MACHINE BUILDING
МАШИНОСТРОЕНИЕ

UDC 628.465.9
https://doi.org/10.23947/2541-9129-2023-7-4-80-96

Original article

Model of Multi-Parameter Optimization of Cable Car Characteristics in a Solid Waste Transportation System

Yulianna V. Marchenko, Viktor V. Deryushev, Sergey I. Popov, Edward V. Marchenko
Don State Technical University, Rostov-on-Don, Russian Federation
✉ marchenko-6470@mail.ru

Abstract
Introduction. Modern scientific and applied literature examines the problems of cable cars functioning quite thoroughly. First of all, it concerns ensuring the reliability and safety of traffic, both during operation and during project development.
In addition, the paper considers the relationship of cable cars with the environment and the level of environmental load from this type of transport. A good solution could be the use of mathematical models that can take into account a set of parameters and criteria that characterize the cable car as a system. The same approach would be useful for optimizing technical characteristics of the object. However, there is no description of such a solution in the literature. This gap is partially filled by the presented work. The study aims to create a model of multivariable optimization of cable car technical characteristics for the transportation of municipal solid waste (MSW).
Material and Methods. To clarify the theoretical basis, the literature describing the problems of cable cars and their solutions in general has been studied. Mathematical calculations were justified by a volume of equations that proved their adequacy in determining the useful transport work, load, adjustment of time and speed of cargo movement and other significant parameters of the system under study. When forming the model, we proceeded from the principles of L.S. Pontryagin (needle variation) and Hamilton — Ostrogradsky (kinematics of a certain road segment). Text data about the features of the system elements and their interaction were summarized in tables. The main calculations results were visualized in the form of graphs.
Results. The solution to the problem of optimal control of the cable car on which solid waste was moved was presented. The motion control vector was shown as a vector of optimized technical parameters of the system: speed of movement, rope tension, number and weight of containers. The well-known solution to the optimization problem was reproduced in a general form, which involved determination of a control vector function and its corresponding trajectory with the achievement of a minimum of the target functional. The weak point of the system of differential equations for the realization of the goals of this scientific work was noted. In this regard, it was proposed to consider the investigated section of the cable car as a dynamic system with distributed parameters. The formulation of the multi-criteria optimization problem was described in detail. The advantages of reducing the number of criteria taken into account were listed and the use of the reduction method, which was based on the hierarchical structuring of the system of partial optimality criteria, was justified. Four main elements of the municipal solid waste (MSW) transportation system were considered in interrelation. This was a cable car, a transport and logistics point, a transport and logistics terminal and an environment that generated solid waste. Within the framework of this work, we considered an urbanized environment. The sub-elements of the named elements were listed and 12 directions of their interactions were shown. In detail, within the framework of a three-level hierarchy, four main complex indicators of the complexity of the system under study were described: environment, road, point and terminal. The solution of a multi-criteria optimization problem was shown, calculations were performed for the optimized parameters — the characteristic of the complexity of the road and the characteristic of the terrain. The results of calculations were presented in the form of graphs. Thus, the dependences of the optimized parameters on the weight of the loaded container, the length and speed of the cable car were illustrated.

Conclusions. The main result of the study is an idea of the possibility of a mathematical solution of a multivariable and multi-criteria problem of optimizing two characteristics of a cable car (complexity and terrain feature). The proposed approach allows you to change the hierarchy in the complex of indicators. The results of this scientific work can be used, if necessary, to integrate the road project with neural network models, to work with fuzzy linguistic indicators, to solve applied problems.

Keywords: cable car complexity, cable car environment complexity, transportation of municipal solid waste, multi-criteria optimization

Acknowledgements. The authors would like to thank their colleagues for their help.

For citation. Marchenko YuV, Deryushev VV, Popov SI, Marchenko EV. Model of Multi-Parameter Optimization of Cable Car Characteristics in a Solid Waste Transportation System. *Safety of Technogenic and Natural Systems.* 2023;7(4):80–96. https://doi.org/10.23947/2541-9129-2023-7-4-80-96

Научная статья

Модель многопараметрической оптимизации характеристик канатной дороги в системе транспортировки твердых бытовых отходов

Ю.В. Марченко, **В.В. Дерюшев**, **С.И. Попов**, **Э.В. Марченко**

Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация

✉ marchenko-6470@mail.ru

Аннотация

Введение. Современная научная и прикладная литература довольно обстоятельно рассматривает проблемы функционирования канатных дорог. В первую очередь речь идет о вопросах обеспечения надежности и безопасности движения — как во время эксплуатации, так и в процессе разработки проекта.

Кроме того, рассматривается взаимосвязь канатных дорог с окружающей средой, выясняется уровень экологической нагрузки от данного вида транспорта. Хорошим решением могло бы стать использование математических моделей, способных учитывать комплекс параметров и критериев, характеризующих канатную дорогу как систему. Этот же подход был бы полезен для оптимизации технических характеристик объекта. Однако в литературе не представлено описание такого решения. Данный пробел отчасти восполняет представленная работа. Ее цель — создание модели многопараметрической оптимизации технических характеристик канатной дороги для транспортировки твердых бытовых отходов (ТБО).

Материалы и методы. Для уточнения теоретической базы изучена литература, в целом описывающая проблемы канатных дорог и их решения. Математические расчеты обоснованы объемной подборкой уравнений, доказавших адекватность при определении полезной транспортной работы, нагрузки, корректировки времени и скорости перемещения грузов и других значимых параметров исследуемой системы. При формировании модели исходили из принципов Л.С. Понтрягина (игольчатая вариация) и Гамильтона — Остроградского (кинематика определенного отрезка дороги). Текстовые данные об особенностях элементов системы и их взаимодействии сведены в таблицы. Итоги главных расчетов визуализированы в виде графиков.

Результаты исследования. Представлено решение задачи оптимального управления канатной дорогой, по которой перемещают ТБО. Вектор управления движением показан как вектор оптимизируемых технических параметров системы: скорость движения, натяжение каната, число и вес контейнеров. Воспроизводится известное решение задачи оптимизации в общем виде, которое предполагает определение вектор-функции управления и соответствующей ему траектории с достижением минимума целевого функционала. Отмечено слабое место системы дифференциальных уравнений для реализации целей данной научной работы. В этой связи предложено рассматривать исследуемый участок канатной дороги как динамическую систему с распределенными параметрами. Детально описана постановка задачи многокритериальной оптимизации. Перечислены преимущества сокращения количества учитываемых критериев и обосновано применение метода редукции, который базируется на иерархической структуризации системы частных критериев оптимальности. Рассмотрены во взаимосвязи четыре главных элемента системы транспортировки твердых бытовых отходов (ТБО). Это канатная дорога, транспортно-логистический пункт, транспортно-логистический терминал и среда, которая генерирует ТБО. В рамках данной работы речь идет об урбанизированной среде. Перечислены подэлементы названных элементов и показаны 12 направлений их взаимодействий. Детально, в рамках трехуровневой иерархии, описаны четыре главных комплексных показателя сложности изучаемой системы: среда, дорога, пункт и терминал. Показано решение многокритериальной задачи оптимизации, выполнены расчеты по оптимизируем параметрам — характеристика сложности дороги и характеристика местности. Результаты расчетов представлены в виде графиков. Таким образом проиллюстрированы зависимости оптимизируемых параметров от массы загруженного контейнера, длины и скорости канатной дороги.

Обсуждение и заключение. Основной итог исследования — сформировано представление о возможности математического решения многопараметрической и многокритериальной задачи оптимизации двух характеристик канатной дороги (сложность и особенность местности). Предложенный подход позволяет менять иерархию в комплексе показателей. Результаты данной научной работы можно использовать при необходимости интеграции проекта дороги с нейросетевыми моделями, в работе с нечеткими лингвистическими показателями, для решения прикладных задач.

Ключевые слова: сложность канатной дороги, сложность среды канатной дороги, транспортировка твердых бытовых отходов, многокритериальная оптимизация

Благодарности. Авторы выражают признательность коллегам за помощь.

Для цитирования. Марченко Ю.В., Дерюшев В.В., Попов С.И., Марченко Э.В. Модель многопараметрической оптимизации характеристик канатной дороги в системе транспортировки твердых бытовых отходов. *Безопасность техногенных и природных систем*. 2023;7(4):80–96. https://doi.org/10.23947/2541-9129-2023-7-4-80-96

Introduction. Modern cable cars are high-tech complexes for passengers and cargo movement. Numerous scientific and applied studies are devoted to them. Technical features of these objects are being studied. The issues of their relationship with the environment are being clarified. Following the trends of recent years, the authors have found out the level of environmental load from this type of transport. The focus of attention is always on ensuring the reliability and safety of traffic — both during operation and during the development of the project.

Many authors and teams have studied the issues of improving technical characteristics of cable cars by improving their designs. The results of such studies have been implemented in passenger and cargo rope transport projects [1–3]. In [4, 5], a different approach to the problem of reliability and safety of operation of the objects under consideration is presented. In this case, the quality of the project is determined by the number of factors that affect the stability of the system. In this regard, it would be advisable to consider the possibilities of multiparametric and multi-criteria optimization of the technical characteristics of cable cars. However, there are no publications on this topic in modern scientific literature.

The work aims to show the possibility of creating a model of multiparametric optimization of technical characteristics of a cable car for the transportation of municipal solid waste (MSW).

Materials and Methods. Within the framework of the presented scientific work, the data from the literature devoted to the issue under study are summarized. One of the approaches to solving the problem is described in [6]. Solid waste is collected in removable containers, compacted, placed in vacuum and delivered by truck to a transport and logistics point. Here the container is moved to the cargo cable car. It connects the transport and logistics point with the transport and logistics terminal, where the container is loaded onto an intermediate decelerating conveyor, removed from the cable car, unloaded, then washed and disinfected. The described scheme assumes environmental control of processes, as well as maintenance and repair.

Let us consider a section of a cable car between two supports (Fig. 1). Let us assume that the supports are located at the same height and at distance l from each other. Between them there can be one or more containers weighing G_{ki} ($i = 1, \ldots, n$) each.

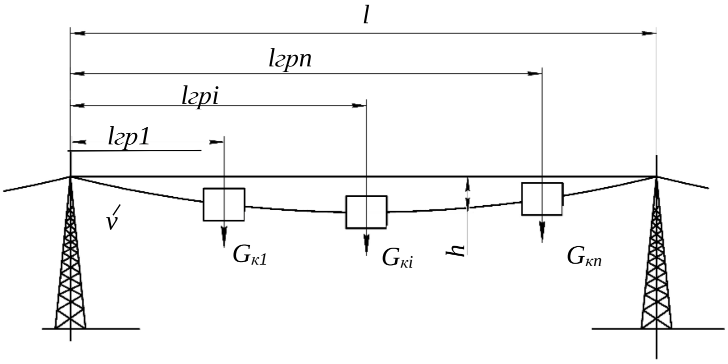

Fig. 1. Diagram of the process of transporting containers on a cable car

On a section of the cable car, the containers with cargo with a total weight of $G_{\text{гр}} = \sum_{i=1}^{n} G_{\kappa i}$ are delivered at a certain distance, and then it is an effective transportation A, equal to the product of cargo in tons $l_{\text{гр}}$ times the distance in km:

$$A = G_{\text{гр}} \cdot l_{\text{гр}} = \sum\nolimits_{(i=1)}^{n} (G_{\kappa i} \cdot l_{\text{гр}i}).$$

Transport work is measured in ton-kilometers. The productivity of the transport process is the useful transport work per unit of time:

$$W = \frac{G_{\text{гр}} l_{\text{гр}}}{t}$$

where t — time taken to move the load with total weight $G_{\text{гр}}$ to the distance of the total load from the support $l_{\text{гр}}$; $l_{\text{гр}} = \sum\nolimits_{(i=1)}^{n} l_{\text{гр}i} / n$.

Value $v = l_{\text{гр}} / t$ represents the speed of movement of goods by cable car. In the first approximation, it can be considered equal to the speed of the rope. In general, taking into account the slackness of the rope with containers by value h, the speed of movement of goods on the cable car will be slightly less than the speed of the rope.

An effective process is the delivery of as much cargo as possible in less time to a given distance. In our case, loads with a given total weight $\sum G_{\text{гр}}$ are moved by a cable car at a distance l between two supports. Then the task of increasing efficiency is reduced to minimizing travel time $t_{\text{гр}}$:

$$t_{\text{гр}} = \frac{\sum G_{\text{гр}} l}{v \sum_{i=1}^{n} G_{\kappa i}} \to \min.$$

When solving problems to reduce the transportation time, such characteristics of the cable car as the speed of movement v, the tension of the rope T, the number of containers between the supports n and the weight of one container with a load $G_{\kappa i}$ vary. Value $G_{\kappa i}$ is assumed to be the same for all containers. Then the task of increasing efficiency is reduced to maximizing:

$$v \sum_{(i=1)}^{n} G_{\kappa i} \to \max. \quad (1)$$

The speed of movement of cargo cable cars is limited by standards in the field of industrial safety[1]. The speed parameter is usually limited by the dynamic coefficient μ:

$$\mu = \frac{A_{\text{д}}}{A_{\text{ст}}},$$

where $A_{\text{д}}$ — amplitude of the container vibrations depending on the speed of the rope; $A_{\text{ст}}$ — static (or equilibrium) amplitude, i.e. static deformation of the elastic bond (maximum rope sagging) under the action of weight forces of all containers at zero or very low speed of movement the rope.

[1]*Ob utverzhdenii federal'nykh norm i pravil v oblasti promyshlennoi bezopasnosti "Pravila bezopasnosti passazhirskikh kanatnykh dorog i funikulerov"*. Order of the Federal Service for Environmental, Technological and Nuclear Supervision No. 441 dated November 13, 2020. Electronic Fund of Legal and Regulatory and Technical Documents. URL: https://docs.cntd.ru/document/573191373 (accessed 25.09.2023).

Changes in the shape and frequency of vibrations [7] lead to changes in dynamic loads on ropes and other power elements. Overload acting on the container in the vertical direction along the z axis:

$$\beta = \frac{P_д}{P_{ст}} = 1 + \frac{\ddot{z}}{g},$$

where $P_д$ — dynamic load, $P_{ст}$ — static load, $\ddot{z}$ — acceleration of the container in the direction of the vertical z axis.

Therefore, we will proceed from the safety requirements. We take into account the influence of rope tension and parameters from expression (1) on the dynamic coefficient and the magnitude of overloads. In this case, solution to the problem of increasing efficiency requires solution to the optimization problem of the cable system dynamics, which is described by a finite set of parameters. Thus, we are talking about a multiparameter problem.

Results

Formulation of the optimization problem for systems with lumped and distributed parameters. To solve the problem, we apply L.S. Pontryagin's needle variation [8] to the invariant features of the actual motion of a dynamical system.

In the classic formulation of the optimal control problem, the cable car between the supports is considered as a holonomic dynamic system the mechanical connections of which are reduced to geometric ones. For the system under consideration, Hamilton—Ostrogradsky principle [9] is valid, according to which on trajectory $q(t)$, that does not contain kinematic foci:

$$\delta J = \int_0^{t_k} (\delta T + \delta' A)\, dt = 0\,, \tag{2}$$

$$t = 0,\ q(0) = q_0,\ t = t_k,\ q(t_k) = q_k,$$

$$\delta q_0 = \delta q_k = 0\,, \tag{3}$$

where J — target functional; $T = T(q,\ \dot{q})$ — kinetic energy; $A = \int_{q(0)}^{q(t_k)} Q dq$ — work of generalized forces that depend on generalized coordinates; $q(t) = [q_1, \ldots, q_n]^T \in R^n$ — vector of specified generalized coordinates; $(t) = [Q_1, \ldots, Q_n]^T \in R^n$ — vector of generalized forces; $t = [0, t_k]$ — time; δ — symbol of variation; δ*'* — symbol of infinitesimal increment of quantities.

Vector of generalized forces depends on control vector $u(t)$:

$$u(t) \in R^m,\ Q = Q(q, \dot{q}, u, t),\ m \leq n. \tag{4}$$

The motion control vector is a vector of optimized technical parameters of the system: speed of movement, rope tension, number and weight of containers.

In general, the optimization problem involves determining the control vector function $u(q, \dot{q})$ and the corresponding trajectory $q(t)$, so that the minimum of the target functional is achieved:

$$J = \int_0^{t_k} F\left(q, \dot{q}\right) dt \to min. \tag{5}$$

Under conditions (2), (3) and control constraints:

$$u \in \overline{G_u}, \tag{6}$$

where $\bar{G}_u$ — closed set of permissible controls in the space of functions $[0, t_k]$ set at a finite time interval; $F(q, \dot{q})$ — sign-constant function.

Let us suppose, in the first approximation, the rope system is modeled as dynamic and consists of a finite number of concentrated masses (containers) connected by elastic constraints. In this case, to solve the optimization problem, it is necessary to determine the laws of speed change $v(t) = \dot{x}(t)$, rope tension $T = f(t)$, the values of the number of containers $n(x, \dot{x})$ and their weight G_{ki} — т such that the target functional J takes the minimum value:

$$J = \int_0^{t_k} \left[\left(x - x_k\right)^2 + \varepsilon \left(\dot{x} - \dot{x}_k \right)^2 \right] dt \to min\,. \tag{7}$$

Initial and terminal conditions for (7):

$$t = 0,\ x\left(0\right) = 0,\ \dot{x}(0) = v_{\min};\ t = t_k,\ x\left(t_k\right) = l, \dot{x}(t_k) = v_{\max}. \tag{8}$$

In addition, taking into account (2), we keep in mind the ordinary differential equations of motion of the dynamical system under consideration. Restrictions are imposed on the speed of movement, the amount of tension, the number and weight of containers:

$$v_{\min} \le v \le v_{\max};\ 0 < T \le T_{\max};\ 1 < n \le n_{\max};\ G_{\min} < G_{ki} \le G_{\max}. \tag{9}$$

In addition, the acceleration of containers in the direction of the x axis, in the transverse direction (along the z axis), as well as the transverse deviations of the i-th container $w(x_i,t)$ along the z axis are limited:

$$\ddot{x}_i(t) \le \ddot{x}_{\max};\ \ddot{z}_t(t) \le \ddot{z}_{\max};\ w(x_i,t) \le w_{\max}. \tag{10}$$

To solve the optimization problem, instead of target functional (7), an extended functional is considered:

$$J = \int_0^{t_x} \left\{ \frac{1}{2}x^2 + \mu \left[\frac{\dot{x}^2}{2} + \int_{x_0}^{x} u\,dx \right] \right\} dt, \tag{11}$$

where μ — Lagrange multiplier.

Let us mention the weak point of constructing a system of ordinary differential equations of motion of the dynamic system under consideration with a variable number of concentrated masses and variable boundary conditions. The fact is that in order to implement this approach, it is necessary to introduce a number of assumptions that reduce the reliability of optimization results. Therefore, we consider the corresponding section of the cable car as a dynamic system with distributed parameters. In this case, to study the dynamic processes of a system with a mobile discrete and distributed inertial load, we use the partial differential equation of transverse rope vibrations reduced to a homogeneous differential equation:

$$\rho(x)\frac{\partial^2 w}{\partial t^2} + 2\rho(x)v\frac{\partial^2 w}{\partial x \partial t} - (T - \rho(x)v^2)\frac{\partial^2 w}{\partial x^2} = 0, \tag{12}$$

where $\rho(x) = \rho_0 + \sum_{i=1}^{n} G_{\text{гр}i}\delta(x - x_i)$; ρ_0 — mass of the rope length unit; $G_{\text{гр}i}$ — mass of the i—th concentrated load; $\delta(x - x_i)$ — Dirac function; x_i — coordinate determining the position of the i-th load; T — rope tension; $w(x,t)$ — transverse deviation; v — longitudinal velocity of the rope.

A detailed review of methods for solving optimization problems for dynamic systems with distributed parameters, including hyperbolic systems of form (10) with controlled connections at the boundaries, is given [9]. Most methods are based on the assumption that of all the permissible control actions on the system under consideration, only one corresponds to the optimal state of the process, i.e. solution of differential equation (10). Another assumption is the convexity of the set of permissible controls in the target functional — for example, as in (7). At the same time, for systems with distributed parameters, the absence of optimal control or the presence of multimodal functions in the target functional with multiparametric optimization is acceptable. In addition, the complexity of obtaining the necessary (and, preferably, sufficient) optimality conditions does not guarantee the adequacy of the results of solving a model optimization problem to the optimization goals for a real object. This disadvantage is also characteristic of dynamical systems modeled by ordinary differential equations.

The above proves the relevance of developing approaches that will overcome the shortcomings noted above. It concerns the methods of so-called suboptimal management. These include multi-criteria optimization methods used in decision-making or selection tasks. In this case, they make it possible to consider simultaneously a larger number of parameters of the optimized system in a multidimensional space of criteria (indicators).

Formulation of a multi-criteria optimization problem. Let U — n-dimensional vector of optimized technical parameters of the system (control vector) and $n > 1$. In our case $n = 4$. Vector components: u_1 — speed of movement, u_2 — rope tension, u_3 — number of containers, u_4 — weight of one container. As noted above, restrictions can be imposed on vector U, which is a closed set $\overline{G_u}$ of form (6), which is called the set of acceptable values of the vector of optimized parameters. The dimension of this set is $r \ge n$. Constraints and limiting functions have form (9) and (10).

Let us introduce vector optimality criterion $K(U)$, defined on the set $\overline{G_u}$, in m-dimensional arithmetic space (criterion space) R_e^m. Here $m \ge 1$, i.e. in the limiting case, for $m = 1$ the optimization problem becomes single-criteria, for $m > 1$ — multi-criteria. The components of the vector optimality criterion are particular optimality criteria:

$$K(U) = \{k_1(U), k_2(U), \ldots, k_m(U)\}. \tag{13}$$

They may also be subject to restrictions. This is due to the need to bring to a dimensionless form and a single scale of changes in values, for example, in the proposed model

$$0 \le k_i(U) \le 1,\ i = [1,\ldots,m]. \tag{14}$$

In addition, in the general case, when forming particular optimality criteria, depending on the optimization goal, the values of some particular criteria should be increased, and the values of others should be reduced. Let us note, however, that the task of criterion minimization by introducing an inverse transformation is reduced to the task of maximization. Therefore, let us assume that maximization of all partial optimality criteria is desirable in the developed model.

We also note possible limitations on the value of m, i.e. on the number of particular optimality criteria (indicators) formed when solving specific problems. Obviously, one criterion, even a complex one, cannot cover all the requirements. Modern computer technologies make it possible to solve problems with a large amount of data without loss of accuracy, so many researchers maximize the number of particular criteria, use even those factors that practically do not affect the result of optimization. At the same time, an increase in the dimensionality of the system makes it difficult to build and may disrupt the stability of computational algorithms, especially in target functionals with multimodal functions.

From a mathematical point of view, reducing the number of criteria reduces the complexity of computational algorithms and opens up the possibility of a simple graphical interpretation of the results (for example, for two-dimensional or three-dimensional criterion spaces). In addition, the verification of algorithms is simplified. The problem can be reduced to a single-criteria one, and there are many proven methods for solving it. In general, reducing the dimension of the formed system of partial optimality criteria (indicators) greatly simplifies the solution to the optimization problem.

Most often, the method of eliminating duplicate or insignificant indicators is used for reduction. However, it is possible to mistakenly exclude important factors. Therefore, within the framework of the presented work, a reduction method was used based on the hierarchical structuring of a system of partial optimality criteria without their artificial exclusion [10].

So, let us consider the functions (processes) of the system under consideration with an optimized object — a cable car (Fig. 2).

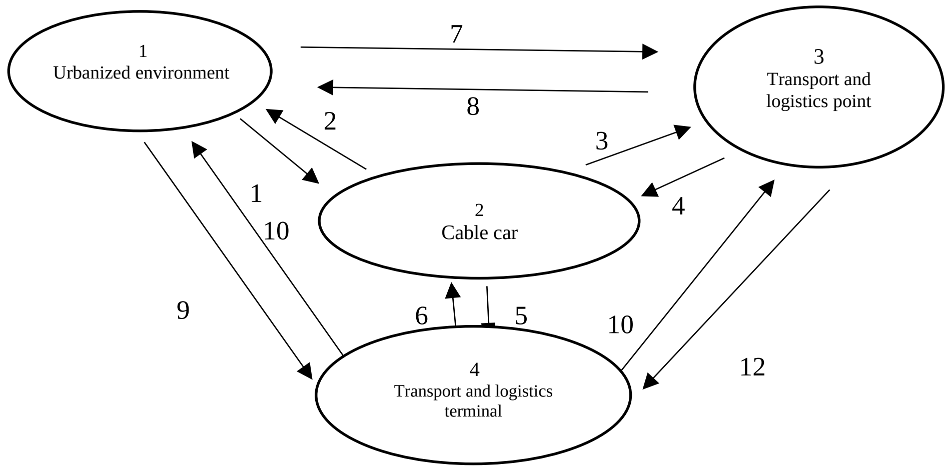

Fig. 2. Functional diagram of the MSW transportation system

Four elements of the MSW transportation system are described in [6].

1. Urbanized environment determines:
– layout of settlements;
– transport infrastructure;
– terrain and landscape;
– natural and climatic conditions;
– weight and volume of generated solid waste;
– time of removal of solid waste.

2. Cable car performs the main function — moving solid waste to the disposal site. The main (including optimized) characteristics of this element of the system:
– type of cable car;
– number of containers on the road and between supports;
– rope tension;
– rope diameter;
– speed of movement;
– step of discrete drives;
– space between the supports.

3. Solid waste is collected and stored for some time at a transport and logistics point. Its main characteristics:
– area;
– height of indoor premises;
– loading and unloading performance;
– dimensions and technical capabilities of conveyors;
– number of empty containers.

4. In the transport and logistics terminal, solid waste is unloaded, moved from the cable car to the disposal site. Emptied containers are sent for washing, storage and inspection. The main characteristics of this element of the system are:
– area;
– height of indoor premises;
– dimensions and technical capabilities of conveyors;
– loading and unloading performance;
– parameters of equipment for washing, drying and disinfection of empty containers;
– number of empty containers.

Table 1 describes the interactions of the elements, which are shown in Figure 2 with numbers from 1 to 12.

Table 1

Interaction of elements of the MSW transportation system by cable car

No	Direction	Interacting elements
1	Urbanized environment — cable car	Volume and weight of solid waste; volume, weight, number of containers; technical characteristics of the road
2	Cable car — urbanized environment	Cable car operation processes; ecological state of the environment; safety indicators of intersected objects (roads, water barriers, buildings, agricultural land, etc.)
3	Cable car — transport and logistics point	Number and weight of empty containers; speed and regularity of arrival of containers at the point
4	Transport and logistics point - cable car	Number and weight of loaded containers; speed and regularity of arrival of containers on the cable car
5	Cable car — transport and logistics terminal	Number and weight of loaded containers; speed and regularity of receipt of containers in the terminal
6	Transport and logistics terminal — cable car	Number and weight of empty containers; speed and regularity of arrival of containers on the cable car
7	Urbanized environment — transport and logistics point	Route length; transport infrastructure; container volume and weight; vehicle load capacity; number of vehicles and containers per vehicle; vehicle speed; speed and regularity of container arrival at the transport and logistics point; climatic conditions
8	Transport and logistics point — urbanized environment	Processes of operation of a transport and logistics point; environmental situation
9	Urbanized environment — transport and logistics terminal	Volume and weight of solid waste; natural and climatic conditions
10	Transport and logistics terminal — urbanized environment	Processes of operation of the transport and logistics terminal; environmental situation
11	Transport and logistics terminal — transport and logistics point	Volume and weight of solid waste; number of empty, excluded and added containers; maintenance and repair processes
12	Transport and logistics point — transport and logistics terminal	Volume, weight of solid waste; number of filled, excluded and added containers

Figure 3 shows the interaction of the main parameters of the system under consideration for a conditional Rostov-on-Don district in the form of a diagram.

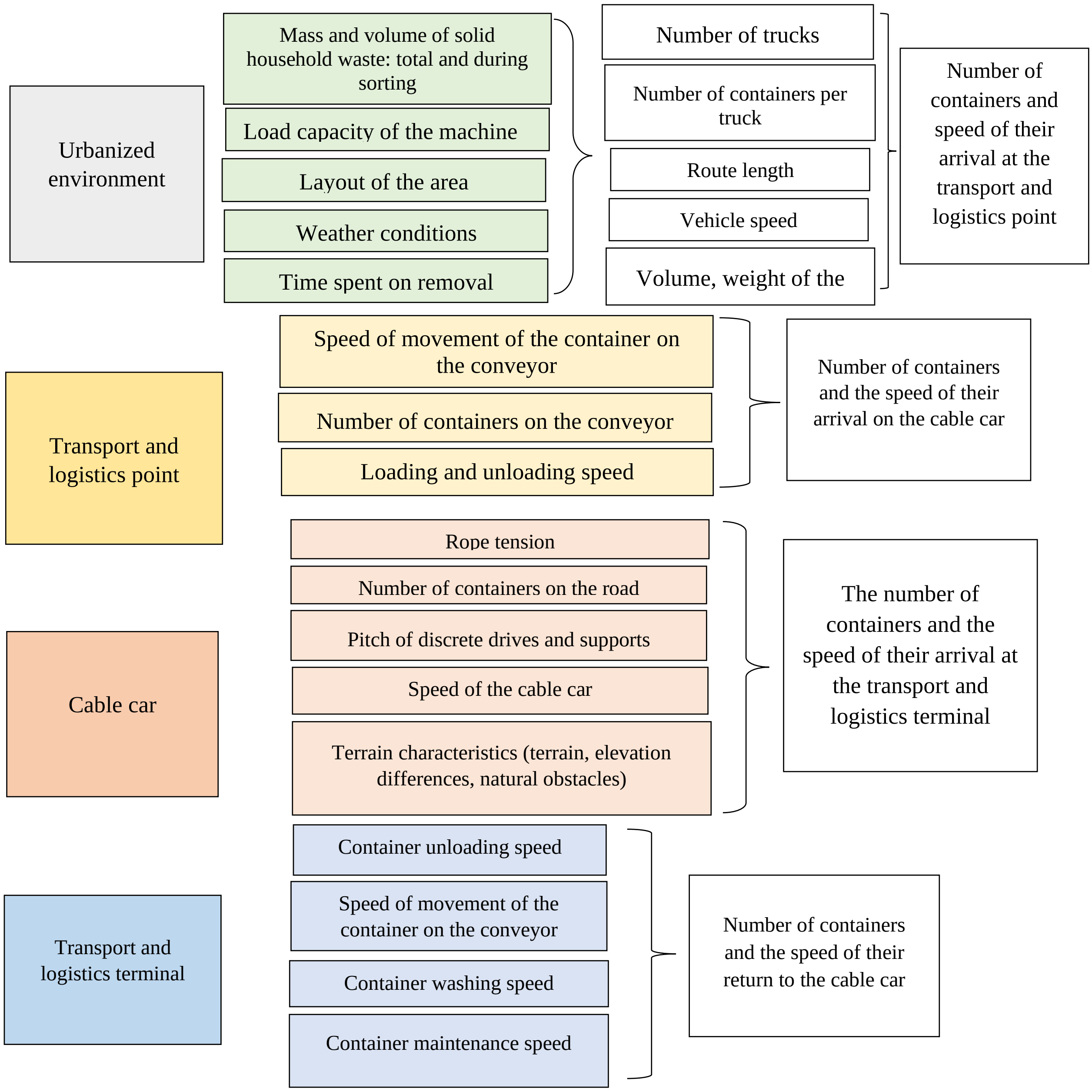

Fig. 3. Scheme of functional interaction of the main indicators of the MSW transportation system from the conditional Rostov-on-Don district

Figures 2 and 3 allow us to build a hierarchy of indicators (Fig. 4).

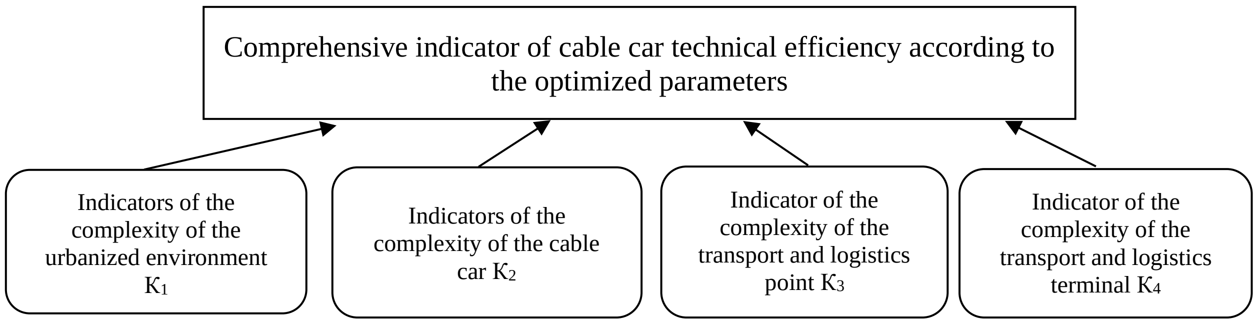

Fig. 4. Hierarchical structure of criteria characterizing the cable car as a system

Tables 2 and 3 show the examples of complex indicators of technical complexity of building and functioning of an eco-friendly system for removal of solid household waste by cargo cable transport in an urbanized environment.

Table 2

Comprehensive indicators of technical complexity of the cable car as a solid waste transportation system

Indicator level			Dimension, unit of measurement
1st	2nd	3rd	
Complexity of an urbanized environment K_1	Layout of the settlement with transport infrastructure K_{11}	Layout of the area K_{111}	Very bad
			Bad
			Average
			Good
			Very good
		State of the transport infrastructure K_{112}	Length of paved streets to the total length of streets
	Terrain and landscape of the area K_{12}		Bad
			Average
			Good
	Characteristics of solid household waste (day) K_{13}	Weight K_{131}	t
		SMW Volume K_{132}	m^3
		Structure K_{133}	Solid
			Liquid
			No classification
	Natural and climatic conditions K_{14}	Temperature K_{141}	C^0
		Wind velocity K_{142}	m/s
		Humidity K_{143}	%
		Number of sunny days in summer K_{144}	Units
	Removal of solid household waste K_{15}	Frequency of solid waste removal K_{151}	Once a week
		Number of trucks K_{152}	Units
		Transportation costs (fuel and lubricants, maintenance) K_{153}	Rub.
		Number of containers per car K_{154}	Units
		Route length K_{155}	km
		Vehicle speed K_{156}	km/h
		Container volume K_{157}	m^3
		Container weight K_{158}	kg
Cable car complexity K_2	Cable car characteristics K_{21}	Cable car length K_{211}	m
		Number of containers on the cable car and between the supports K_{212}^*	Units
		Rope tension K_{213}^*	kN
		Cable car speed K_{214}^*	m/s
		Distance between supports K_{215}	m
		Rope diameter K_{216}^*	mm
		Weight of loaded containers K_{217}	kgr
	Terrain characteristics K_{22}	Height difference K_{221}	m
		Obstacles along the way K_{222}	Bad
			Average
			Good
Transport and logistics point complexity K_3	Layout of a transport and logistics point K_{31}	Occupied area K_{311}	m^2
		Height of indoor spaces K_{312}	m
	Characteristics of loading and unloading operations K_{32}	Number of unloading platforms K_{321}	Units
		Number of loading platforms K_{322}	Units
		Unloading performance K_{323}	Units /hour
		Loading performance K_{324}	Units /hour
	Characteristics of the	Conveyor length K_{331}	m

	conveyor for empty containers K_{33}	Number of containers to be placed K_{332}	Units
		Number of empty containers sent for storage K_{333}	Units
	Characteristics of the accelerating conveyor K_{34}	Conveyor speed K_{341}	m/s
		Conveyor length K_{342}	m
		Load capacity K_{343}	t
		Drive power K_{344}	kW
	Characteristics of the decelerating conveyor K_{35}	Conveyor speed K_{351}	m/s
		Conveyor length K_{352}	m
		Load capacity K_{353}	t
		Drive power K_{354}	kW
Transport and logistics terminal complexity K_4	Terminal size K_{41}	Occupied area K_{411}	m^2
		Height of indoor spaces K_{412}	m
	Characteristics of the decelerating conveyor K_{42}	Conveyor speed K_{351}	m/s
		Conveyor length K_{352}	m
		Load capacity K_{353}	t
		Drive power K_{354}	kWт
	Parameters of the equipment for unloading solid waste from the container K_{43}	Efficiency K_{431}	Units /hour
		Number of tilters K_{432}	Units
		Number of unloading platforms K_{433}	Units
	Parameters of equipment for washing, drying and disinfection of empty containers K_{44}	Line length K_{441}	m
		Number of washing positions K_{442}	Units
		Water pressure K_{443}	MPa
		Characteristics of detergents K_{444}	Bad
			Average
			Good
		Drying speed K_{445}	min
	Characteristics of the conveyor for maintenance and repair of empty containers K_{45}	Conveyor length K_{451}	m
		Number of containers to be placed K_{452}	Units
		Number of empty containers sent for maintenance and repair K_{453}	Units
		Container maintenance K_{454}	Bad
			Average
			Good
	Characteristics of the accelerating conveyor K_{46}	Conveyor speed K_{461}	m/s
		Conveyor length K_{462}	m
		Load capacity K_{463}	t
		Drive power K_{464}	kW
K^* — optimized parameters.			

Table 3

Intervals of changes in cable car complexity indicators

Level 3 Indicator	Unit of measurement, dimension	Change interval
Cable car length K_{211}	m	1000…50000
Number of containers on the cable car and between the supports K_{212}^*	Units	1…20
Rope tension K_{213}^*	kN	10…15
Cable car speed K_{214}^*	m/s	0.5…5
Distance between the supports K_{215}	m	40…150
Rope diameter K_{216}^*	mm	10…1000
Weight of loaded containers K_{217}	kg	500…1500
Height difference K_{221}	m	0…2000
Obstacles along the way K_{222}	Bad	0…1
	Average	
	Good	

In general, there should be at least two indicators at each level of the hierarchy (with the exception of the topmost one, which represents the target function). When grouping particular criteria at each level, the number of criteria (indicators) in the group can vary from one to some specified maximum value, i.e. $1 \le m \le m_{max}$. At $m = 1$ the indicator of the upper level moves to the lower one without change and vice versa. The maximum value is determined by the dimension of the criterion space and the complexity of constructing a computational optimization procedure in this space. Let us take $m_{max} = 8$.

All criteria (indicators) of the lower level can be measurable and immeasurable. The examples for the first case: "height difference", "total length". For the second case — "relief" (simple, complex, very complex). To describe such criteria, it is proposed to use the methods of fuzzy set theory, i.e. to determine the function of an object belonging to the corresponding set, as in [10].

So, let us formulate the task of multi-criteria optimization to the maximum for each group of partial optimality criteria at all levels. It is necessary to determine the vector function of the optimized system parameters (control vector) U on a closed set $\overline{G_u}$ so that the maximum of the target functional is achieved

$$K(U) \rightarrow \max \tag{15}$$

under condition (13) and constraints (9, 10 and 14).

$\overline{G_u}$ — closed set of permissible controls in the space of specified functions (permissible values of the vector of optimized parameters).

Vector $U^* \in \overline{G_u}$ is the global solution to problem (15) if $K(U^*) \ge K(U)$ for all $U \in \overline{G_u}$.

To solve the multi-criteria optimization problem, we will use scalarization method of vector criterion (13). To this end, we apply the additive function:

$$K_c(U) = \sum_{i=1}^{m} \alpha_i k_i(U). \tag{16}$$

For coefficients α_i the conditions must be met:

$$\alpha_i \ge 0 \text{ при } i = 1,...,m; \sum_{i=1}^{m} \alpha_i = 1. \tag{17}$$

Then initial problem (15) is reduced to finding the maximum of integral indicator (16). In this case, the method of determining the coefficients α_i is especially important. These are the convolution coefficients of vector criterion (13) from the multicriteria space to the numerical axis of scalar criterion (16) with the physical meaning "better" — "worse".

To calculate the convolution coefficients, one can use the methodology proposed in [10]. In this case, fuzzy relations on pairs of objects from the training sample and integral scalar exponent (16) are considered. A computational procedure is constructed for the functional that determines the magnitude of the discrepancy.

After determining the convolution coefficient vectors for all criteria of the hierarchy, it is necessary to find the vector function of the optimized parameters of the system (control vector) U, when additive function (16) reaches the maximum for the criterion of the upper level of the hierarchy (objective function). At the same time, on a set of parameters, the objective function can have several local maxima. Among them, you need to find a global one. There are several computational methods for solving such problems [11]. The so-called evolutionary methods have certain advantages. Some of them are implemented on the basis of a specialized multidisciplinary platform ModeFrontier. To solve this problem, we propose genetic algorithm [12].

Calculations. The optimized parameters of the cable car, as shown in Table 2, are included in K_2 indicator:

$$K_2 = 0,6K_{21} + 0,4K_{22}.$$

K_{21} (cable car complexity characteristic) is determined by the formula:

$$K_{21} = 0,1K_{211} + 0,15K_{212} + 0,15K_{213} + 0,25K_{214} + 0,1K_{215} + 0,1K_{216} + 0,15K_{217}.$$

K_{22} (terrain characteristics), determined by the formula:

$$K_{22} = 0,5K_{221} + 0,5K_{222}.$$

The use of applied software products made it possible to show the results of calculations in the form of graphical dependencies K_{21} and K_2 on the optimized parameters in Fig. 5–8. At the same time, the numerical values of the variable parameters were determined according to Table 2.

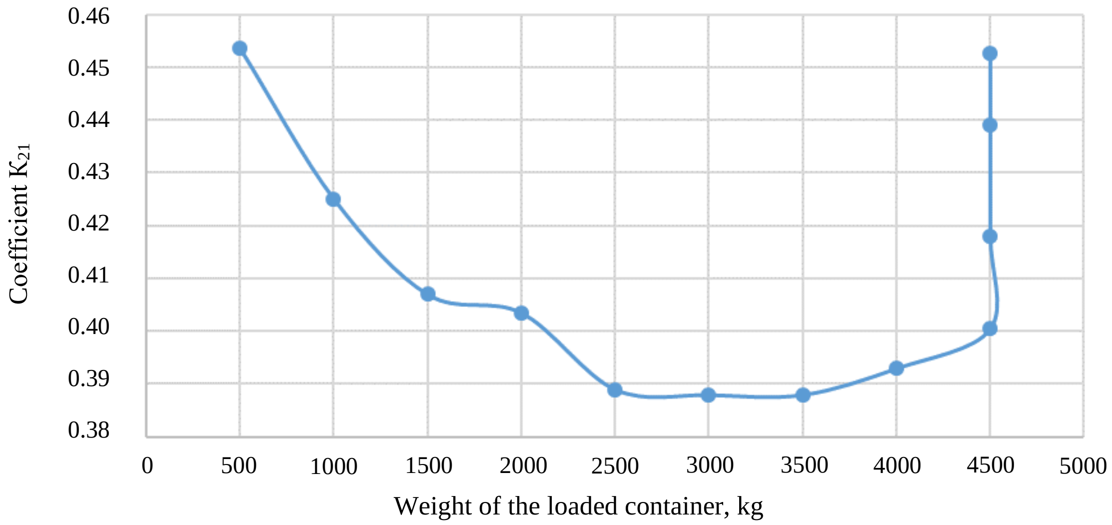

Fig. 5. Dependence of K_{21} coefficient on the weight of the loaded container with a cable car with a length of 20 thousand meters

Fig. 6. Dependence of K_{21} coefficient on the weight of the loaded container with a cable car with a length of 40 thousand meters

Figures 5 and 6 demonstrate a pronounced extremum for K_{21} indicator (cable car complexity characteristic) in the weight range of the loaded container 2500–4500 kg. This can be explained by the fact that when using containers with low mass, it is necessary to increase their number to ensure a given performance. As a result, the number of elements of the system increases, that is, it becomes more complicated. The use of containers with a large mass requires the introduction of elements such as additional discrete drives, vibration damping systems, increasing the thickness of the rope, etc., which also complicates the system.

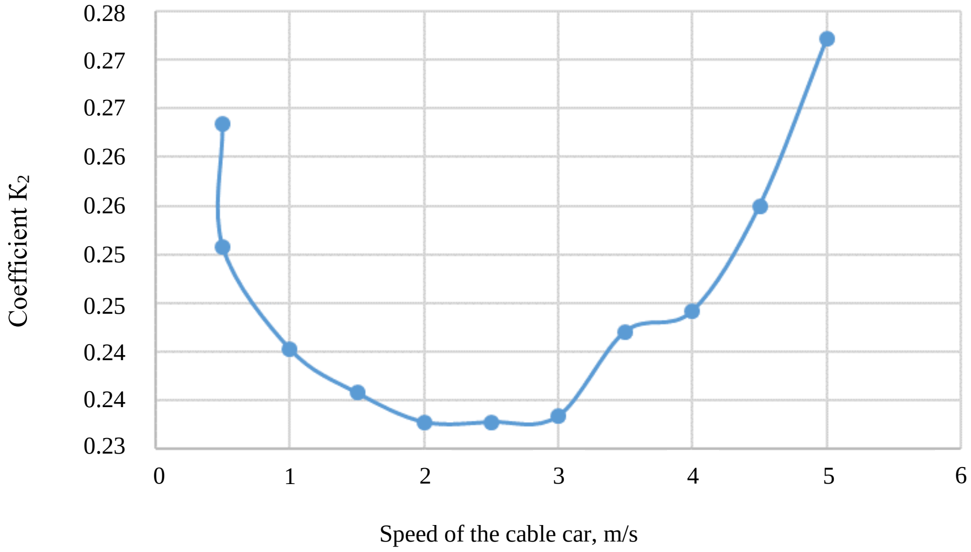

Fig. 7. Dependence of K_2 coefficient on the speed of a cable car with a length of 20 thousand meters

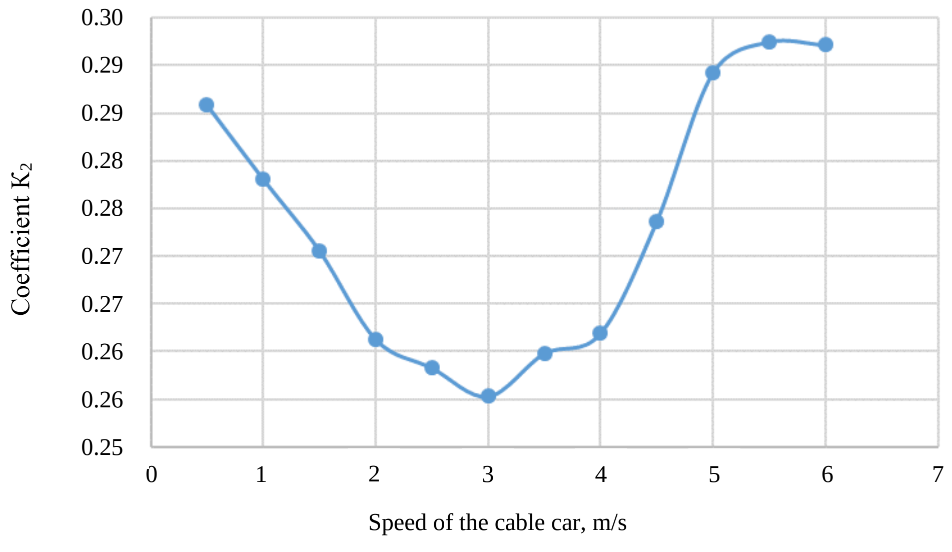

Fig. 8. Dependence of K_2 coefficient on the speed of a cable car with a length of 40 thousand meters

Figures 7 and 8 show that in the speed range of the cable car 1.5...3.5 m/s, K_2 indicator has the lowest difficulty values, since at low speeds more containers are required, and at high speeds additional devices are needed to stabilize movement.

Discussion and Conclusion. The paper considers cable car complexity and terrain features as cable car optimized parameters. In the first case, for optimization, it is necessary to take into account the length of the road, the number of containers, the weight of loaded containers, the tension and diameter of the rope, the speed of the cable car and the distance between the supports. In the second case, the calculation is based on the data on the height difference and possible obstacles along the way. Both groups of these parameters demonstrate the complexity of the cable car in terms of technology and environment (indicator of the 1st level K_2)

A model for solving a multiparametric and multi-criteria problem of optimizing the characteristics of a cable car is proposed. It allows you to change the hierarchy of indicators. This approach can be used if it is necessary to integrate the project with neural network models, to work with fuzzy linguistic indicators, and to solve applied problems.

References

1. Korotkii AA, Lagerev AV, Meskhi BCh, Lagerev IA, Panfilov AV. *Razvitie transportnoi infrastruktury krupnykh gorodov i territorii na osnove tekhnologii kanatnogo metro.* Rostov-on-Don: Don State Technical University; 2017. 344 p. URL: http://ntb.donstu.ru/content/razvitie-transportnoy-infrastruktury-krupnyh-gorodov-i-territoriy-na-osnove-tehnologii-kanatnogo-metro (accessed: 25.08.2023). (In Russ.).

2. Lagerev AV, Lagerev IA. Optimizatsiya shaga ustanovki promezhutochnykh opornykh konstruktsii vdol' linii kanatnogo metro. *Vestnik Bryanskogo gosudarstvennogo universiteta*. 2014;4:22–30. URL: http://vestnik-brgu.ru/wp-content/numbers/v2014_4.pdf (accessed: 09.08.2023). (In Russ.).

3. Korotky AA, Marchenko EV, Popov SI, Marchenko JuV, Dontsov NS. Theoretical foundations of modeling the process of transport vehicles steel ropes structural defects formation. In: *E3S Web of Conferences*. 2020;175:05018. https://doi.org/10.1051/e3sconf/202017505018

4. Kinzhibalov AV. *Povyshenie bezopasnosti passazhirskikh kanatnykh dorog na osnove otsenki riska i rezervirovaniya privoda.* Author's abstract. Novocherkassk; South-Russian State Technic University: 2008. 24 p. URL: https://viewer.rusneb.ru/ru/000199_000009_003457469?page=1&rotate=0&theme=white (accessed: 09.08.2023). (In Russ.).

5. Korotky AA, Marchenko EV, Ivanov VV, Popov SI, Marchenko JuV, Dontsov NS. Model of forming vibration mechanochemical solid lubrication coating on surface of steel rope. In: *IOP Conference Series. Earth and Environmental Science*. 2019;403:012116. https://doi.org/10.1088/1755-1315/403/1/012116

6. Marchenko JuV, Korotky AA, Popov SI, Marchenko EV, Galchenko GA, Kosenko VV. Municipal waste management in an urbanized environment based on ropeway technology. *Lecture Notes in Networks and Systems*. 2022;246:235–241. https://doi.org/10.1007/978-3-030-81619-3_26

7. Anisimov VN, Litvinov VL. Transverse vibrations rope moving in longitudinal direction. *Izvestia of Samara Scientific Center of the Russian Academy of Sciences*. 2017;19(4):161–166. URL: https://cyberleninka.ru/article/n/poperechnye-kolebaniya-kanata-dvizhuschegosya-v-prodolnom-napravlenii/viewer (accessed: 09.08.2023). (In Russ.).

8. Kostoglotov AA, Deryushev VV, Kostoglotov AI. Identifikatsiya parametrov dinamicheskikh sistem na osnove ob"edinennogo printsipa maksimuma. *Bulletin of Higher Education Institutes. North Caucasus region. Natural sciences.* 2004;S2:13–18. URL: https://cyberleninka.ru/article/n/identifikatsiya-parametrov-dinamicheskih-sistem-na-osnove-obedinennogo-printsipa-maksimuma/viewer (accessed: 09.08.2023). (In Russ.).

9. Arguchintsev AV. *Optimal'noe upravlenie nachal'no-kraevymi usloviyami giperbolicheskikh sistem.* Author's abstract. Irkutsk; 2004. 237 p. (In Russ.).

10. Deryushev VV, Korobetskiy DI, Sorokina DN. Mathematical model of construction of the complex index of safe operation of hoisting machines. *Safety of Technogenic and Natural Systems.* 2019;4:13–18. https://doi.org/10.23947/2541-9129-2019-4-13-18

11. Marchenko JuV, Popov SI. The use of a unified container in an ecological automated system for the removal of solid household waste in an urbanized environment based on rope transport technologies. *Lecture Notes in Networks and Systems*. 2023;575:1304–1311. https://doi.org/10.1007/978-3-031-21219-2_146

12. Chernykh SV. Mnogoparametricheskaya optimizatsiya mnogomodal'nykh funktsii. *Vestnik of Immanuel Kant Russian State University.* 2010;(10):94–103. URL: https://journals.kantiana.ru/upload/iblock/367/iimdxxrrccww.pdf (accessed: 09.08.2023). (In Russ.).

Received 12.10.2023
Revised 29.10.2023
Accepted 01.11.2023

About the Authors:

Yulianna V. Marchenko, Cand. Sci. (Eng.), Associate Professor of the Operation of Transport Systems and Logistics Department, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344003, RF), ScopusID, AuthorID, ORCID, marchenko-6470@mail.ru

Viktor V. Deryushev, Dr. Sci. (Eng.), Professor of the Operation of Transport Systems and Logistics Department, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344003, RF), ResearcherID, ScopusID, AuthorID, ORCID

Sergey I. Popov, Cand. Sci. (Eng.), Associate Professor of the Operation of Transport Systems and Logistics Department, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344003, RF), ResearcherID, ScopusID, AuthorID, ORCID, spopov1957@yandex.ru

Edward V. Marchenko, Cand. Sci. (Eng.), Associate Professor of the Operation of Transport Systems and Logistics Department, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344003, RF), ScopusID, AuthorID, ORCID, daedwardrambler.ru@mail.ru

Claimed contributorship:

YuV Marchenko, SI Popov: development of the research concept, functional scheme of solid waste transportation, scheme of functional interaction of the system main indicators, development of the hierarchical structure of criteria.

YuV Marchenko: formulation and solution of the problem of multi-criteria optimization for systems with concentrated and distributed parameters.

EV Marchenko: determination of the optimized parameters of a cable car, consideration of the examples of complex indicators of the technical complexity of the construction and functioning of the solid waste removal system by cargo cable transport.

Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Поступила в редакцию 12.10.2023
Поступила после рецензирования 29.10.2023
Принята к публикации 01.11.2023

Об авторах:

Юлианна Викторовна Марченко, кандидат технических наук, доцент кафедры эксплуатации транспортных систем и логистики Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), ScopusID, AuthorID, ORCID, marchenko-6470@mail.ru

Виктор Владимирович Дерюшев, доктор технических наук, профессор кафедры эксплуатации транспортных систем и логистики Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), ResearcherID, ScopusID, AuthorID, ORCID

Сергей Иванович Попов, кандидат технических наук, доцент, кафедры эксплуатации транспортных систем и логистики Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), ResearcherID, ScopusID, AuthorID, ORCID, spopov1957@yandex.ru

Эдвард Викторович Марченко, кандидат технических наук, доцент кафедры робототехники и мехатроники Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), ScopusID, AuthorID, ORCID, daedwardrambler.ru@mail.ru

Заявленный вклад соавторов

Ю.В. Марченко, С.И. Попов — разработка концепции исследования, функциональной схемы транспортировки твердых бытовых отходов, схемы функционального взаимодействия основных показателей системы, разработка иерархической структуры критериев.

Ю.В. Марченко — постановка и решение задачи многокритериальной оптимизации для систем с сосредоточенными и распределенными параметрами.

Э.В. Марченко — определение оптимизируемых параметров канатной дороги, рассмотрение примеров комплексных показателей технической сложности построения и функционирования системы вывоза твердых бытовых отходов грузовым канатным транспортом.

Конфликт интересо: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.