05</td></tr>
<tr><td>12</td><td>0.05</td></tr>
<tr><td>13</td><td>0.05</td></tr>
<tr><td>14</td><td>0.04</td></tr>
<tr><td rowspan="4">E</td><td rowspan="4">0.17</td><td>15</td><td>0.04</td></tr>
<tr><td>16</td><td>0.05</td></tr>
<tr><td>17</td><td>0.03</td></tr>
<tr><td>18</td><td>0.05</td></tr>
<tr><td rowspan="2">F</td><td rowspan="2">0.13</td><td>19</td><td>0.06</td></tr>
<tr><td>20</td><td>0.08</td></tr>
<tr><td>Σ</td><td>1.0</td><td>–</td><td>1.0</td><td>–</td><td>–</td><td>–</td><td>–</td></tr>
</table>

Note: GWT_j – a quality indicator for work groups; WT_i – the level of quality of work; $LWT_{(i)}$ – a quality indicator for the workforce; $MWT_{(i)}$ – a quality indicator for materials and products; $EWT_{(i)}$ – a quality indicator for construction machinery and equipment; $AWT_{(i)}$ – quality score for administration

With the help of the optimization module DCtcq (Ukraine), developed by the authors, which was built on the basis of the algorithm for applying the cost and duration management model of road projects and implemented by the MS Excel macro studio (USA), the selection of parameters of this project was carried out (Table 5). The criteria for the optimization process that are accepted are the probability of a crossover (ε_r=0.5) and a mutation coefficient (F=0.8).

Thus, if one sets the quality level to 0.98 and above, and the cost is 15 million monetary units, the project implementation time will be 172 days.

Table 5 makes it possible to determine the numerical dependence of the elements of the triangle TCQ for a given project, taking into consideration the specified factors. After analyzing the calculation data given in a given table, one can clearly determine over which most optimal time and at lower cost a contract can be implemented in compliance with the required level of quality. For example, if a project manager needs to implement a contract in about T=160–170 days, and the quality level should not be lower than Q=0.8, he can use this model to calculate the approximate cost of implementing the contract, which for a given example will be C=8.0–11.0 million monetary units. In the same way, one can determine the time if the cost is fixed, or, based on time and cost, find out with at what level of quality the road maintenance project will be implemented.

Table 5

Calculated tabular relationship between time, cost, and quality

Cost (C), million monetary units													Quality (Q)
3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	
229	211	185	178	173	167	–	–	–	–	–	–	–	0.74
–	218	189	181	175	168	167	–	–	–	–	–	–	0.76
–	–	195	182	177	173	167	161	–	–	–	–	–	0.78
–	–	198	185	180	176	167	164	161	–	–	–	–	0.80
–	–	–	186	182	176	172	166	162	158	–	–	–	0.82
–	–	–	198	185	182	176	167	164	159	–	–	–	0.84
–	–	–	–	195	183	179	173	167	161	158	155	–	0.86
–	–	–	–	198	184	179	175	167	164	160	157	155	0.88
–	–	–	–	200	189	184	177	168	165	162	157	160	0.90
–	–	–	–	213	189	184	179	174	166	163	159	162	0.92
–	–	–	–	–	190	186	180	175	168	164	161	164	0.94
–	–	–	–	–	192	191	180	175	169	165	162	168	0.96
–	–	–	–	–	–	–	–	176	170	165	162	172	0.98
–	–	–	–	–	–	–	–	–	–	–	–	–	1.00
Time (T), day													

The next step was to perform a test of the adequacy of the model according to Fisher's criterion. The data that were obtained on the quality level indicator were compared with the project data (Table 6).

Table 6

Source data to perform an adequacy check

No. of entry	Quality level	
	Estimated value, Q (x)	Project value Q_N (y)
1	0.74	0.70
2	0.76	0.70
3	0.78	0.75
4	0.80	0.80
5	0.82	0.80
6	0.84	0.80
7	0.86	0.85
8	0.88	0.90
9	0.90	0.90
10	0.92	0.95
11	0.94	0.95
12	0.96	1.00
13	0.98	1.00

The check was performed by the built-in functions of Excel (Table 7).

Table 7

The results of the test of the adequacy of the model according to the Fisher criterion

Indicator	Value
Correlation coefficient *r*	0.988356214
Estimated value of *t*-test *tp*	21.54346946
Tabular value of *t*-test *trh*	2.776445105
Tabular value of the standard normal distribution *zy*	1.959963985
The value of the Fisher transformation *z′*	2.570145473
Left interval score for *z*	1.95035044
Right interval score for *z*	3.189940505
Left interval score for *rxy*	0.960346639
Right interval score for *rxy*	0.996615089
Standard deviation for *rxy*	0.046078895
Estimated error	0.03626845

Thus, the model for determining the cost and duration of road maintenance projects was tested for adequacy using the Fisher criterion with a significance level of 0.05.

6. Discussion of results of testing the simulation model for assessing the effectiveness and risks of long-term contracts

Analysis of the experience in determining the cost and duration of projects showed the need to build an original model for managing the cost and duration of road projects, which is based on the main characteristics of the «silver triangle» (Fig. 1). According to the results of the theoretical study, a conceptual model for managing the cost and duration of projects for the maintenance of highways was built (Fig. 2). In this case, the factors of influence are grouped into 4 classes.

A mathematical model of cost management and duration of projects on maintenance of highways (24), (25) has been constructed, which, unlike the traditional approach, is based on the main provisions of graph theory and structural approach (Table 2). The main purpose of the model development is to determine the main parameters of the project of long-term maintenance of roads, such as time and cost at a given quality of work (Fig. 3). This will take into consideration the uniqueness of each individual project by determining the likely impact of different groups of factors on the cost, duration, and quality on the principle of pairwise comparison. The built model harmoniously combines the mathematical method and the heuristic approach to solve the problems of optimizing the parameters of the «silver triangle».

The cost and duration management model of road maintenance projects is implemented in the Excel environment in the form of a separate optimization module. When testing the model according to a real project, all works and services were divided into 6 groups (Table 3). As a result of modeling, an individual matrix of interdependence of the components of the «silver triangle» for this project was built (Table 5). The adequacy of modeling the parameters of the project, which was tested by Fisher's criterion with a level of significance of 0.05, showed a deviation of 3 % from tabular values. The standard deviation of the model parameters was 5 %. This confirms the reliability of the received actual data by calculations. Thus, the level of quality of modeling data makes it possible for project managers to perform effective management of road maintenance projects.

The main limitation of the use of the devised model is the problem of determining the parameter «quality» in the triangle *TCQ*. In the further development of this study, it is proposed to pay attention to the optimization of the time-cost ratio when variating the «quality» parameter.

7. Conclusions

1. A conceptual model for managing the cost and duration of road maintenance projects was built, which is based on the main provisions of the «silver triangle» theory. In contrast to the existing approaches, it was proposed to apply the main provisions of the «silver triangle» to the processes of cost, duration, and quality management of projects in the road industry.

2. A mathematical model for managing the cost and duration of projects for the maintenance of highways based on the allocation of resources for their implementation, which is based on graph theory and structural method, has been constructed. The mathematical model of project cost and duration management and the algorithm for determining cost and duration in the aggregate were the basis for the development of the author's software module on the Eclipse Java platform (USA) with further integration into MS Excel (USA). This makes it possible to simplify the process of determining the duration and cost of road maintenance projects at specified restrictions, at a certain level of quality. Determining the parameters of the road maintenance project, such as cost, duration, and quality, has a multiplier effect, which is expressed in reducing the administrative costs of the customer, reducing the responsibility of road services, creating prerequisites for stable financing of road works, the satisfaction of road users, creating strong partnerships between the customer and the contractor.

3. The model built was tested on the example of a real project of long-term maintenance of a section of the highway. The calculated values of the model parameters were compared with the design values and tested for adequacy using the Fisher criterion with a significance level of 0.05. According to the results of the test, it was determined that the estimated error according to the model was about 3 %, and the standard deviation was 5 %, which confirms the reliability of the data obtained. This means that our studies are of practical value and can be used by road organizations at the stage of designing services and works on road maintenance using an automated calculation based on the developed DCtcq software (Ukraine).

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