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MATHEMATICAL MODEL OF RAILWAY FUNCTIONING FROM THE PERSPECTIVE OF SUSTAINABLE DEVELOPMENT

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МАТЕМАТИЧНА МОДЕЛЬ ФУНКЦІОНУВАННЯ ЗАЛІЗНИЦЬ З ПОЗИЦІЇ СТАЛОГО РОЗВИТКУ

Purpose. The article is aimed to ensure the most efficient variant of railway functioning from the perspective of sustainable development.

Methodology. A comprehensive analysis of works in the field of increasing the functioning of railway transport subdivisions and implementing the principles of sustainable development was carried out. This analysis makes it possible to identify the main directions of increasing the efficiency of railway functioning from the perspective of sustainable development. The model of railway functioning was developed using the mathematical apparatus of the theory of sets and graphs that allows structuring the railway as a complex system. The basic stages and the relationships during the simulation of railway functioning processes at the macro and micro levels were shown.

Findings. A mathematical model of the railway functioning was developed on the basis of which the simulation of the railway functioning process is carried out at two levels. The macro level is the simulation of the car traffic volume displacement in the transport network within the railway and the micro level is the simulation of processing the car traffic volume at the stations of the railway.

Originality. The article includes an adequate description of the process of railway functioning from the perspective of sustainable development, based on the apparatus of the theory of sets and graphs.

Practical value. On the basis of the proposed model of the railway functioning at the macro level it is possible to solve the problems of optimal distribution of freight operation not only between the stations encompassing the approach lines of the mining enterprises, but also between all railway stations perating local car traffic volumes. Using the proposed model of functioning of the technical freight station at the micro level the problem of determining the optimal quantitative characteristics of the production capacities of the stations is solved.

Keywords: *mining industry, railway transport, sustainable development, mathematical model*

Introduction. One of the main directions of foreign policy of Ukraine is to join the European Union. For Ukraine, European integration is a way to modernize the economy, overcome the technological backwardness, improve the competitiveness, and enter global markets. The modern development of Ukraine is aimed at economic growth, whereas the social protection of society and environmental issues lack proper attention. European standards are already guided by the laws of sustainable development, so considering the issues specific for sustainable development is an important step to strengthen the positions in the European system. The issues are as follows: reducing the negative impact on the environment, introduction of resource-saving technologies, and improving the social security of employees. In theory, the sustainable development of the country is provided by the entire national economic complex, and by every branch of it, respectively.

Unresolved aspects of the problem. The task to ensure the sustainable development of the mining industry includes not only the implementation of the principles of sustainable development in the industry, but also the optimal use of transport modes for the transportation of goods. According to the analysis, the mining products (ore – 21 %, coal – 17 %, petroleum and petroleum products – 35 %, ferrous metals – 6 %) constitute a major part of the cargo transported by the railway transport (79 %). However, the attractiveness of railway transport for the mining industry has been decreased lately. This is due to the tariff imbalances, irregularity of car delivery to industrial enterprises, considerable wear of the rolling stock, which entails a significant loss of cargo during transportation. Reduction of railway transport competitiveness in transportation of mining products can lead to increase in environmental pollution and, thus, to increase in costs associated with the transport operation (as of 2012 the external costs associated with the operation of motor vehicles totaled 43.2 bln. UAH, and the costs associated with the railway transport operation – 12.4 bln. UAH). The above mentioned data actualize the problem of implementation of principles of sustainable development when using the railway transport for transportation of goods of the mining complex.

Analysis of the recent research. A. A. Bosov, Yu. S. Barash, T. V. Begun, Yu. V. Kosov, S. N. Bobylev, N. V. Ostrovskii, N. P. Tarasova, O. L. Kuznetsov considered application of the concept of sustainable development and its implementation in the management of complex systems in their works.

Research in the field of increasing the efficiency of the railway transport subdivisions is described in the works of domestic and foreign scientists, such as A. O. Muradian, P. A. Novikov, D. V. Lomotko, N. V. Panova, A. A. Anchugina, T. V. Polishko, M. M. Sergiienko, V. I. Pasichnik, A. M. Maslov, D. I. Kochneva, A. S. Miroshnik, M. M. Chekhovskoy, U. V. Antoniuk, V. N. Ponomarev, Ye. L. Kuzina, A. A. Mashukov, etc.

Comprehensive analysis of works allowed identifying **previously unresolved aspects of the general problem**. The analyzed works do not contain models which allow proposing the measures, which account the essential requirements for sustainable development in the complex to the full extent. Thus, the relevance of the research is determined by the necessity to ensure the efficient functioning of the railways on the way to implementing the concept of sustainable development.

Objectives of the article. The article is aimed to develop a mathematical model of the railway functioning to solve the problem of finding the most efficient variant of the railway functioning from the perspective of sustainable development.

Presentation of the main research. The work [1] proposes a problem statement of sustainable development of the railways which is defined as the problem of determining the optimal distribution of capital investments in the direction of sustainable development. The solution of this optimization problem allows provision of such variant of railway development, at the implementation of which the railway functioning is characterized by the maximal value of the proposed integrating efficiency indicator. An efficient way to solve the problem of finding the rational ways to improve the railway efficiency involves mathematical models.

The railway represents a set of elements (railway stations) with a corresponding complex structure. Mathematically, it is advisable to describe such an object using the apparatus of the set theory [2]. Software implementation of the objects that make up the system is carried out at the class level, at this the properties of the objects are described as the corresponding fields of classes, and the processes of their functioning are implemented in the class method [3].

At the upper hierarchical level, the system represents a set of stations unified by the communication lines, and in the process of functioning they create and ensure the promotion of material flows [4]

$$RW = \{S;\ CL;\ F_M\}, \tag{1}$$

where S is a set of stations of the railways; CL is a set of objects of the communication lines; F_M is material flows circulating in the system.

The station is a subsystem including the group of elements that directly support the processes of promotion of material flow (station tracks, shunting locomotives, the area of cargo handling operations, sorting devices) [5]. The elements of the railway station as a serving system operate in the process of meeting the requirements for transport services, which are formalized in the models like freight train traffic volumes plying between the stations, and arriving at the stations.

At the same time the railway stations are divided into intermediate, district, marshalling and freight ones according to the type and volume of the performed technological operations. Stations of different types have similar basic elements, at the same time types of stations are determined by the presence of certain elements or their different sizes (power).

In the model of a station as a railway subsystem in general terms it is proposed to allocate a set of elements that directly provide the processes of promotion of material flow, as well as the demand for the station services [6]

$$S = \{\Lambda_S;\ \Omega_S;\ L_S;\ S_S;\ D_S\}, \tag{2}$$

where Λ_S is a set of the station tracks; Ω_S is a set of depots located in the territory of the station; L_S is a set of shunting locomotives of the station; S_S is a set of sorting devices of the station; D_S is the demand for the station services.

The absence of any element for the station of a certain type in the station model is represented as the inclusion of the corresponding empty set in the expression (2).

The approach line Λ as a station element is a subsystem of the following hierarchical level, which consists of a set of locomotives serving the approach line, the cargo handling area related to the approach line, and freight depots, served at this approach line. Moreover, the transport demand satisfied by the track resources refers to the model of the approach line. In general, the approach line represents the following set [7]

$$\Lambda = \{L_\Lambda;\ \Omega_\Lambda;\ A;\ D_\Lambda\}, \tag{3}$$

where L_Λ is a set of locomotives serving the approach line; Ω_Λ is a freight depot served at the approach line; A is the cargo handling area of the approach line; D_Λ is the demand satisfied by the track resources of the approach line.

If the shunting locomotives of the station can serve several approach lines, then

$$L_\Lambda = \bigcap_{\Lambda=1}^{N_\Lambda} L_C, \tag{4}$$

where N_Λ is the number of approach lines of the freight station.

The model of the cargo handling area A is formalized as a set of objects of the cargo handling mechanisms, which are part of it

$$A = \bigcup_{i=1}^{N_G} G_i, \tag{5}$$

where G_i is the i-th cargo handling mechanism in the cargo handling area; N_G is the number of cargo handling mechanisms in the cargo handling area.

The model of communication lines between railway stations can be represented as a set of the sections U, the characteristics of which are as follows:

- the length of section L, km;
- the type according to the number of tracks N_t (single-track $N_t = 1$, double-track $N_t = 2$);
- availability of electrification of the section ρ_{el} (non-electrified $\rho_{el} = 0$, electrified $\rho_{el} = 1$);
- the points of transport network, limiting the section: $S^{(1)}$ and $S^{(2)}$.

Thus,

$$CL = \bigcup_{i=1}^{N_{\text{sec}}} U_i, \qquad (6)$$

where U_i is the i-th section of the transport network within the railway

$$U_i = \{L_i, N_{ti}, \rho_{eii}, S_i^{(1)}, S_i^{(2)}\}. \qquad (7)$$

The hierarchy of the objects that are used to describe a complex system during development of the models of its functioning is represented in Fig. 1.

It is advisable to carry out the simulation of railway functioning process at two levels:
- the macro level: simulation of the displacement process of the car traffic volume along the transport network within the railway;
- the micro level: simulation of processing of the car traffic volume at the railway stations.

Model of railway functioning at the macro level. Within the described hierarchy of objects used during simulation of the railway functioning processes, the system model at the macro level can be represented as a directed graph G_{RW} [8]. The graph nodes are objects of the type S – the stations, and the graph links are the objects of the type U – the sections of communication lines (Fig. 2).

The demand for transport services within the transport network is formalized by the matrix of correspondences which displays the volumes of the departure and arrival of freight trains at the freight stations. The elements of the matrix are the values that display the number of freight trains that are dispatched from the i-th freight railway station to the j-th one.

The task of increasing the efficiency of the railway functioning at the macro level is defined as the determination of such a variant of the distribution of the car traffic volumes along the transport network, which will provide minimal total time expenditures T_Σ for displacement of all correspondences

$$T_\Sigma = \sum_{i=1}^{N_c} T_i \to \min, \qquad (8)$$

where T_i is the total time of displacement along the sections of the transport network of the car traffic volume of the i-th correspondence, h; N_c is the number of correspondences.

The solution of the problem (8) is carried out by finding the optimal route for each correspondence. It is advisable to use the Dijkstra's algorithm [8, 9] as the basic method of solution. At this, the passage time along the section of the transport network can be used as the weight values of the graph links. If for the railway transport network it is fair the assumption about the constant value of the average service speed for all links of the network, then it is sufficient to use the lengths of the railway hauls of the transport network as the weight coefficient.

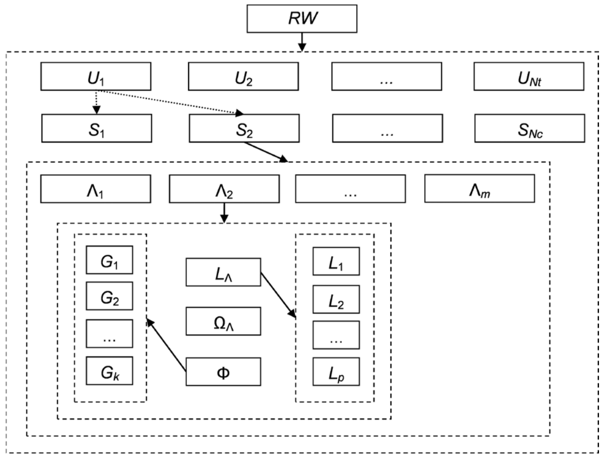

Fig. 1. The hierarchy of complex system objects

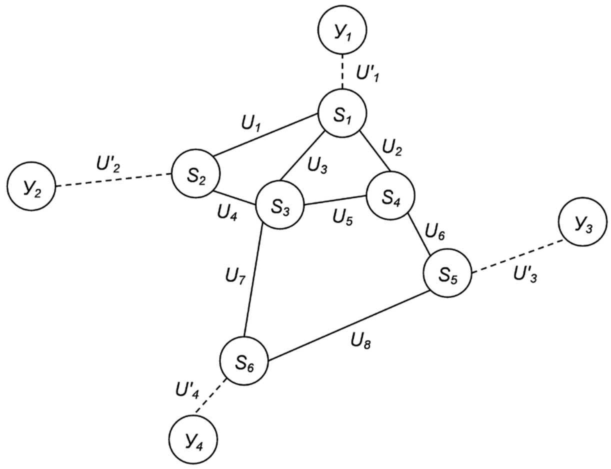

Fig. 2. A fragment of the graph model of the railways

It is advisable to consider the correspondences with the highest values as the priority correspondences (which are considered first of all when determining the route), since the correspondence of smaller capacity can be divided into the longer routes with smaller losses of the total time in the criteria (8). Introduction of prioritization is required due to the limited bandwidth sections of the transport network. The priority ranking is required due to the limited working capacity of the transport network sections. The section of transport network loaded to the limit value of working capacity on the basis of the route determination for the previous correspondences is not considered in the graph model of the transport network in determining the route for the next correspondences.

The vector $\boldsymbol{\lambda} = \lambda_1, \lambda_2, \ldots, \lambda_{N\text{sec}}$, whose elements λ_k represent the values of traffic intensity at the k-th section of the transport network, is a result of solving the task of operational management on the determination of the route for freight trains in the transport network of the railway.

These values are used as a result of network optimization in order to improve the quality of customer service. The values of the vector λ for non-electrified sections of communication lines within the railway can also be used as a criterion to choose the section of transport network for electrification (according to the maximal value of the car traffic volume intensity).

Operation model of the freight technical station. Freight technical stations perform technological operations for processing inbound and outbound material flows. The random variables of the number of freight cars in the supply N_w and interval between car supply ζ [7] are the basic characteristics of the demand to perform the freight station operations. Numerical characteristics Nw and ζ are conditioned by parameters of the matrix of correspondences describing the demand for transport services.

The problem of increasing the efficiency of the railways and providing their sustainable development at the micro level (the level of functioning of the separate stations) is formulated as the determination of the quantitative characteristics of the transport modes of the station.

It is advisable to consider the amount of shunting locomotives of the station N_l and the number of handling mechanisms N_g. as the basic quantitative characteristics of the transport vehicles, which provide the processing of material flow. Then the problem of minimizing the operational costs can be represented as follows

$$E_{op} = E_{lok}(N_l) + E_{hm}(N_g) \to \min, \qquad (9)$$

where $E_{loc}(N_l)$ is the dependence of operational costs for the station locomotive functioning on their quantity; $E_{hm}(N_g)$ is the dependence of the operational costs for the functioning of the handling mechanisms of the station on their quantity.

The technological process of servicing the material flow at the stations is stochastic, which is caused by the influence of a large number of environmental factors on the individual sub-processes. In the model of station operation this fact is taken into account by considering the duration of the certain technological operations as random variables.

Thus, in general terms from the point of view of the system approach the model of functioning of technical freight station is described by the following functional dependence

$$E_{op} = f(N_l, N_g, N_w, \zeta). \qquad (10)$$

The proposed model considers N_l and N_g as control variables, and the incoming influences of the external environment are described by random variables N_w and ζ.

If we consider the process of car traffic volume servicing as the process of servicing the combination of units with similar technical and economic characteristics (or if we use the weighted average values of the technical and economic characteristics) at this to describe the service means we use a similar approach (consider the locomotives as the units with the same technical and economic characteristics), then the mathematical model of the station functioning as part of the railway system takes the following form

$$\begin{aligned} E_{op} = {} & 24 \cdot N_l \cdot c_p^{lok} + 90 \cdot \frac{(c_m^{lok} - c_p^{lok}) \cdot N_l^{0,664} \cdot \xi_q^{0,884}}{\xi_t^{0,885}} + \\ & + 2172 \cdot \frac{c_p^l \cdot \xi_q^{2,527}}{N_l^{0,429} \cdot \xi_t^{1,979}} + 176 \cdot \frac{c_p^e \cdot \xi_q^{0,978}}{N_l^{0,054} \cdot \xi_t^{0,865}} + \\ & + 104 \cdot \frac{(c_m^l + c_m^e) \cdot \xi_q^{1,054}}{\xi_t^{0,961}} + 24 \cdot c_p^m \cdot N_g + \\ & + 48\,704 \cdot \frac{c_p^l \cdot N_l^{0,305} \cdot \mu_\tau^{1,129} \cdot \xi_q^{2,982}}{N_g^{2,368} \cdot \xi_t^{2,698}} + \\ & + 123 \cdot (c_p^l + c_p^m - c_m^m) \cdot \mu_\tau. \end{aligned} \qquad (11)$$

The optimal from the point of view of sustainable development of the railway quantitative characteristics of transport vehicles and handling operations of the stations can be determined on the basis of this model. The optimal number of shunting locomotives of the station and cargo handling machines as part of the handling operations area are defined as the values of the extrema of the function (11) by solving the system of equations

$$\begin{cases} \dfrac{\partial E_{op}}{\partial N_l} = 0 \\ \dfrac{\partial E_{op}}{\partial N_g} = 0 \end{cases}.$$

It should be noted that the problem of determining the optimal quantitative characteristics of transport vehicles and handling operations of the stations is solved by using the results of solving the problem of optimal distribution of freight operation between the railway stations as an input data. At this the principle of hierarchical pattern of planning the process of system functioning is preserved – from the macro level to the level of the separate elements.

The proposed model of railway functioning based on the mathematical apparatus of the theory of sets makes it possible to structure the railway as a complex system. This approach allows us to formulate a number of tasks, the solution of which makes it possible to determine the optimal parameters of the system functioning relative to the components of the integrating efficiency indicator proposed in the work [1].

Conclusions and recommendations for further research. On the basis of the proposed model of railway functioning at the macro level it is possible to solve the problems of optimal distribution of freight operation not only between the stations serving the approach lines of the mining industry, but also between all the railway stations serving the local car traffic volumes. Using the proposed model of operation of the freight technical station at the micro level one can solve the problem of determining the optimal quantitative characteristics of the production capacity of the stations.

In prospect the simulation results can be used as a set of basic data to solve the problem of optimal allocation of capital investments to ensure the most efficient variant for sustainable development of the railways, which is described in the work [10], as well as to solve the problem of increasing the efficiency of interaction between the railway transport and mining enterprises.

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Мета. Забезпечення найбільш ефективного варіанту функціонування залізниць з позиції сталого розвитку.

Методика. Виконано комплексний аналіз робіт в області функціонування підрозділів залізничного транспорту та впровадження принципів сталого розвитку. Це дозволило виділити основні напрями підвищення ефективності функціонування залізниць з позиції сталого розвитку. Розробка моделі функціонування залізниць проводилася з використанням математичного апарату теорії множин і графів, що дозволяють структурувати поняття „залізниця" як складну систему. Показані основні етапи та взаємозв'язки при моделюванні процесів функціонування залізниць на макро- й мікрорівнях.

Результати. Розроблена математична модель процесу функціонування залізниць на двох рівнях: макрорівень – моделювання процесу пересування вагонопотоку по транспортній мережі в рамках залізниці; мікрорівень – моделювання процесу обробки вагонопотоку на станціях у складі залізниці.

Наукова новизна. Адекватний опис процесу функціонування залізниць із позиції сталого розвитку, оснований на апараті теорії множин і графів.

Практична значимість. На базі запропонованої моделі функціонування залізниць на макрорівні можливе рішення завдань оптимального розподілу вантажної роботи не лише між станціями, обслуговуючими під'їзні колії підприємств гірничодобувної промисловості, але й усіма станціями залізниць при обслуговуванні місцевих вагонопотоків. З використанням запропонованої моделі функціонування вантажної технічної станції на мікрорівні вирішується задача визначення оптимальних кількісних характеристик виробничих потужностей станцій.

Ключові слова: *гірничодобувна промисловість, залізничний транспорт, сталий розвиток, математична модель*

Цель. Обеспечение наиболее эффективного варианта функционирования железных дорог с позиции устойчивого развития.

Методика. Выполнен комплексный анализ работ в области функционирования подразделений железнодорожного транспорта и внедрения принципов устойчивого развития. Это позволило выделить основные направления повышения эффективности функционирования железных дорог с позиции устойчивого развития. Разработка модели функционирования железных дорог проводилась с использованием математического аппарата теории множеств и графов, которая позволяет структурировать понятие „железная дорога“ как сложную систему. Показаны основные этапы и взаимосвязи при моделировании процессов функционирования железных дорог на макро- и микроуровнях.

Результаты. Разработана математическая модель процесса функционирования железных дорог на двух уровнях: макроуровень – моделирование процесса передвижения вагонопотока по транспортной сети в рамках железной дороги; микроуровень – моделирование процесса обработки вагонопотока на станциях в составе железной дороги.

Научная новизна. Адекватное описание процесса функционирования железных дорог с позиции устойчивого развития, основанное на аппарате теории множеств и графов.

Практическая значимость. На базе предложенной модели функционирования железных дорог на макроуровне возможно решение задач оптимального распределения грузовой работы не только между станциями, обслуживающими подъездные пути предприятий горнодобывающей промышленности, но и всеми станциями железных дорог при обслуживании местных вагонопотоков. С использованием предложенной модели функционирования грузовой технической станций на микроуровне решается задача определения оптимальных количественных характеристик производственных мощностей станций.

Ключевые слова: *горнодобывающая промышленность, железнодорожный транспорт, устойчивое развитие, математическая модель*

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CONCEPTUAL BASES OF HAUL TRUCKS COMPETITIVENESS FORMATION FOR ROCKS TRANSPORTATION IN OPEN-CUT MINING

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КОНЦЕПТУАЛЬНІ ЗАСАДИ ФОРМУВАННЯ КОНКУРЕНТОСПРОМОЖНОСТІ АВТОСАМОСКИДІВ ДЛЯ ТРАНСПОРТУВАННЯ ГІРСЬКИХ ПОРІД У КАР’ЄРАХ

Purpose. Economical implementation of competitive strengths of haul trucks by the generalization of scientific thoughts, tenets and principles forming a high level of competitiveness of the trucks.

Methodology. Results are received through the application of several methods: critical analysis and systematization were used in order to determine the notion of competitiveness and indexes of quality evaluation; ABC-analysis and mathematical statistics were exploited in order to rank the indexes of competitive strength evaluation depending on technical characteristics of a vehicle; economical and mathematical modeling were applied in order to determine the expenditures concerning the transportation of rocks; finally, the method of network modeling assisted to the optimization of staffing and interrelated projects.

Findings. Special aspects regarding competitive strengths of the haul trucks which are designated for exploitation in open-pit mines were revealed. This identifies technical characteristics of the trucks which are adjusted to special conditions and rules of roach transportation according to the requirements of mining enterprises.

It is demonstrated that practicality concerning the substitution of certain haul truck models and means of developing their competitive strengths should be determined according to the integrated index of competitiveness which is supposed to be calculated as a ratio between group economical indexes and group technical indexes. The economical