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ДЕРЖАВНИЙ УНІВЕРСИТЕТ ІНФРАСТРУКТУРИ ТА
ТЕХНОЛОГІЙ

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ДЕРЖАВНОГО УНІВЕРСИТЕТУ
ІНФРАСТРУКТУРИ ТА ТЕХНОЛОГІЙ

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Determination of the optimal cargo operations strategy of a bulk carrier vessel, with continuous ensuring its seaworthiness

The correct loading of bulk carriers is essential for their maritime safety. Inadequate loading can lead to various risks, including compromised hull strength, reduced stability and violation of the vessel's seaworthiness. Existing shipboard instruments do not allow for timely planning and real-time control of loading operations, which can lead to potential risks. The high intensity of loading operations at dry bulk terminals exacerbates the problem, as there is often insufficient time to adequately prepare and verify loading plans, increasing the risk of overloading cargo holds. To address this problem, the article proposes the development of new methods for bulk carriers cargo operations planning. These methods would optimise the distribution of bulk cargo, taking into account factors such as port facilities, ship design and nautical restrictions of the planned voyage. The aim is to formalise cargo operations in terms of a mathematical model of the vessel and to establish functional relationships between parameters that affect the seaworthiness of the vessel. By analysing the relationships between different parameters, the researchers aim to determine the best strategy for cargo operations that will ensure the continuous seaworthiness of the bulk carriers. This approach would help to improve bulk carrier's safety and reduce the risks associated with incorrect loading. The development of such methods is seen as a promising area of scientific research that can enhance the safety of those vessels. By determining the best strategy for cargo operations based on the criterion of continuous seaworthiness, it aims to prevent the deterioration of the vessel's structural integrity and ensure that the vessel remains in a seaworthy condition throughout the loading process. The article emphasizes the need for scientific research in this area to enhance the safety of bulk carriers and proposes the development of new methods based on mathematical modeling to optimize cargo operations and maintain the vessel's seaworthiness throughout the process.

Keywords: bulk carrier, maritime safety, cargo operations, optimisation, permissible loading, ship stability, the vessel strength.

Introduction. Maritime safety includes maintaining the acceptable limits of a ship's seaworthiness parameters. These parameters are maintained by proper loading of the vessel during cargo operations. The stability and strength criteria apply to all categories of vessels and are defined in the conventions of the International Maritime Organisation (IMO). Cargo handling in ports has a significant impact on the safety of shipping, especially for bulk carriers.

Statement of the problem and analysis of recent research. The seaworthiness is an abstract concept used in maritime law that indicates how safe and ready a vessel is to sail. In the broadest sense, seaworthiness means the fitness of the vessel to meet the ordinary hazards contemplated for the voyage. The concept of seaworthiness also extends to the fitness of the vessel to receive, carry and care for its intended cargo. Regular inspections must be carried out to ensure that the highest standards are

maintained on board the vessel at all times. If shipowners are found to be negligent, they will face severe action.

In accordance with the International Convention for the Safety of Life at Sea (SOLAS), it is mandatory for a vessel's crew to carefully plan and execute loading operations to ensure that the vessel remains seaworthy throughout the process and ready to sail at any stage of port operations.

To ensure the seaworthiness of dry bulk carriers, each ship is designed by the shipbuilder with specific guidelines for loading options. These guidelines are set out in the loading manual or in specialised computer loading programs, which enable the ship's seaworthiness parameters to be assessed on the basis of the loading option selected. It is the responsibility of the ship's cargo officer to determine the most suitable loading option within the ship's allowable stability and strength parameters.

However, existing documentation for typical ship cargoes covers only a limited range of loading scenarios and may not cover all possible loading situations or the specific requirements of a particular voyage. As a result, finding the optimal cargo plan can require considerable effort on the part of the ship's personnel. In the fast-paced environment of modern dry bulk terminals, where time constraints often prevent thorough preparation and verification of new cargo plans, there is an inherent risk of overloading individual cargo holds. This can compromise the local and longitudinal strength of the hull and ultimately the seaworthiness of the ship. The use of modern computer technology makes it possible to calculate the permissible ship loading, taking into account the restrictions of the seaworthiness criteria, provided that the ship loading process is formalised and loading algorithms and programs are developed.

A method (strategy) should be developed for the optimal distribution of a given amount of dry bulk cargo, taking into account the available port cargo facilities and the design characteristics of the vessel itself, while maintaining the parameters of its draft, trim, stability and overall longitudinal strength.

The development of such a method should be based on theories of systems analysis and operations research as well as mathematical modelling tools.

To solve this problem, it is necessary to formalise the cargo operations in terms of a mathematical model of the ship and to identify the functional relationship between the parameters that affect the seaworthiness of the vessel.

Clearly, the development of this method is a relevant and promising area of scientific research aimed at ensuring the safety of bulk carriers.

The subject of maritime safety in relation to bulk carriers is examined in the next sources [1-3].

The International Maritime Organisation (IMO) has established conventions that provide guidelines for the planning and execution of bulk carrier cargo operations [4-7].

An important resource for understanding the safe operation of bulk carriers is the knowledge and experience of seafarers actively involved in this field [8-11].

Gaichenya O.V. and Klimenko E.N. proposed the application of systems analysis and operations research principles to the cargo operations of bulk carriers and multipurpose vessels [12, 13].

The authors Tsybal M.M. and Vaskov Y.Y. [14, 15] introduce mathematical models aimed at optimising the loading processes of bulk carriers and solve this problem by applying linear programming techniques.

The study presented in [16] focuses on the selection of a specific selection of bulk carrier cargo holds for efficient loading of bulk cargoes. It outlines a method for structuring the stages of bulk carrier loading operations when dealing with non-standard loads.

The aim of this article is to examine the potential methods for determining acceptable variations in ship loading that comply with the constraints imposed by maritime safety parameters. While complying with the general requirements for maritime safety, different types of ships have additional specifications based on their design or cargo carrying technology.

Consequently, specific requirements are imposed on general cargo vessels when loading general cargo. These requirements mainly include ensuring compatibility of cargoes within a single cargo space, accommodating a large number of cargoes for transportation, adhering to a specific sequence of ports for discharge and limiting the number of cargo levels based on the strength of the cargo packaging.

Bulk carriers have more stringent loading requirements due to their considerable length. These requirements are imposed by the overall longitudinal and local strength of the ship's hull, which affects various aspects of cargo operations. In particular, bulk carriers typically carry out cargo and ballast operations simultaneously. These operations are carried out in several stages (up to twenty), depending on the number of holds to be handled simultaneously and the specific cargo volume.

Shipbuilders usually provide specific loading manuals for bulk carriers, tailored to the cargo volume and number of holds involved. These manuals focus exclusively on a single type of cargo to be loaded. Each manual outlines a sequence of loading stages, specifying which holds are to be loaded, the corresponding cargo increments and the combination of tanks used for ballast operations. At the end of each stage, the ship must be in an acceptable seaworthy condition.

Difficulties arise when dealing with non-standard loading situations not covered by the shipbuilder's instructions. The planning and execution of cargo operations in such cases becomes challenging, as it is necessary to ensure the seaworthiness of the vessel and optimise the utilisation of cargo space and deadweight capacity. Shipowners are forced to develop a series of steps that address the problem of maximising cargo placement in the holds while taking into account the simultaneous handling of the required group of ballast tanks. Compliance with numerous seaworthiness restrictions becomes a critical aspect in these scenarios.

In order to build a mathematical model for optimising the loading process of a bulk carrier, it is necessary to formalise it, which systematises complex various processes associated with cargo and ballast operations.

To describe the loading process of a vessel, it is necessary to define a set or space of its states U , and each specific loading state of a vessel u belonging to this set U should be defined as a set of parameters of the vessel's seaworthy parameters, which depend on the distribution of cargo in holds and ballast and reserves in tanks and vessel's compartments. Thus, each specific loading state of a vessel u can be accepted as a certain variant of the distribution of cargo, ballast and supplies to the respective holds, tanks and spaces.

Each vessel's condition u can be analytically expressed as follows.

$$u = \{w_{ci}, w_{bi}, w_{zi}\}, \quad (1)$$

where w_{ci} – is the weight of cargo in the i -th cargo space;

w_{bi} - is the weight of ballast in the i -th ballast tank;

w_{zi} - weight of stores in the i -th tank or storage space;

$i = 1, 2, \dots, n$ - number of cargo spaces, ballast tanks and storage spaces, respectively.

Thus, the state of the vessel u can be represented as an n -dimensional vector, the number of elements of which is equal to the total number of cargo holds, ballast tanks and storage spaces involved in the cargo operations. The weight loads w_{ci} , w_{bi} , w_{zi} in the vessel's state vector are defined by upper limits \bar{w}_{ci} , \bar{w}_{bi} , \bar{w}_{zi} determined by the cargo holds and ballast tanks capacity, as well as the local strength of the cargo spaces, and act as limiters for technological parameters.

The vessel loading process is thus a vector trajectory $u(t)$ in the space of possible states U . Moreover, the space of states U is n -dimensional with a finite value (constraints on technological parameters) along each dimension.

On the other hand, the loading of a vessel is characterized by its seaworthiness, which can be described by the vector S_u , whose components are the parameters of vessel's draught, trim, stability and strength.

Mean draught T_m , trim t and heel angle θ are important parameters of a vessel's seaworthiness.

The mean draught T_m is a function of the vessel's displacement W of the vessel and the density of the supporting water ρ , i.e:

$$T_m = f(W, \rho) \quad (2)$$

This dependence is presented in a tabular or graphical form in the "Information on the stability and strength of the ship" (Loading manual).

The displacement of the vessel W is the sum of the weight of the empty vessel w_0 , the weight of the vessel's stores (fuel, oil, water) w_s , including the weight of equipment, provisions and crew, the weight of cargo w_c and the weight of ballast w_b , and is expressed by the following equation:

$$W = w_0 + w_s + w_c + w_b. \quad (3)$$

The vessel's trim t is determined by the following analytical expression:

$$t = \frac{W(x_G - x_B)}{\bar{M}}, \quad (4)$$

where W - the displacement of the vessel;

x_G, x_B - abscissas of the centre of gravity and the centre of buoyancy, respectively;

\bar{M} - is the moment trimming the vessel by 1 cm.

The difference $x_G - x_B$ represents the shoulder of the pair of forces (i.e. the equal-action forces of weight and support forces) and expresses the distance measured horizontally between the centre of gravity and the centre of buoyancy.

The value of the centre of gravity x_g abscissa is calculated using the formula

$$x_g = \frac{M_x}{W}, \quad (5)$$

where M_x - is the vessel's static moment of mass relative to the centre of gravity of the waterline plane; W - the displacement of the vessel.

The static moment of mass of a vessel relative to the centre of gravity of the waterline plane is calculated using a formula which takes into account the components of the moment from an empty vessel, the ship's constant, the ship's reserves, cargo and ballast

$$M_x = w_0 x_0 + \sum_{i=1}^n w_{si} x_{si} + \sum_{i=1}^n w_{ci} x_{ci} + \sum_{i=1}^n w_{bi} x_{bi}, \quad (6)$$

where w_0 - the weight of the empty vessel;

w_{si} - the amount of ship's stores in the i -th storage space;

w_{ci} - the amount of cargo in the i -th hold;

w_{bi} - the amount of ballast in the i -th tank;

x_0 - the abscissa of the centre of gravity of an empty vessel;

x_{si} - the abscissa of the centre of gravity of the vessel's supplies in the i -th compartment;

x_{ci} - the abscissa of the centre of gravity of the cargo in the i -th hold;

x_{bi} - the abscissa of the centre of gravity of the ballast in the i -th tank;

$i=1, 2, \dots, n$ - number of cargo spaces, ballast tanks and storage spaces respectively.

The abscissa of the centre of buoyancy x_B is a function of the mean draft, i.e. displacement W and density of the water in which the vessel is situated ρ

$$x_B = f(W, \rho), \quad (7)$$

This dependency is usually presented in tabular form in the Loading manual, which is usually prepared by the shipbuilder for each particular vessel.

The value of the moment that trimming the vessel by 1 cm \bar{M} also depends on the mean draft and is a function of displacement W and density of the water ρ

$$\bar{M} = f(W, \rho). \quad (8)$$

Ship stability is the ability of a vessel to withstand external forces that disturb its equilibrium and to return to its original equilibrium position when these forces cease to act. It is one of the most important seaworthiness characteristics of a vessel.

The vessel's stability is characterised by the following parameters: initial metacentric height h , the capsizing moment of the ship M_{cap} , maximum righting lever of the static stability curve l_{max} , the angle of the static stability curve maximum θ_{max} , the angle of stability curve vanishing θ_{min} .

The initial metacentric height h is determined by the following expression

$$h = z_m - z_g + \Delta h, \quad (9)$$

where, z_m and z_g are the applicate of the transverse metacentre and the centre of gravity, respectively; Δh - correction to the initial metacentric height in the presence of free surfaces of liquid stores and ballast.

The metacentre applicate z_m depends on the mean draft of the vessel. This dependence is expressed in a tabular form in the vessel's documents.

The centre of gravity applicate z_g depends on the static moment of mass M_z relative to the vessel's main plane and displacement and is calculated using the formula

$$z_g = \frac{M_z}{W}, \quad (10)$$

The value of the static moment M_z is determined by the following expression

$$M_z = w_0 z_0 + \sum_{i=1}^n w_{si} z_{si} + \sum_{i=1}^n w_{ci} z_{ci} + \sum_{i=1}^n w_{bi} z_{bi}, \quad (11)$$

where w_0 - the weight of the empty vessel;

w_{si} - the amount of ship's stores in the i -th storage space;

w_{ci} - the amount of cargo in the i -th hold;

w_{bi} - the amount of ballast in the i -th tank;

z_0 - the applicate of empty ship's centre of gravity;

z_{si} - the applicate of ship's stores in the i -th storage space;

z_{ci} - the applicate of cargo in the i -th hold;

z_{bi} - the applicate of ballast in the i -th tank;

$i=1, 2, \dots, n$ - number of cargo spaces, ballast tanks and storage spaces respectively.

The parameters characterising stability can be obtained from static and dynamic stability diagrams. The static and dynamic stability curves are plotted along the static stability levers corresponding to certain heel angles of the ship. The static stability levers can be obtained either by means of a universal stability curve or by using Cross Curves of Stability (KN curves) provided in the ship's documentation.

The levers of the static stability curve, as well as the curve itself, depend on the displacement W , the density of the water supporting the vessel ρ and the static moment M_z . The values of the capsizing moment M_{cap} , the angle of the static curve vanishing θ_{min} , the maximum righting lever l_{max} and the

corresponding heel angle θ_{max} which can be obtained from the static stability curves, are also functions of displacement, water density and static moment.

The constant heel angle of the ship θ depends mainly on the static moment of the masses relative to the diametrical plane of the vessel M_y , which is given by the following expression

$$M_y = w_0 y_0 + \sum_{i=1}^n w_{si} y_{si} + \sum_{i=1}^n w_{ci} y_{ci} + \sum_{i=1}^n w_{bi} y_{bi}, \quad (12)$$

where, w_0 - the weight of the empty vessel;

w_{si} - the amount of ship's stores in the i -th storage space;

w_{ci} - the amount of cargo in the i -th hold;

w_{bi} - the amount of ballast in the i -th tank;

y_0 - the ordinate of the centre of gravity of an empty vessel;

y_{si} - the ordinate of the centre of gravity of ship's stocks in the i -th storage space;

y_{ci} - the ordinate of the centre of gravity of cargo in the i -th hold;

y_{bi} - the ordinate of the centre of gravity of ballast in the i -th tank;

$i=1, 2, \dots, n$ - number of cargo spaces, ballast tanks and storage spaces respectively.

The following functional dependence of the heel of the vessel can be written down

$$\theta = f(W, \rho, M_z, M_y). \quad (13)$$

The strength parameters include the shear forces SF_i and bending moments BM_i in the i -th section of the hull resulting from the vessel's loading, and the local strength P_i of the i -th cargo hold.

When calculating the strength of a vessel's hull, the vessel own weight and water support forces acting on the vessel are taken into account. The vessel's weight forces acting on the hull are represented in the form of two components - the weight forces of the hollow vessel and the weight forces from the loads that constitute the deadweight.

In this case, the bending moments BM_i and shear forces SF_i for each section of the vessel are expressed as the sum of three components

$$BM_i = BM_0 + BM_w + BM_s, \quad (14)$$

$$SF_i = SF_0 + SF_w + SF_s \quad (15)$$

where BM_i, SF_i - bending moments and shear forces in the i -th section of the vessel;

BM_0, SF_0 - components of bending moment and shearing force from the weight of the empty vessel;

BM_w, SF_w - components of the bending moment and shear force, respectively, from the loads included in the deadweight;

BM_s, SF_s - components of the bending moment and shear force, respectively, due to the action of support forces.

The components of the bending moment and shear force due to the weight of the empty vessel for each monitored section are constant and are given in the ship's documentation. The components of the bending moment and shear force from the loads included in the deadweight are determined by the arrangement of cargo in holds, ballast in tanks and stores in the relevant vessel spaces and tanks, and are calculated in tabular form using elementary relations.

To calculate the components of the shear force and bending moment due to support forces, the vessel's Loading manual contains information in the form of tables or graphs.

The local strength P_i is characterised by the ratio of the amount of cargo received to the area of the cargo space in which the cargo is stored. The ship's documentation specifies the permissible loads per square metre of cargo hold and upper deck.

Thus, the maritime safety vector S_u can be formally expressed as follows

$$S_u = (T_m, t, \theta, h, M_{cap}, l_{max}, \theta_{max}, \theta_{min}, SF_i, BM_i, P_i), \quad (16)$$

The vector is characterised by a range of permissible values determined by IMO or classification society requirements for the values of the landing, stability and strength parameters.

Ship cargo operations can be considered as an optimisation task. It is necessary to consider the restrictions that may be imposed when setting an optimisation task.

There are two categories of restrictions that apply to the loading of a vessel and the determination of permissible loads. The first category consists of general restrictions that are applicable to all types of vessels and are intended to ensure the seaworthiness of the vessel. The second category consists of specific restrictions that are unique to each type of vessel.

Let's focus on the first category of restrictions, which are designed to ensure the seaworthiness of the vessel. These restrictions mainly concern the draft of the vessel, which includes the mean permissible draft T_m and the permissible limits of its trim t . In most cases, restrictions on the heel θ of the vessel are also included in this category. However, it is common practice for the ship's crew to minimise the heel of the vessel during cargo operations, so separate restrictions for heel may not be necessary.

Limits on the mean permissible draft T_m arise from a number of factors, including the International Load Line Convention, shipbuilders' specifications, current voyage draft limits and the need to maintain minimum necessary forward and aft draughts to avoid slamming or propeller exposure. These considerations impose restrictions on T_m , resulting in limitations on its value.

$$T_{min} \leq T_m \leq T_{max}, \quad (17)$$

where T_{min} and T_{max} - respective, the lower and upper limits of the mean vessel draft T_m .

The lower limit for a vessel's trim t_{min} can be set to zero to avoid having a bow trim which would complicate ballast operations and cargo calculations. On the other hand, the upper limit t_{max} is determined by various factors such as ballast and liquid measurement tables, operational limitations of the ship's equipment and the seaworthiness of the vessel. The limitation on the vessel's trim can be defined as follows

$$t \in [0, t_{max}]. \quad (18)$$

The limitations that ensure the necessary stability of the vessel are primarily defined by the limitation of the initial metacentric height h , as expressed in equation

$$h_{min} \leq h \leq h_{max}. \quad (19)$$

In this equation h_{min} and h_{max} represent the lower and upper limits of the initial metacentric height, respectively. In addition, the minimum value of h_{min} is determined by the International Maritime Organisation (IMO) requirements for the initial stability of ships.

Several parameters related to vessel stability, such as the capsizing moment of the vessel M_{cap} , the maximum arm of the static stability curve l_{max} , the angle of heel of the vessel at which the maximum arm occurs θ_{max} and the angle of vanishing stability θ_{min} , are derived from the static stability curve. The values of these parameters are also subject to restrictions imposed by the IMO regulations for the initial stability of vessels, denoted as M_{cap}^{imo} , l_{max}^{imo} , θ_{max}^{imo} and θ_{min}^{imo} respectively.

The third set of parameters relates to the overall longitudinal strength of the vessel and is represented by the maximum allowable values of bending moments BM_i and transverse shear forces SF_i for each control section of the vessel.

All the restricted parameters that define the seaworthiness of the vessel $T_m, t, h, M_{cap}, l_{max}, \theta_{max}, \theta_{min}$ depend on the displacement, the longitudinal static moment M_x and the vertical static moment M_z of the vessel. Consequently, the longitudinal moment M_x is related to the vessel's trim t , bending moments BM_i and shear forces SF_i , while the moment M_z is related to the initial metacentric height h and the characteristics of the static stability curve $M_{cap}, l_{max}, \theta_{max}, \theta_{min}$.

Taking into account the prescribed values for $t_{max}, h_{max}, h_{min}, M_{cap}^{imo}, l_{max}^{imo}, \theta_{max}^{imo}, \theta_{min}^{imo}, BM_i, SF_i$ which express the requirements for the seaworthiness of the vessel, it is possible to determine the limiting values for the displacement of the vessel W_{max} , the minimum M_x^{min} and maximum M_x^{max} longitudinal moments and the upper M_z^{min} and lower M_z^{max} limits of the vertical moment.

Let's consider, W', M'_x, M'_z as the displacement and static moments that occur in a selected loading configuration of the vessel. It is clear that certain loading configurations satisfy the following conditions

$$\begin{cases} W' \leq W_{max}; \\ M'_x \in [M_x^{min}, M_x^{max}]; \\ M'_z \in [M_z^{min}, M_z^{max}]. \end{cases} \quad (20)$$

These loading configurations must fall within the range of permissible loads set U based on maritime safety requirements. However, it is important to note that there may be specific restrictions that are unique to a particular type of ship. These restrictions may limit the loading possibilities within the allowable set of options U .

From a maritime safety perspective, it is crucial to consider not only the seaworthiness of a vessel at the final stage of the loading process t_{fin} , but also the current state of the ship at each stage t_{cur} , from the start of loading to its completion. This requires strict adherence to a number of limitations within the system.

$$\begin{cases} W'(t_{cur}) \leq W_{max}; \\ M'_x(t_{cur}) \in [M_x^{min}, M_x^{max}]; \\ M'_z(t_{cur}) \in [M_z^{min}, M_z^{max}]; \\ t_{cur} \in [0, t_{fin}], \end{cases} \quad (21)$$

where t_{fin} - the moment at which the ship's cargo operations are finished.

When formulating the optimisation problem for cargo operations, it is important to consider additional specific limitations that take into account the unique characteristics of different types of vessels. For example, when dealing with bulk carriers, the following constraints should be considered:

1. The number of port cargo facilities involved in handling the vessel.
2. The number of stages involved in loading and unloading the vessel.
3. The number of holds and ballast tanks used for cargo and ballast operations at each stage.
4. The amount of cargo to be handled for each hold and the amount of ballast required for each tank.

5. Cargo and ballast operations speed variations at each stage.

These limitations, together with the requirements to ensure the seaworthiness of the ship, are essential factors in formulating the optimisation problem.

Conclusions. The article presents a methodology for determining an acceptable range of vessel loads. This approach allows the selection of an optimum strategy for carrying out cargo operations, with the emphasis on maintaining the seaworthiness of the ship at all times. The key objective is to ensure that the ship's seaworthiness parameters, in particular stability, overall longitudinal and local strength, remain within acceptable limits throughout the period of cargo operations. By carefully managing the variations in cargo and ballast, it is possible to achieve continuous compliance with these critical parameters.

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Пошук оптимальної стратегії вантажних операцій навіювального судна за умови постійного збереження його морехідних якостей

Безпека мореплавства є важливим аспектом морської індустрії. Забезпечення параметрів морехідної безпеки судна в допустимих межах на протязі всього рейсу, у тому числі і під час вантажних операцій, є одним із ключових елементів цієї безпеки. Міжнародна морська організація (ІМО) розробила конвенції, які встановлюють універсальні вимоги до морехідної

безпеки суден. Одна з таких конвенцій - Міжнародна конвенція з безпеки людей на морі (СОЛАС), яка містить вимоги до планування та проведення вантажних операцій з метою забезпечення безпеки судна. СОЛАС вимагає, щоб судновий персонал планував і проводив вантажні операції таким чином, щоб судно завжди відповідало критеріям мореплавства. Для навалювальних суден (балкерів) існують підвищені вимоги щодо морехідної безпеки і на сам перед вони стосуються їх остійності та повздоанької міцності. Для забезпечення морехідності навалювальних суден суднобудівник розробляє інструкцію зі стандартних варіантів завантаження (Loading Manual) та спеціальні комп'ютерні програми завантаження судна. Ці інструменти дозволяють оцінити параметри морехідності судна залежно від обраного варіанту завантаження. Однак існуюча суднова документація не охоплює всі можливі ситуації завантаження, різноманітність номенклатури вантажів і специфіку майбутнього рейсу. Однак існуюча суднова документація не охоплює всі можливі ситуації завантаження, різноманітність номенклатури вантажів і специфіку майбутнього рейсу. Для ефективного визначення оптимальних варіантів завантаження суден, повинні використовуватись методи, що дозволять автоматично моделювати вантажні операції та оцінювати параметри морехідності судна. Ці методи повинні враховувати різноманітні фактори, такі як технічні особливості самого судна, характеристики вантажів та умови рейсу. Метою даної статті є аналіз можливостей визначення допустимих варіантів завантаження навалювального судна, які задовольняють обмеженням, що накладаються параметрами морехідної безпеки, а також формалізація вантажних операцій у вигляді математичної моделі судна та встановлення функціональних зв'язків між параметрами, що впливають на морехідні якості судна. Дотримання параметрів остійності та міцності судна в допустимих межах на всіх етапах його рейсу є критичним для запобігання аваріям та збереження життя та майна на морі.

Ключові слова: навалювальне судно, морехідна безпека, вантажний план, оптимізація, остійність, міцність судна.

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Analysis of shunting locomotive operating modes when performing traction tasks

The paper considers the modes of operation of shunting diesel locomotives ČME3 when performing traction tasks at the service areas of the locomotive depot Koziatyn. A mathematical model of train movement with a ČME3 diesel locomotive has been developed, which has been used to solve a series of traction problems. It was found that the operating modes of a diesel engine are most influenced by the profile of the track section. It is determined that when moving from the Koziatyn station, the relative duration of the traction mode is 14...39% of the total movement time. When moving in the direction of the Koziatyn station, the relative duration of the traction mode is 28...90%. In the traction mode, the diesel engine operates at rated power. For the examined sections of the movement, we evaluated the diesel fuel consumption for a serial diesel locomotive, a diesel locomotive with a modern diesel engine, and a battery locomotive charged from an onboard diesel generator set. It has been determined that a diesel locomotive with a modern diesel engine consumes 18...22% less fuel than a standard diesel locomotive. In the case of a battery locomotive, fuel consumption can be either lower or higher compared to a diesel locomotive with a modern diesel engine. At the same time, the accumulation of energy in the onboard energy storage device during electrodynamic braking and its use in traction modes helps to reduce fuel consumption.

Key words: shunting locomotive, modernization, energy efficiency, energy storage, traction task

Introduction. Railway transport is a key element in the transportation system of Ukraine. According to [1, 2], in 2009-2021, about 46...60% of all freight transportation was carried out by rail. The main negative factor affecting rail transportation is the deterioration of rolling stock, in particular, locomotives. The inventory park of locomotives exceeds the number of locomotives required for transportation, but the technical characteristics of outdated locomotives are worse than those of modern locomotives [3]. This leads to higher costs for fuel and energy resources, maintenance and repair. At the same time, there is an increase in the cost of work required to ensure the proper technical condition of locomotives [3]. The solution to the problem lies in the renewal of traction rolling stock both by modernizing existing locomotives and purchasing new ones.

Analysis of recent research and problem statement. The use of shunting diesel locomotives for traction and transfer operations is a well-established practice on railways. At JSC "Ukrzaliznytsia", diesel locomotives of the ČME3 series are used for these types of work [4]. Although the wear and tear of the park of these diesel locomotives is 100%, for some locomotives it is possible to extend the service life of the bearing structures by 10-15 years [5]. Therefore, such diesel locomotives are widely used for deep modernization with the use of a modern diesel engine, AC-DC electric power transmission, electric drive of fan motors and compressor, microprocessor control system, etc. In Ukraine, such modernization was carried out at Poltava Locomotive Repair Plant LLC [6]. Similar projects have been implemented at the Vilnius Locomotive Repair Depot and in the CIS countries. In general, deep modernization is widely used to upgrade shunting locomotives of various types [7,8]. According to the results of the operation of modernized diesel locomotives, fuel consumption reduces by 30...45% depending on the type of operation [9].

At the same time, many researchers note that the use of a diesel engine close in power to the original one is redundant. Numerous results of observations of the operating modes of diesel generator sets of shunting locomotives show that the duration of their idling operation is at least 50% of the total operating time [10, 11]. When performing shunting operations at the station, the power of the traction generator varies in the range of 50...250 kW [10]. In traction operations, the rated power of a diesel engine is required for acceleration and uphill driving, but the duration of these driving modes is insignificant [12]. At the same time, when using a lower power diesel engine, the train dynamics will be unsatisfactory.

Therefore, it is considered expedient to use a power plant on shunting diesel locomotives, the structure and parameters of which most closely correspond to the operating modes of the locomotive. In [13-15], the expediency of using hybrid power plants in the modernization of the ČME3 diesel locomotive was proposed and substantiated. A possible option is to use a power plant based on several diesel engines [16]. Paper [13] summarizes the results of the author's research on the selection of parameters of a hybrid shunting locomotive power plant when using a modern diesel engine and an onboard energy storage device. In [14], the author presents the results of research using an energy storage device on an original diesel locomotive, in particular, an assessment of the reduction of harmful emissions. In both cases, the researches are carried out with the use of original collector traction motors. Paper [15], which summarizes the author's work, investigates a traction system based on AC electric machines. These works mainly investigate the modes of movement of a locomotive on a run. Papers [10, 11] analyze the modes of operation of the ČME3 diesel locomotive when performing shunting operations at the station. Taking into account the fact that shunting diesel locomotives are used for both types of operations - shunting and transferring - it seems advisable to conduct further research, the results of which will allow creating an efficient locomotive.

Purpose and objectives of the study. The purpose of the study is to investigate and analyze the parameters of shunting locomotive operation modes when performing traction tasks. The goal is achieved by mathematical modeling to solve a series of traction problems and analyze their results.

Materials and methods of research. The study of shunting diesel locomotives operating modes is usually carried out by processing data from onboard diagnostic systems, fuel metering BIS-R, etc. Such systems record only a part of the data, which makes it difficult to comprehensively assess the parameters of the locomotive's operating mode. The use of specialized measuring systems [11] solves this problem, but requires additional equipment. It should be noted that this approach is used mainly to record the parameters of operating modes during regular operation. An alternative approach is the use of mathematical modeling, which allows conducting experiments that determine the impact of certain factors on the performance of a locomotive [12]. Of course, mathematical models must provide an acceptable level of convergence.

The modeling of train movement is carried out in accordance with the provisions of the theory of traction using methodological materials for traction calculations [19,20].

The mathematical model of a train with a ČME3 diesel locomotive is based on the model given in [21].

The system of equations of motion has the form

$$\begin{cases} \frac{dV}{dt} = \frac{\xi}{\rho} (f_L - (w_L + w_W) - b) \\ \frac{dS}{dt} = V \end{cases}, \quad (1)$$

where is ξ – coefficient that takes into account the units of measurement;

V – train speed;

t – time;

S – distance;

ρ – coefficient that takes into account the rotation of the crew unit;

f_L – specific tangential force of the locomotive in the mode of traction or electrodynamic braking;

w_L – specific drag force of the locomotive;

w_W – specific drag force of the railcars;

b – specific braking force of the pneumatic brakes.

The specific tangential force of the locomotive in the mode of traction or electrodynamic braking was determined by the equation

$$f_L = \frac{F_L}{\sum_{k=1}^s M_{Lk} + \sum_{j=1}^n M_{Wj}}, \quad (2)$$

where is F_L – the tangential force of the locomotive in the mode of traction or electrodynamic braking;

M_{Lk} – the mass of the locomotive;

s – the number of locomotive sections;

M_{Wj} – the mass of the wagon;

n – the number of wagons.

The tangential force is defined as

$$F_L = \begin{cases} F_{DCP}(V), & V \leq V_{\max} - \Delta V \\ -B_{DCP}(V), & V > V_{\max} \end{cases}, \quad (3)$$

where is $F_{DCP}(V)$ – traction characteristics that correspond to the current position of the driver's controller;

$B_{DCP}(V)$ – braking force dependence on speed.

The control modeling used the positions presented in [12]. The shunting diesel locomotive ČME3 has 8 deterministic traction characteristics [22]. Operation on each of the characteristics is set by the position of the driver's controller. The mathematical description of the driver's controller switching is as follows

$$DCP = \begin{cases} DCP + 1, & V \leq (V_{\max} - \Delta V) \\ 0, & V > (V_{\max} - \Delta V) \end{cases}, \quad (4)$$

where is DCP – position number of the driver's controller.

The traction characteristics at each position of the driver's controller are taken from the technical documentation for the locomotive.

In the electrodynamic braking modes, it is assumed that braking is performed with a tangential power of 1000 kW at speeds that correspond to the mode of operation on a hyperbola of equal power. The limit braking force is assumed to be 300 kN. This roughly corresponds to the braking properties of the ČME3T diesel locomotive and modernized diesel locomotives.

The specific drag of the locomotive and railcars was determined by the equation

$$w = w_o + w_i + w_r + w_b, \quad (5)$$

where is w_o – basic specific resistance to movement;

w_i – additional specific resistance to movement due to slope;

w_r – additional specific resistance to movement due to movement along a curve;

w_b -additional specific resistance when starting additional specific resistance when starting.

The calculation expressions for determining the resistivity and recommendations for use are given in [19,20]. The train is modeled as a system of solids connected by rigid links, so the additional resistivity due to slope and curve movement is determined for each railcar or locomotive separately. A railcar or locomotive is considered to be on a track profile element if its center of mass is on that element.

The tangential power was determined by the equation

$$P_L = F_L V. \quad (6)$$

Mechanical work "on the wheel" in the traction mode is determined by the equation

$$E_T = \sum_{i=1}^n \int_0^{t_i} P_{Li}(t) dt, \quad (7)$$

where is t_i – the duration of the i -th traction mode.

Mechanical work "on the wheel" in the electrodynamic braking mode is determined by the equation

$$E_T = \sum_{j=1}^n \int_0^{t_j} P_{Lj}(t) dt, \quad (8)$$

where is t_j – is the duration of the j -th mode of electrodynamic braking.

The train traffic was modeled on the sections Koziatyn-I-Popilnia, Koziatyn-I-Kalynivka, and Koziatyn-I-Berdychiv. These sections are serviced by diesel locomotives ČME3 of the locomotive depot of Koziatyn. The profile of the section Koziatyn-I-Popilnia with a total length of 55.9 km is shown in Fig. 1a, the profile of the section Koziatyn-I-Kalynivka (length - 39.4 km) - in Fig. 1b, the profile of the section Koziatyn-I-Berdychiv (length - 26.6 km) - in Fig. 1c.

As can be seen from Fig. 1, the peculiarity of the sections is that Koziatyn-I station is located higher than the adjacent stations and, in general, traffic from Koziatyn-I station will be carried out on slopes with localized ascents. The modeling was carried out with different number of railcars at different permissible speeds - 40 and 60 km/h.

The relative duration of operation of the DGU under load was determined by the equation

$$t'_t = \frac{t_t}{t_a} 100\% \tag{9}$$

where is t_t – total duration of traction modes;

t_a – total duration of movement.

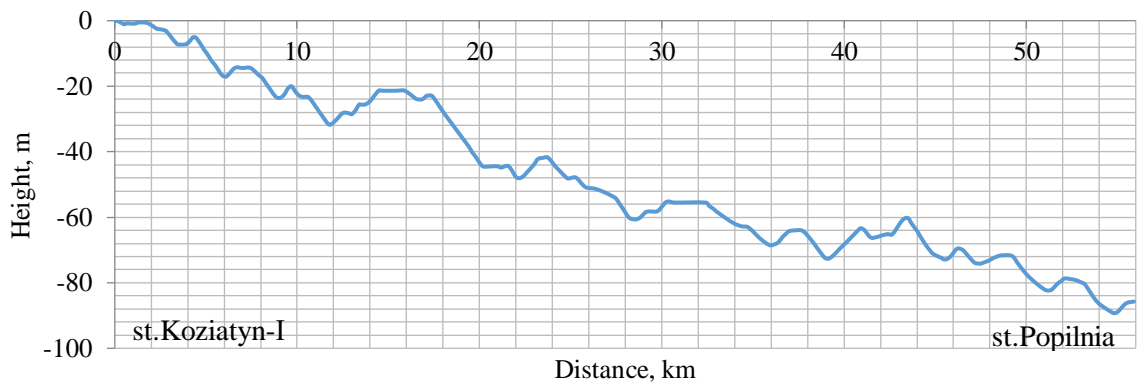
The relative duration of idle operation of the DGU was determined by the equation

$$t'_n = \frac{t_b + t_c}{t_a} 100\% \tag{10}$$

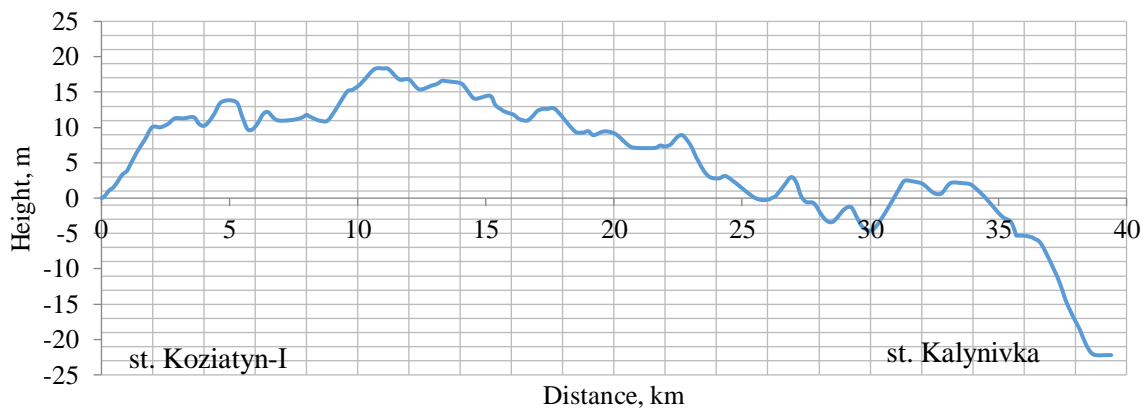
where is t_b – total duration of electrodynamic braking modes;

t_c – total driving time.

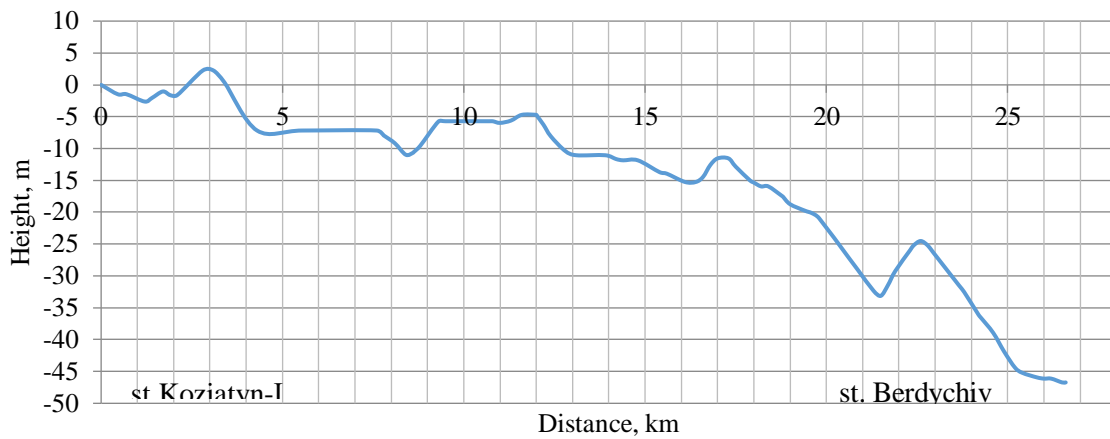
The results of calculations of traffic parameters on the Koziatyn-I-Popilnia section are shown in Table 1. Figure 2 shows the dependence of the speed of a train with 10 railcars.



a)



b)



c)

Fig.1. Profile of the road sections: a - Koziatyn-I-Popilnia; b - Koziatyn-I-Kalynivka; c - Koziatyn-I-Berdychiv

Table 1. Calculation results for traffic from Koziatyn-I to Popilnia

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Total duration of movement, s	5394	5414	5354	3565	3591	3589
Duration of traction modes, s	969	1231	1415	1193	1248	1150
Duration of electrodynamic braking modes, s	1013	1488	1889	715	1221	1617
Duration of run-up modes, s	3413	2695	2050	1657	1122	822
Relative duration of operation in traction mode, %.	18,0	22,7	26,4	32,6	34,8	32,0
Relative duration of operation without traction load, %.	82,0	77,3	73,6	67,4	65,2	68,0
Work "on the wheel" in the traction mode, kWh	180,0	243,7	285,4	238,0	254,6	236,0
Work "on the wheel" of electrodynamic braking, kWh	318,0	469,0	597,7	223,1	378,0	495,8

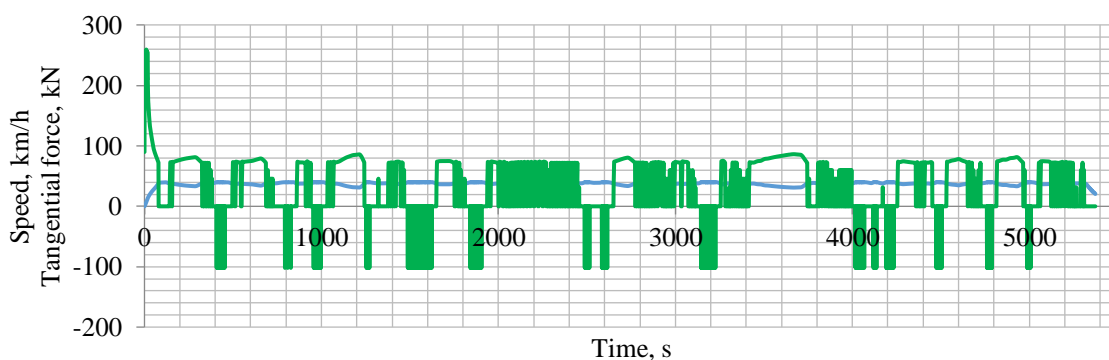


Fig.2. Dependences of speed (blue line) and tangential force (green line) when moving along the section from Koziatyn-I to Popilnya station with 10 freight railcars

Table 1 shows that the relative duration of the diesel generator operation under traction load is 18...35%, depending on the train weight and permissible speed. The rest of the time, the diesel generator

operates with a load determined by the capacity of the locomotive's auxiliary systems. Fig. 3 shows the distribution of the diesel locomotive operating time in the speed-pulling force coordinates.

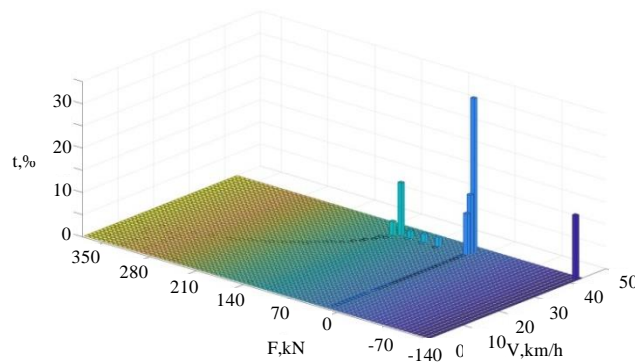


Fig.3. Distribution of diesel locomotive operating modes duration when moving with 10 freight railcars and an allowable speed of 40 km/h on the Koziatyn-I-Popilna section

As can be seen from Fig. 3, in the traction mode, the most frequent operating modes are performed when driving at the permissible speed. The traction force reaches the highest level, which corresponds to operation at the 8th position of the driver's controller. The longest is the movement in the run-up mode at a speed close to the permissible speed. This is due to the profile of the section: in fact, the movement is downhill with localized elevations. Electrodynamic braking is used to maintain the permissible speed with the greatest braking force. The dependencies for other design cases are similar to those shown in Fig. 3.

Table 2 shows the results of the calculations when driving from Popilna station to Koziatyn-I station. Fig. 4 shows the dependence of speed and tangential force. Fig. 5 shows the distribution of the diesel locomotive operation time.

Table 2. Calculation results for traffic from Popilna to Koziatyn-I

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Total duration of movement, s	5552	5810	6058	3788	4008	4215
Duration of traction modes, s	2661	3143	3622	2579	2995	3319
Duration of electrodynamic braking modes, s	256	449	617	172	289	340
Duration of run-up modes, s	2635	2218	1819	1037	724	556
Relative duration of operation in traction mode, %.	47,9	54,7	59,8	68,1	74,7	78,7
Relative duration of operation without traction load, %.	52,1	45,9	40,2	31,9	25,3	21,3
Work "on the wheel" in the traction mode, kWh	521,5	636,0	743,2	531,4	626,6	697,1
Work "on the wheel" of electrodynamic braking, kWh	80,4	141,2	194,4	53,7	90,3	106,0

Table 2 shows that the duration of operation in the traction mode is 50...80%, depending on the train weight and permissible speed. This is due to the fact that the movement from Popilna station to Koziatyn-I station is generally carried out on an ascent. This requires a longer operation of the locomotive in the traction mode to ensure movement at the permissible speed. At the same time, Fig. 4 shows that there is a decrease in the speed below the permissible speed, which indicates a lack of locomotive power.

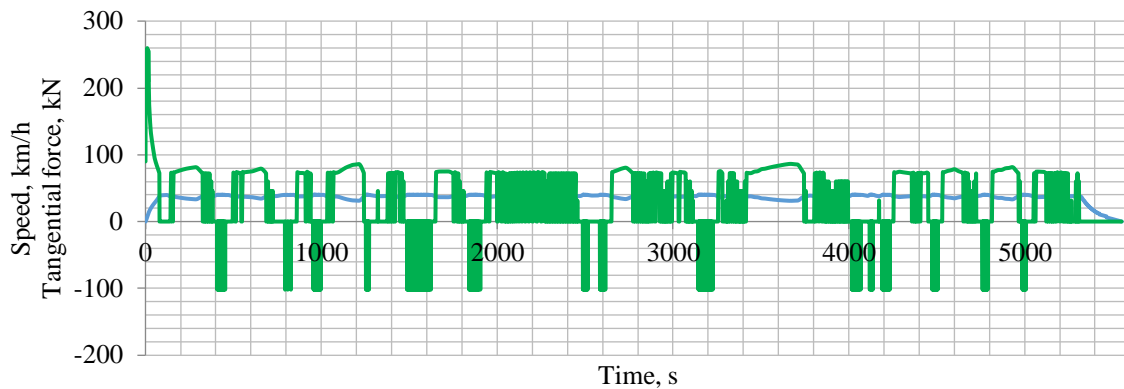


Fig.4. Dependences of speed (blue line) and tangential force (green line) when moving along the section from Popilnya to Koziatyn-I with 10 freight railcars

Fig. 5 shows the distribution of the diesel locomotive operation time when moving with 10 freight railcars at a permissible speed of 40 km/h along the Popilna-Koziatyn-I section. As you can see, traction is carried out at 8 positions of the driver's controller at speeds close to the permissible speed. The dependencies for other design options are similar to this one.

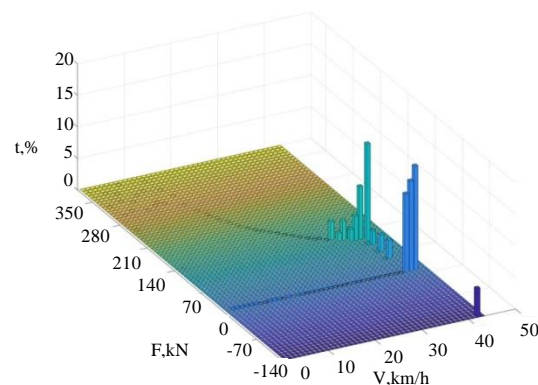


Fig.5. Distribution of diesel locomotive operating modes duration when moving with 10 freight railcars at a permissible speed of 40 km/h on the Popilna-Koziatyn-I section

As you can see from the above, the duration of diesel engine operation under traction load primarily depends on the profile of the section. The operating modes are influenced by the train weight, speed, and locomotive control strategy. For the case of movement from Koziatyn-I to Popilnia station, it can be noted that the power of the ČME3 diesel locomotive (1350 hp (990 kW) by diesel engine, tangential power with a nominal diesel engine power of about 700 kW) allows to withstand the high-speed mode of movement. However, the duration of the diesel engine's operation for the traction load is 18...35% of the total travel time: the rest of the time, the diesel engine operates at a minimum speed and serves to drive auxiliary systems. This leads to increased fuel consumption and irrational consumption of the diesel engine's motor resource. At the same time, when moving with freight railcars from Popilnia to Koziatyn-I, the power of the ČME3 diesel locomotive is not enough to maintain the permissible speed.

Tables 3 and 4 show the calculated data on traffic parameters for the Koziatyn-I-Kalynivka section, and Tables 5 and 6 show the calculated data for the Koziatyn-I-Berdychiv section.

Table 3. Calculation results for traffic from Koziatyn-I to Kalynivka

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Total duration of movement, s	4055	4084	3869	2610	2788	2977
Duration of traction modes, s	742	947	1146	777	977	1154
Duration of electrodynamic braking modes, s	441	660	806	397	522	621
Duration of run-up modes, s	2872	2477	1917	1436	1289	1202
Relative duration of operation in traction mode, %.	18,3	23,2	29,6	29,8	35,0	38,8
Relative duration of operation without traction load, %.	81,7	76,8	70,7	70,2	65,0	61,2
Work "on the wheel" in the traction mode, kWh	134,9	183,7	228,9	152,0	197,6	235,0
Work "on the wheel" of electrodynamic braking, kWh	138,6	208,2	254,4	123,3	162,4	192,9

Table 4. Calculation results for traffic from Kalynivka to Koziatyn-I

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Total duration of movement, s	4058	4059	4039	2685	2928	3204
Duration of traction modes, s	1117	1431	1735	868	1302	1748
Duration of electrodynamic braking modes, s	244	362	464	289	298	310
Duration of run-up modes, s	2697	2266	1840	1528	1328	1146
Relative duration of operation in traction mode, %.	27,5	35,3	43,0	32,3	44,5	54,5
Relative duration of operation without traction load, %.	72,5	64,7	57,0	67,7	55,5	45,5
Work "on the wheel" in the traction mode, kWh	203,7	276,8	345,0	169,0	261,7	358,0
Work "on the wheel" of electrodynamic braking, kWh	76,7	113,9	146,1	90,2	93,0	96,6

Table 5. Calculation results for traffic from Koziatyn-I to Berdychiv

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Total duration of movement, s	3998	4056	3988	2564	2627	2681
Duration of traction modes, s	570	672	748	642	703	728
Duration of electrodynamic braking modes, s	458	666	855	418	589	728
Duration of run-up modes, s	2970	2718	2385	1504	1335	1225
Relative duration of operation in traction mode, %.	14,3	16,6	18,8	25,0	26,8	27,2
Relative duration of operation without traction load, %.	85,7	83,4	81,2	75,0	73,2	72,8
Work "on the wheel" in the traction mode, kWh	89,5	112,4	130,4	107,0	125,5	133,9
Work "on the wheel" of electrodynamic braking, kWh	144,0	210,0	270,9	130,3	183,0	224,7

Tables 3-5 show that when moving from Koziatyn-I station (i.e., on an incline), the relative duration of diesel operation per traction load is 14...39%. In the opposite direction, the relative duration of diesel operation for traction load is 28...90%. The duration significantly depends on the track profile. The distribution of operation time in the coordinates "speed-tangential traction force" is similar to Figures 3

and 5: the most frequent is operation at the ultimate traction characteristic and at the permissible speed (Figure 6).

Table 6. Calculation results for traffic from Berdychiv to Koziatyn-I

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Total duration of movement, s	3923	4089	4301	3162	3200	3192
Duration of traction modes, s	1883	2432	2963	2868	2829	2780
Duration of electrodynamic braking modes, s	137	172	189	9	33	50
Duration of run-up modes, s	1903	1485	1149	285	338	362
Relative duration of operation in traction mode, %.	48,0	59,5	68,9	90,7	88,4	87,1
Relative duration of operation without traction load, %.	52,0	40,4	31,1	90,3	11,6	12,9
Work "on the wheel" in the traction mode, kWh	352,1	479,3	601,1	602,1	590,7	577,8
Work "on the wheel" of electrodynamic braking, kWh	43,1	54,3	59,9	2,8	10,3	15,6

It is worth noting that for the studied cases, when moving in the direction of the Koziatyn-I station (uphill), the power of the ČME3 diesel locomotive is not enough to move at the permissible speed. However, the use of a more powerful diesel engine on a locomotive will result in its inefficient use when operating on flat areas. Thus, on the one hand, it seems necessary to use a more powerful diesel engine. However, due to the presence of sufficiently long idling modes, inefficient use of the diesel engine, consumption of motor resources, and increased fuel consumption will be observed. If a less powerful diesel engine is used, it may not be possible to drive at an acceptable speed. Therefore, it seems advisable to use a power plant whose parameters can be adapted to the current operating conditions. This is possible through the use of a hybrid power plant and a power plant made up of discrete modules. In the first case, the power plant consists of a diesel generator and an energy storage device [23,24]. The most common variant of the second approach is the use of two and three diesel generators, which can be supplemented by an energy storage device [25,26]. It is possible to use gas engines, hydrogen piston engines, fuel cells, etc. [27-29].

Let's estimate the fuel consumption when performing traction work in the studied areas. Let us consider three variants of the locomotive: a) a serial diesel locomotive; b) a diesel locomotive with a single modern diesel engine; c) a battery locomotive, which is powered only by an onboard energy storage device (we assume that the capacity of the energy storage device is sufficient to move on the track section). Energy flows in traction systems of locomotives for these options are shown in Fig. 7. We assume that all three locomotives have identical traction characteristics.

The analysis of the tangential power dependencies shows that in traction modes, the locomotive operates with the rated power of the diesel engine. This allows us to calculate the fuel consumption for diesel locomotives equipped with a diesel engine only as follows

$$G = g_l \frac{t_t}{3600} + g_n \frac{t_b + t_c}{3600} \quad (11)$$

where is g_l – the hourly fuel consumption when operating at rated power.

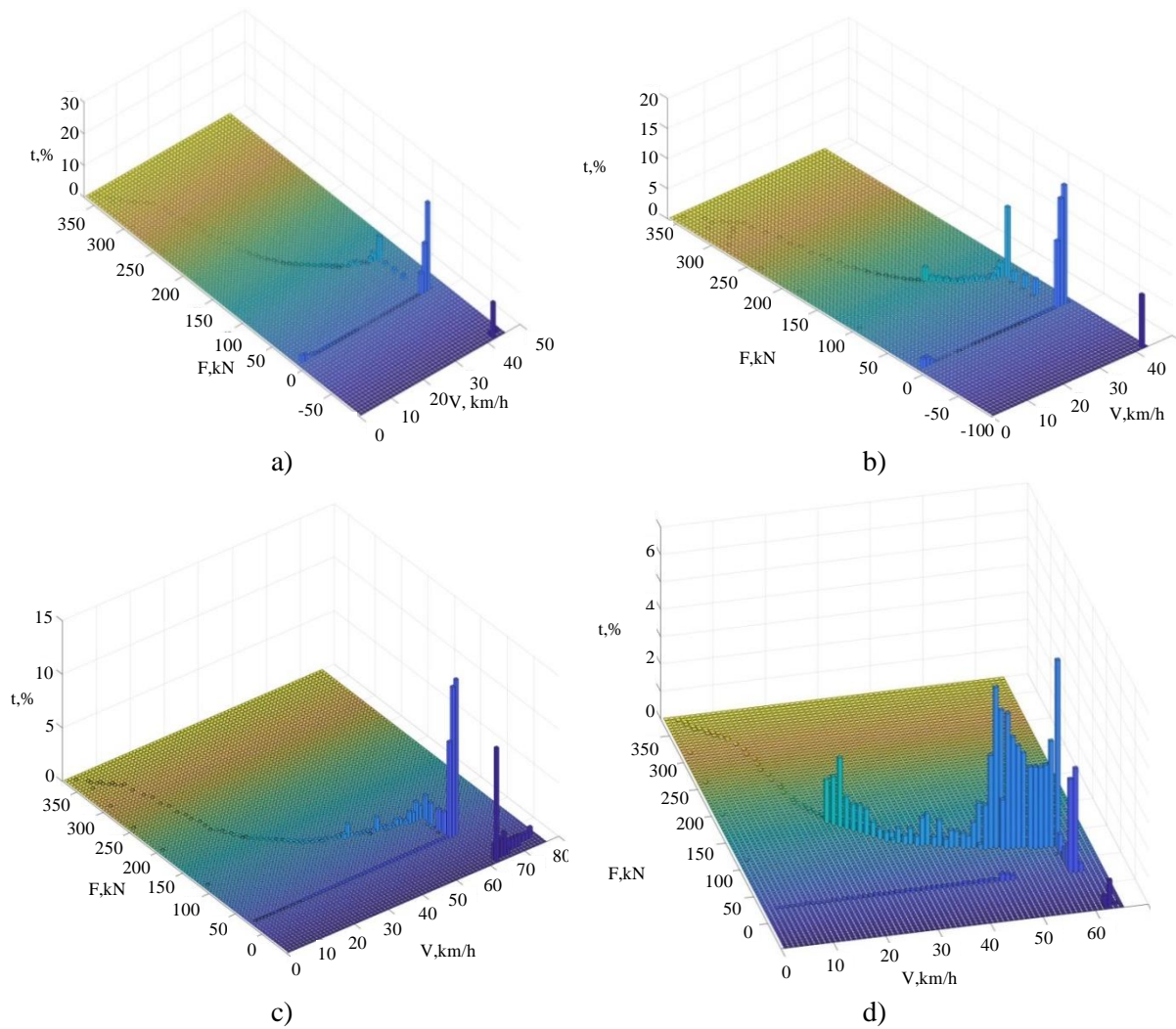


Fig.6. Distribution of diesel locomotive operating time

a - when moving with 15 freight railcars at a permissible speed of 40 km/h on the section Koziatyn-I-Kalynivka; b - when moving with 15 freight railcars at a permissible speed of 40 km/h on the section Kalynivka-Koziatyn-I; c - when moving with 20 freight railcars at a permissible speed of 60 km/h on the section Koziatyn-I-Berdychiv; d - when moving with 20 freight railcars at a permissible speed of 60 km/h on the section Berdychiv-Koziatyn-I

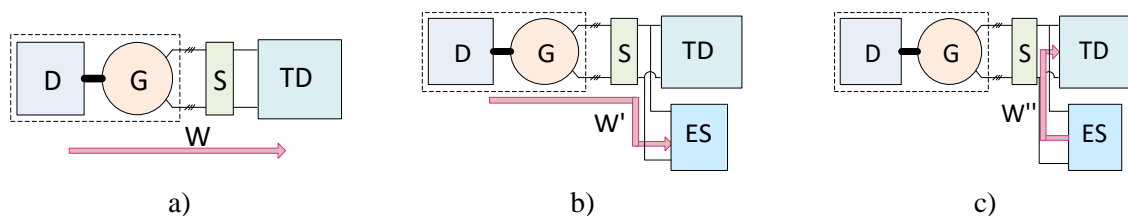


Fig.7. Distribution of diesel locomotive operating time:

a – energy transmission in the traction system of diesel locomotive with a modern diesel engine; b – energy transfer when charging the accumulator locomotive's energy storage; c – energy transfer when powering the traction system of a hybrid locomotive (D – diesel; G – synchronous generator; S – semiconductor converters; TD – traction electric drive; ES – energy storage; W, W', W'' – energy flows)

We take it equal to 220 kg/h for the diesel engine of the ČME3 diesel locomotive and 180 kg for a modern 900 kW diesel engine [30]; g_n – hourly fuel consumption when operating at idle. We assume 11 kg/h for the diesel engine of the ČME3 diesel locomotive and 7 kg for a modern diesel engine.

For a battery locomotive, it is traditional to use a diesel generator of relatively low power, which is mainly used to charge the energy storage device. The fuel consumption of a diesel generator set of a hybrid locomotive for charging the energy storage device before moving is determined by the equation

$$G' = g \frac{A_t(1 + \beta)}{\eta_{TD}\eta_{ES}\eta_G} \tag{12}$$

where is g – specific fuel consumption by a diesel engine, assumed to be 0.2 kg/kWh;

A_t – wheel work, determined as a result of solving the traction problem;

β – coefficient that takes into account the power of the locomotive auxiliary systems (averaged).

We take 0.2. η_{TD} , η_{ES} , η_G – are the efficiencies (averaged) of the traction electric drive, the charge-discharge cycle of the energy storage device, and the traction generator with rectifier, respectively. We assume the efficiency of the traction electric drive to be 0.92, the charge-discharge efficiency of the energy storage device to be 0.95, and the efficiency of the generator and rectifier to be 0.94.

The calculation results are shown in Tables 7-12.

Table 7. Estimation of fuel consumption when driving from Koziatyn-I to Popilnia

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Fuel consumption by diesel locomotive ČME3, kg	72,7	88,0	98,5	80,1	83,4	77,7
Fuel consumption by diesel locomotive with modern diesel engine, kg	57,0	69,6	78,4	64,2	66,9	62,2
Fuel consumption by a hybrid locomotive, kg	52,5	71,1	83,3	69,5	74,3	68,9

Table 8. Estimation of fuel consumption when driving from Popilna to Koziatyn-I

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Fuel consumption by diesel locomotive ČME3, kg	171,4	200,2	228,78	161,2	186,1	205,5
Fuel consumption by diesel locomotive with modern diesel engine, kg	138,6	162,3	185,8	131,3	151,7	167,62
Fuel consumption by a hybrid locomotive, kg	152,3	185,7	217,1	155,2	183,0	203,6

Table 9. Estimation of fuel consumption when driving from Koziatyn-I to Kalynivka

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Fuel consumption by diesel locomotive ČME3, kg	55,4	67,4	78,3	53,0	65,2	76,0
Fuel consumption by diesel locomotive with modern diesel engine, kg	43,5	53,4	62,5	42,4	52,3	61,2
Fuel consumption by a hybrid locomotive, kg	39,4	53,6	66,8	44,4	57,7	68,6

Table 10. Estimation of fuel consumption when driving from Kalynivka to Koziatyn-I

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Fuel consumption by diesel locomotive ČME3, kg	77,2	95,4	113,0	58,5	84,5	111,2
Fuel consumption by diesel locomotive with modern diesel engine, kg	61,5	76,6	91,2	46,9	68,2	90,2
Fuel consumption by a hybrid locomotive, kg	59,5	80,8	100,7	49,3	76,4	104,5

Table 11. Estimation of fuel consumption when driving from Koziatyn-I to Berdychiv

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Fuel consumption by diesel locomotive ČME3, kg	45,3	51,4	55,6	45,1	48,8	50,4
Fuel consumption by diesel locomotive with modern diesel engine, kg	35,1	40,1	43,7	35,8	38,8	40,1
Fuel consumption by a hybrid locomotive, kg	26,1	32,8	38,0	31,2	36,6	39,1

Table 12. Estimation of fuel consumption when driving from Berdychiv to Koziatyn-I

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Fuel consumption by diesel locomotive ČME3, kg	121,3	153,6	185,1	176,1	174,0	171,1
Fuel consumption by diesel locomotive with modern diesel engine, kg	98,1	124,8	150,7	143,9	142,1	139,8
Fuel consumption by a hybrid locomotive, kg	102,8	140,0	175,5	175,8	172,5	168,7

The analysis of the data in Tables 7 and 12 shows that the use of a modern diesel engine reduces fuel consumption. This is a consequence of its higher fuel efficiency. For the studied operating modes, the reduction in fuel consumption is 18...22%. It is worth noting that a significant portion of fuel is consumed during traction modes.

In many cases, the theoretical fuel consumption of a diesel generator for charging the energy storage device of a hybrid locomotive generally exceeds the fuel consumption of a diesel locomotive with a modern diesel engine. This is primarily due to the fact that in the case of a hybrid locomotive, it is necessary to charge the energy storage device and discharge it, which is accompanied by energy losses both in the storage device and in the matching converters. Accordingly, additional fuel consumption occurs. When the traction electric drive is directly powered, these additional losses are absent. Paper [31] formulates a condition for the feasibility of using an energy storage device in traction power transmission: the energy efficiency (or efficiency of the storage device) must be high enough to reduce diesel fuel consumption. At the same time, the presence of an energy storage device allows energy to be accumulated during electrodynamic braking, which means that less fuel will be consumed when the energy storage device is next charged. A significant advantage of the energy storage device is the ability to charge it from a source with a low cost of electricity, which reduces the cost of operation "on the wheel". It is worth noting that in the investigated cases, the "on-wheel" operation reaches 700 kWh, which will require an energy storage system with a working capacity of about 1000 kWh, taking into account auxiliary systems. The placement of such a storage device on a locomotive requires additional study. For the effective use of an energy storage device on a shunting locomotive in traction operations, it is necessary to conduct research on strategies for controlling the hybrid power plant and train modes [32-34].

Thus, preliminary calculations show the feasibility of upgrading shunting diesel locomotives used in traction operations. The choice of the upgrade option, in particular, the power plant, should take into account the operating modes of the locomotive (shunting operations at the station, operation on the sorting hill, traction operation, etc.).

Conclusions. The article considers the operation of a shunting diesel locomotive used for traction operations between a marshalling yard and adjacent stations. A mathematical model was developed to solve the traction problems of train movement on the sections Koziatyn-I-Popilnia, Koziaty-I-Kalynivka, Koziatyn-I-Berdychiv and in the opposite direction. Based on the results of the calculations, the fuel consumption was estimated and it was shown that the use of modern diesel on shunting diesel locomotives used for traction operations leads to a decrease in diesel fuel consumption by 18...22% compared to a production diesel locomotive. A preliminary assessment of fuel consumption when using a battery locomotive with an onboard energy storage device, for charging which a low-power diesel generator is used before moving, shows both lower and higher fuel consumption compared to a diesel locomotive equipped with a modern diesel engine. Further research is needed to select the structure of the power plant for a shunting diesel locomotive used in traction operations.

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Дослідження режимів роботи маневрового тепловозу при виконанні вивізної роботи

Розглянуті режими роботи маневрових тепловозів ЧМЕЗ при виконання вивізної роботи на ділянках обслуговування локомотивного депо Козятин. Розроблено математичну модель руху поїзду з тепловозом ЧМЕЗ, за допомогою якої вирішена серія тягових задач. Встановлено, що на режими роботи дизельного двигуна найбільший вплив має профіль ділянки шляху. Визначено, що при русі від станції Козятин відносна тривалість режиму тяги складає 14...39% від загального часу руху. При русі у напрямку станції Козятин відносна тривалість режиму тяги складає 28...90%. У режимі тяги дизельний двигун працює з номінальною потужністю. Для досліджуваних ділянок руху проведено оцінку споживання дизельного палива для серійним тепловозом, тепловозом із сучасним дизельним двигуном та акумуляторним локомотивом, який заряджається від бортової дизель-генераторної установки. Визначено, при тепловоз із сучасним дизельним двигуном споживає на 18...22% менше палива, ніж серійний тепловоз. У випадку акумуляторного локомотиву споживання палива може бути як меншим, як і більшим у порівнянні з тепловозом із сучасним дизельним двигуном. При цьому акумуляування енергії у бортовий накопичувач енергії при електродинамічному гальмуванні і її використання у тягових режимах сприяє зменшенню споживання палива.

Ключові слова: маневровий локомотив, модернізація, енергетична ефективність, накопичувач енергії, тягова задача

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The theoretical basis of the choice of new locomotives for Ukraine in the post-war period

In the case of the research of promising locomotives, we are dealing with a complex event – "choosing a locomotive for implementation". To effectively solve this problem, it is suggested to decompose this event. Therefore, the purpose of this work is to develop a methodology for modeling the evaluation process according to objective criteria of various options of new traction rolling stock. The Saaty method has been developed by transforming the hierarchy into an artificial neural network. The training of this network occurs automatically when analyzing the matrices of pairwise comparisons, and at the output we have a generalized criterion – the rating of the locomotive R , the value of which varies from 0 (the worst indicator) to 1. This allowed, unlike the existing approach, not to compare locomotives by compiling a matrix of comparisons at the last stage. Instead, a matrix of comparisons of the most important criteria by which traction rolling stock is evaluated has been compiled. The developed method has the ability to support various strategies for the operation of the locomotive park. This is implemented at the stage of drawing up the second-level criteria comparison matrix. Depending on the tasks facing the railways, it is also possible to adjust the degree of preference of one criterion over another. This provides even greater flexibility in using the proposed method.

Keywords: rolling stock, diesel locomotive, transport system, the Saaty method, artificial neural network.

Introduction. Updating the locomotive park of Ukraine is a priority task in the post-war development of the state. Over the past decades, the structure of the fleet of freight and passenger locomotives has practically not changed. The most significant implementation was the acquisition of new TE33AS diesel locomotives manufactured by General Electric. But this implementation has not yet received further development and these diesel locomotives make up a small part of the operational fleet of railways. In addition, some difficulties arose during the commissioning of these locomotives, which could have been avoided with a more detailed analysis of their characteristics and operating conditions.

Analysis of recent research and problem statement. Currently, the theoretical provisions describing the choice between existing alternatives and management decision-making are sufficiently developed. They are based on the pattern recognition theory presented in works [1-4]. Direct use of approaches given in similar sources is not always possible. It is necessary to carry out sufficiently extensive preparation of initial data, adaptation of physical quantities and characteristics of the rolling stock to the conditions of theoretical calculations. The use of neural networks is also a promising method for solving selection tasks [5,6]. This allows to conduct network training in an automated mode and obtain reliable selection results. But this method is limited by the need to have a training sample. In our case, it is necessary to have all the parameters of an "ideal locomotive" for training a neural network according to classical algorithms [7]. This is usually impossible, as the choice is made from a limited number of competing models. In addition, within one series of the locomotive, the characteristics may deviate significantly within the established norms [8]. And if it is possible to conditionally set the "ideal" values of individual parameters, then it is difficult to create a complex of such values under the condition of their most optimal ratio, which can reduce the adequacy of the final result of the neural network.

Considering the above, the most promising is the use of the method of analysis of hierarchies [9] to solve the task of choosing new locomotives. The Saaty method allows to evaluate several competing series of locomotives based on a combination of their technical characteristics, operating conditions and expert opinion.

The purpose and tasks of the study. Currently, there is no complete theoretical justification for the selection of new locomotives among several competing series, which would take into account a wide range of criteria and operational factors inherent in the operating conditions of Ukrainian railways.

In the process of planning the introduction of new equipment, railway transport specialists determine a list of promising objects planned for implementation and evaluate the advantages and disadvantages of each of them according to various criteria [10–12]. In the case of the research of promising locomotives, we are dealing with a complex event – "choosing a locomotive for implementation". To effectively solve this problem, it is suggested to decompose this event. Although the decompositions carried out by different people may differ from each other [13], experience shows that experts get close estimates at the operational level when describing and defining this or that option for implementing new technology on railways. Therefore, it is necessary to obtain a formalized model to describe this complex procedure, which would allow taking into account a wide range of factors influencing the final choice of a locomotive and obtain quantitative indicators of this choice. Therefore, the purpose of this study is to develop a methodology for modeling the evaluation process according to objective criteria of various options of new traction rolling stock.

Materials and methods of research. Building a hierarchy of locomotive selection.

Let's introduce some notation. Under the terms of the locomotive selection task, let's obtain a set of locomotives

$$L \in (l_1, l_2, \dots, l_n) \quad (1)$$

where L – set of all locomotives intended for selection;

l_n – a separate locomotive series from the set L .

When comparing locomotives, let's use the plural

$$C \in (c_1, c_2, c_3, \dots, c_n) \quad (2)$$

where C – the set of all significant criteria for choosing a locomotive;

c_n – a separate criterion from the set C by which locomotives are compared.

If the set L is known and defined, then the set C needs clarification and structuring. This is due to the fact that there is a very wide range of characteristics of locomotives. Different experts determine the number of significant elements of the set C from 10 to 60, depending on the approaches and selection tasks. In connection with such a large number of evaluation criteria, this work proposes to create a

hierarchy of criteria for the selection of locomotives, which will ensure the structuredness, logic and visibility of the representation of the set C.

According to the Regulation on the State Administration of Railway Transport of Ukraine [14], the main tasks of Ukrzaliznytsia are:

- 1) organization of the coordinated work of railways and enterprises in order to meet the needs of public production and the population in transportation;
- 2) ensuring effective operation of railway rolling stock, its repair and renewal;
- 3) development of railway transport development concepts;
- 4) taking measures to ensure the safety of railway transport, its infrastructure and the reliability of its work.

In addition, there are three main regulatory documents that affect the strategy of using traction rolling stock: the rules of technical operation of railways of Ukraine, the manual for the operation of a separate series of rolling stock, and the financial plan of Ukrzaliznytsia. Therefore, it is considered appropriate to combine all criteria for the selection of locomotives according to the following three groups: "economic criterion", "operational criterion" and "safety criterion".

As a result of the analysis, a list of all significant criteria that influence the decision to choose a new locomotive was obtained. The resulting set C consists of both individual elements (criteria) and subsets (formula 3)

$$C \in (c_1, c_2, c_3, c_4(), c_5(), c_6, c_7, c_8, c_9, c_{10}(), c_{11}, c_{12}) \quad (3)$$

where c_1 – "price of the locomotive" criterion;

c_2 – "relative consumption of fuel and lubricants" criterion;

c_3 – "life cycle of the locomotive" criterion;

$c_4()$ – a subset of criteria "costs for service maintenance and repair";

$c_5()$ – a subset of "reliability" criteria;

c_6 – "coefficient of useful action of the locomotive" criterion

c_7 – "coefficient of useful use of power of the internal combustion engine" criterion;

c_8 – "design speed" criterion;

c_9 – "power of the locomotive" criterion;

$c_{10}()$ – a subset of criteria "permissible influence on the track of a typical design" [15];

c_{11} – "modernity (year of commissioning of the series)" criterion;

c_{12} – "working conditions of the locomotive brigade" criterion.

Subsets of criteria include the following criteria for evaluating locomotives.

$$c_4() \in (c_{41}, c_{42}, c_{43}) \quad (4)$$

where c_{41} – "depot conversion costs" criterion;

c_{42} – "maintenance costs" criterion;

c_{43} – "expenses for current repairs" criterion.

$$c_5() \in (c_{51}, c_{52}, c_{53}, c_{54}, c_{55}) \quad (5)$$

where c_{51} – "quality of the on-board diagnostic system" criterion;

c_{52} – "longevity of the locomotive" criterion;

c_{53} – "repairability of the locomotive" criterion;

c_{54} – "locomotive reliability" criterion;

c_{55} – "locomotive maintainability" criterion.

$$c_{10}() \in (c_{101}, c_{102}, c_{103}, c_{104}) \quad (6)$$

where c_{101} – "axle load" criterion;

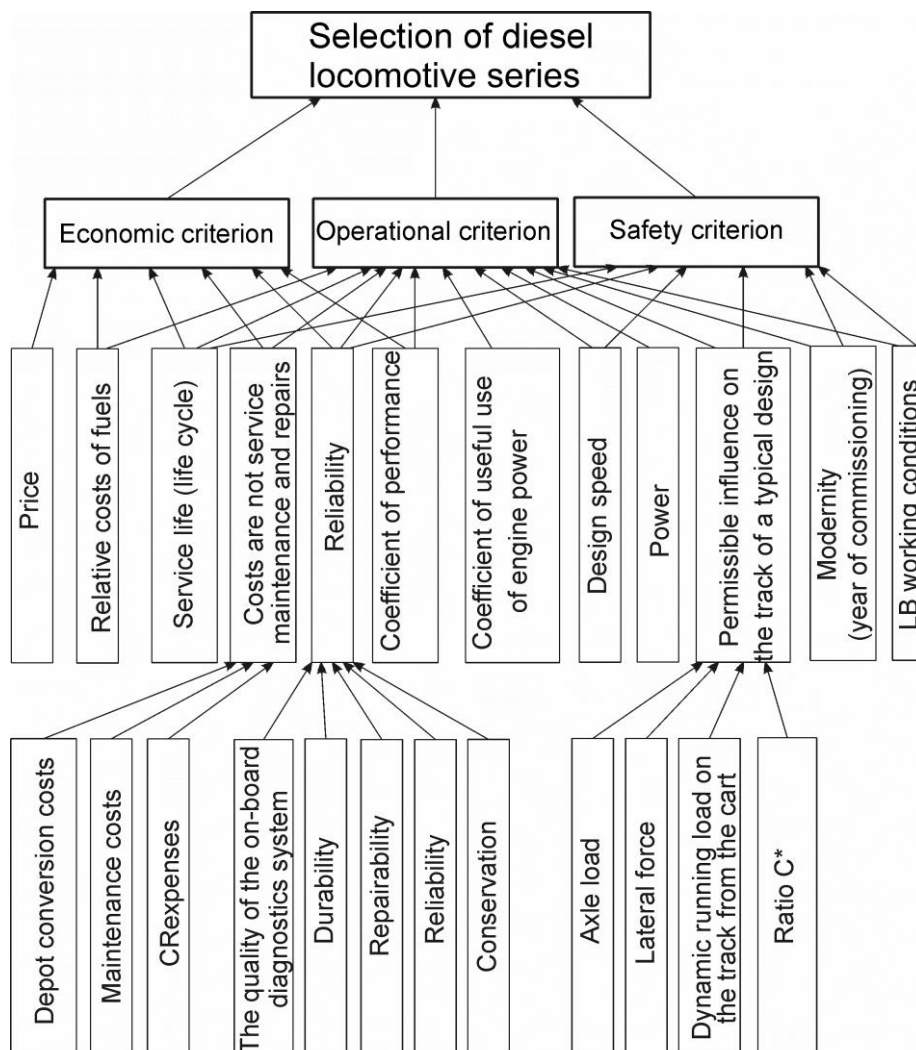
c_{102} – "lateral force" criterion;

c_{103} – "dynamic running load on the track from the cart" criterion;

c_{104} – "the ratio of the maximum horizontal load to the average vertical load from the rail to the sleeper" criterion.

The resulting hierarchy of locomotive selection criteria is presented in Fig. 1.

In this way, a general four-level hierarchy was obtained, at the top of which there is the goal – to choose for purchase the most suitable locomotive for the existing conditions. For the practical use of the Saaty method, it is necessary to obtain an algorithm that will ensure the achievement of the goal when entering the initial data. The initial data are the values of all the criteria of the fourth (lower) level and the values of the criteria belonging to the set C, with the exception of the subsets $c_4()$, $c_5()$ and $c_{10}()$. These subsets represent the results of processing the fourth level criteria.



C^* - the ratio of the maximum horizontal load to the average vertical load from the rail to the sleeper, no more

Fig. 1. Structure of the hierarchy of significant criteria for choosing a new locomotive.

At each level of the hierarchy, elements of this level are compared with each other [16]. Moreover, the comparison is performed several times: as many elements as are contained at the highest level. Each

comparison is made "from the position" of one of the elements of the higher level, which acts as a criterion by which the elements of the current level are compared pairwise.

All groups of criteria, actually criteria and options are compared with each other according to the classic scale 1..9 according to the scheme "each with each", the results of the comparison are presented in the form of a matrix of paired comparisons. A vector of weighting coefficients is formed for each matrix of pairwise comparisons. For greater scientificity of the method, Saaty recommends calculating the weighting coefficients as an eigenvector of the matrix of pairwise comparisons, which corresponds to the largest eigenvalue of this matrix. There is no problem of calculating this eigenvector, but there is no particular need for its calculation either: if to normalize the elements of the columns of the matrix of pairwise comparisons by their sums, and then average the results obtained in each row, the result will be very close to the Saaty eigenvector.

The construction of the matrix of pairwise comparisons is as follows. Let's set a qualitative pairwise comparison scale with the following conversion into points:

- exactly, don't care = 1
- slightly superior (worse) = 3 (1/3)
- better (worse) = 5 (1/5)
- much more preferable (worse) = 7 (1/7)
- fundamentally preferable (worse) = 9 (1/9)
- They are used in the case of an intermediate opinion
- intermediate points 2, 4, 6, 8.

Next, using the given scale, let's build a matrix of pairwise comparisons of the criteria of the second level of the hierarchy. The purpose of this is to establish which criterion has the greatest influence when choosing a locomotive. According to the survey of 26 experts (specialists in the fields of operation and repair of locomotives, managers of locomotive depots, representatives of railway management), the following matrix was obtained (Table 1).

Using the scale and terms given above, it is possible to say that the economic criterion is "slightly more important" (3 on the scale) than the operational one.

Table 1. Matrix of pairwise comparisons of criteria of the second level

Criterion name	Economic criterion	Operational criterion	Safety criterion
Economic criterion	1	3	1/5
Operational criterion	1/3	1	1/2
Safety criterion	5	2	1

Let's analyze the matrix in Table 1. To do this, let's normalize the matrix: find the sum of the elements of each column (7) and divide all the elements of the matrix by the sum of the elements of the corresponding column (8):

$$S_j = a_{1j} + a_{2j} + a_{3j} \tag{7}$$

$$A_{ij} = \frac{a_{ij}}{S_j} \tag{8}$$

As a result, let's get a matrix of weighted average ratios between the criteria. By adding the average values of each row to the tabular representation of this matrix, let's get the weight column of the criteria according to the goal (Table 2.)

Table 2. Normalized mean values of ratios between criteria

Criterion name	Economic criterion	Operational criterion	Safety criterion	Criterion weight
Economic criterion	0,1579	0,5000	0,1176	0,2585
Operational criterion	0,0526	0,1667	0,2941	0,1711
Safety criterion	0,7895	0,3333	0,5882	0,5703

In practice, the "Weight of criteria" column allows to evaluate individual criteria according to their importance and rank them. In our case, priority is given to the safety criterion when choosing locomotives. It should be noted that in this way, the weight of the criteria based on the opinion of the expert community is obtained. But an approach is also possible, when the railway management, when making a decision to update the locomotive park, is guided by a given development strategy. This strategy could theoretically involve prioritizing cost minimization or minimizing the time to process and deliver cargo. Then, according to the goals, the decision-maker can manually assign weights to individual criteria. Also, in the future, when carrying out specific calculations, it is possible to obtain the relative cost of increasing the weight of safety or operational priorities, or evaluate the impact of an operational criterion on the safety of transportation, etc.

The next step is the analysis of the third level criteria (Fig. 1). For example, let's give this process for establishing the relative weight of sub-criteria related to the "Economic criterion". the matrix of comparisons in this case will be presented in the form of a Table 3.

Table 3. Matrix of paired comparisons of the third-level criteria in relation to the "Economic criterion"

	Subcriterion name	1	2	3	4	5	6
1	Price	1	3	6	1/5	3	5
2	Relative costs of fuels	1/3	1	7	2	1/3	3
3	Term of operation	1/6	1/7	1	1/6	1/3	4
4	Service and repair costs	5	1/2	6	1	6	8
5	Reliability	1/3	3	3	1/6	1	3
6	Efficiency coefficient (Efficiency)	1/5	1/3	1/4	1/8	1/3	1

Let's determine the average values of the relationships between the economic subcriteria and obtain their weights (Table 4)

Table 4. Normalized average values of relations between economic subcriteria

	Subcriterion name	1	2	3	4	5	6	Criterion weight
1	Price	0,14	0,38	0,26	0,05	0,27	0,21	0,22
2	Relative costs of fuels	0,05	0,13	0,30	0,55	0,03	0,13	0,20
3	Term of operation	0,02	0,02	0,04	0,05	0,03	0,17	0,05
4	Service and repair costs	0,71	0,06	0,26	0,27	0,55	0,33	0,36
5	Reliability	0,05	0,38	0,13	0,05	0,09	0,13	0,14
6	Efficiency coefficient (Efficiency)	0,03	0,04	0,01	0,03	0,03	0,04	0,03

Using the example in Tables 2 and 3, tables of normalized average values of relations between other sub-criteria of the third level, as well as between sub-criteria of the fourth level (Fig. 1) are prepared.

The next stage is the preparation of the initial data for the calculation of the selection of the locomotive. Based on the physical meaning of the criteria of the third and fourth level, they all have different dimensions and values. For the possibility of their processing, it is proposed to normalize the initial data, that is, to present them in the form of numbers in the interval $0 < w_{Ci} \leq 1$, and the minimum values are the least acceptable, and the maximum values are, respectively, the most acceptable for the selection of the locomotive. Let's also note that it is not desirable to obtain a normalized value of the criterion equal to 0, since this automatically excludes the criterion in the calculation of the higher-level criterion in further calculations. This can lead to a distortion of the final result.

When carrying out normalization, it is necessary to take into account the logic of each indicator in the general structure of the hierarchy. There are values whose increase has a positive effect on the choice of a locomotive (efficiency coefficient, service life, power utilization factor, etc.), and there are values whose increase has a negative effect on the choice (the price of the locomotive, the cost of its maintenance, fuel consumption). Based on this, the formula for normalization of input values will have the following form:

$$\left| \begin{aligned} \chi_{Ci} &= \frac{c_{ipresent}}{c_{imax}}, \text{ if } c_i \rightarrow \max \\ \chi_{Ci} &= 1 - \frac{c_{ipresent} - c_{imin}}{c_{imax}}, \text{ if } c_i \rightarrow \min \end{aligned} \right. \quad (9)$$

where χ_{Ci} – the normalized value of the criterion;

$c_i \rightarrow \max$ ($c_i \rightarrow \min$) – an increase (decrease) in the value of the criterion increases the probability of choosing a locomotive;

c_{imax} – the maximum value of the criterion value from all locomotives selected for inspection;

c_{imin} – the minimum value of the criterion value from all locomotives selected for inspection;

$c_{ipresent}$ – the current value of the criterion value of the locomotive being checked at the moment.

Using formula (9) will approximate the normalized value of the criterion to 1 for all types of criteria, provided that this value contributes to the final selection of the current locomotive being calculated.

From the lower level of the hierarchy to the upper level, information is transferred according to the following expression:

$$\chi_{zi} = \sum_{i=1}^k w_{C(z-1)i} \cdot \chi_{C(z-1)i} \quad (10)$$

where - the normalized value of the i-th criterion of the z-th level of the hierarchy

k – the number of criteria at the hierarchy level (z-1).

$w_{C(z-1)i}$ – the weight of criterion si, calculated based on the results of the analysis of the matrix of pairwise comparisons of the criteria of the (z-1)-th level of the hierarchy.

An artificial neural network can be built based on the hierarchy shown in Figure 1 [17] (Figure 2).

A set of analytical expressions describing the one shown in Fig. 2 neural network, offered in the following form:

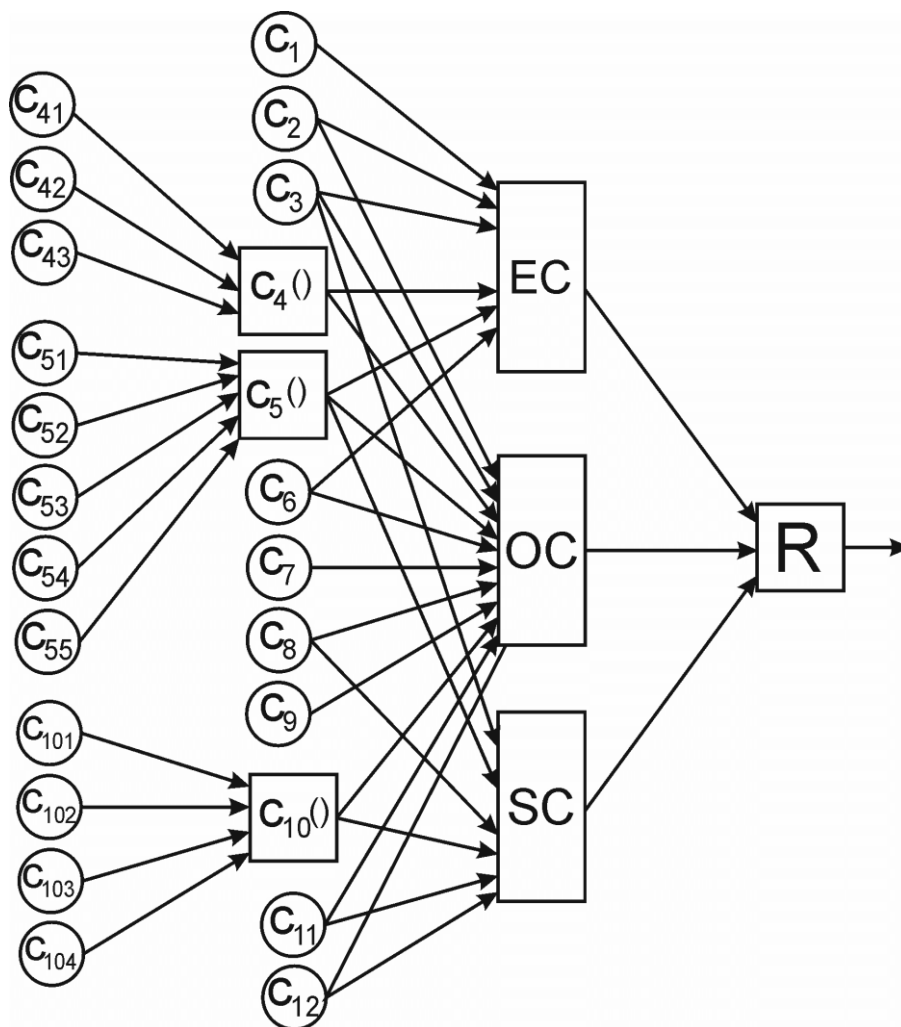


Fig. 2. Artificial neural network for locomotive selection

$$\left\{ \begin{array}{l}
 c_4() = \sum_{i=1}^3 w_{c40i} \cdot \chi_{c40i} \\
 c_5() = \sum_{i=1}^5 w_{c50i} \cdot \chi_{c50i} \\
 c_{10}() = \sum_{i=1}^4 w_{c100i} \cdot \chi_{c100i} \\
 EC = w_{e1}\chi_{e1} + w_{e2}\chi_{e2} + w_{e3}\chi_{e3} + w_{e4}c_4() + w_{e5}c_5() + w_{e6}\chi_{e6} \\
 OC = w_{o2}\chi_{o2} + w_{o3}\chi_{o3} + w_{o4}c_4() + w_{o5}c_5() + w_{o6}\chi_{o6} + w_{o7}\chi_{o7} + \\
 + w_{o8}\chi_{o8} + w_{o9}\chi_{o9} + w_{o10}c_{10}() + w_{o11}\chi_{o11} + w_{o12}\chi_{o12} \\
 SC = w_{s3}\chi_{s3} + w_{s5}c_5() + w_{s8}\chi_{s8} + w_{s10}c_{10}() + w_{s11}\chi_{s11} + w_{s12}\chi_{s12} \\
 R = w_{EC} \cdot EC + w_{OC} \cdot OC + w_{SC} \cdot SC
 \end{array} \right. \quad (11)$$

where c – the parameters of the locomotive (input data of the neural network) contained in the set (3);
 w – the weight of the relevant criteria, which was obtained during the analysis of the comparison matrices;

χ - normalized values entering the input of the neural network from the set (3);

EC, OS, SC – values of economic, operational and safety criteria, respectively;

R – the value of the final rating of the locomotive from the set (1).

The presented neural network for locomotive selection has three layers: input neurons (marked by circles), an inner layer (marked by squares) and an output layer consisting of one neuron R. The activation function of the neural network is a simple linear function $f(x)=x$. In our case, the neural network is already trained, using the method of hierarchy analysis we obtained the criteria weights, which for the neural network are the synapse weights. The output neuron R at the output gives the value $[0;1]$, which characterizes a specific locomotive, represents its rating in comparison with other locomotives. The maximum value of the rating makes it possible to choose the most suitable locomotive from all presented for comparison.

Conclusions. When planning the introduction of new series of locomotives, railway management faces a complex multi-criteria task. Obtaining a mathematical apparatus that will allow to objectively evaluate each locomotive and predict the consequences of its operation will significantly speed up and formalize this process. The method of analyzing hierarchies has already proven itself sufficiently and in this case gives quite adequate results. This article develops the Saaty method by transforming the hierarchy into an artificial neural network. The training of this network occurs automatically when analyzing the matrices of pairwise comparisons, and at the output we have a generalized criterion - the rating of the locomotive R, the value of which varies from 0 (the worst indicator) to 1. This allowed, unlike the existing approach, not to compare locomotives by compiling a matrix of comparisons at the last stage. Instead, a matrix of comparisons of the most important criteria by which traction rolling stock is evaluated has been compiled. In this case, it is possible to enter input data for any locomotive and get its general rating for the conditions embedded in the neural network. To retrain the network for other conditions of operation of promising locomotives, it is only necessary to change the priorities of the criteria in the matrices of their comparisons (for example, in the matrices of Table 1 and Table 3)

In addition, the developed method has the ability to support various strategies for the operation of the locomotive fleet. This is implemented at the stage of drawing up the second-level criteria comparison matrix. If the strategy of railway development is the preference of operational indicators over economic ones, then this can be easily implemented by adjusting pairwise comparisons within the given scale, i.e. giving greater preference to the "Operational Criterion". Depending on the tasks facing the railways, it is also possible to adjust the degree of preference of one criterion over another. This provides even greater flexibility in using the proposed method.

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Теоретичне підґрунтя вибору нових локомотивів для України у післявоєнний час

У випадку з дослідженням перспективних локомотивів ми маємо справу зі складним заходом – «вибір локомотива для впровадження». Для ефективного вирішення цієї проблеми пропонується розкласти цю подію. Тому метою даної роботи є розробка методології моделювання процесу оцінки за об'єктивними критеріями різних варіантів нового тягового рухомого складу. Метод Saaty був удосконалений шляхом перетворення ієрархії в штучну

нейронну мережу. Навчання цієї мережі відбувається автоматично при аналізі матриць попарних порівнянь, а на виході маємо узагальнений критерій – рейтинг локомотива R , значення якого змінюється від 0 (найгірший показник) до 1. Це дозволило, на відміну від існуючого підходу, не порівнювати локомотиви шляхом складання матриці порівнянь на останньому етапі. Натомість складено матрицю порівнянь найважливіших критеріїв, за якими оцінюється тяговий рухомий склад. Розроблений метод має можливість підтримувати різні стратегії функціонування локомотивного парку. Це реалізується на етапі складання матриці порівняння критеріїв другого рівня. Залежно від завдань, які стоять перед залізницею, також можна регулювати ступінь переваги одного критерію над іншим. Це забезпечує ще більшу гнучкість використання запропонованого методу.

Ключові слова: рухомий склад, дизельний локомотив, транспортна система, метод Saaty, штучна нейронна мережа.

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Modeling and using intelligent multi-agent system in smart city: ontological approach

The article discusses the problems of using intelligent multi-agent systems in solving a set of problems in managing and planning processes in a modern city. The concept of constructing intelligent multi-agent systems in systems that support the concept of a Smart City based on ontological modeling is considered. The proposed approach makes it possible to build formalized ontological models and flexibly configure an intelligent multi-agent system to solve problems of coordinating the work of all services of a modern city. The transition from a city in the usual sense to a Smart City is extremely necessary due to the huge gap between the increased complexity of the political, social and economic environment of modern settlements and the already outdated administrative and technological infrastructure, unable to function effectively in the new conditions. The article shows the need to rethink the key elements and general concept of the Smart City. The definition of a Smart City as a multiagent intelligent system is presented. An ontological approach is described, which involves minimal interference in the work of city services, ensures smooth changes and can be carried out by several teams of specialists in parallel. Currently, the method is used by the authors in a project aimed at developing Smart City – a digital ecosystem of services that allows achieving a synergistic effect between various subsystems (transport, ecology, energy, urban design, etc.).

Keywords: modeling, ontology, metaontology, information system, multi-agent system, intelligent multi-agent system, Smart City.

Introduction. Nowadays, more and more attention is paid to the concept of “Smart City”. The use of modern technologies to design a Smart City to achieve a synergistic effect between various subsystems (transport, logistics, security, energy, administrative sector, etc.) is described in [1].

In [2, 3] the Smart City concept is shown for:

- narrow tasks (for example, optimizing energy consumption, improving air quality, noise insulation, regulating transport systems);
- global projects (for example, maintaining the identity of a particular city/village and its urban structure, i.e. historical, cultural, environmental or aesthetic aspects).

An approach is used in a broader sense in the form of the concepts of “Smart Village” or “Smart Region”.

The relationship between energy, transport and city infrastructure is of great interest [4].

Numerous goals of sustainable development of the city's infrastructural environment can be achieved with the help of possible innovative solutions, in particular, such as:

- optimization of the functioning of all city services;
- reduction of travel time to places requiring the intervention of relevant city services;
- improvement of the operation of transport support of all services of the city (choice of routes, reduction of time of arrival to the city of an accident, fire, etc.);
- reduction of energy consumption by services supporting the infrastructural functioning of the city.

Analysis of recent research and problem statement. In [5, 6] it is considered as a Smart City, being a complex system, to achieve the effective functioning of which cooperation between architects, lawyers, investors, experts in the field of transport and energy, information technology, politics, and sociology is necessary.

The use of information received from the target audience makes it possible to adjust behavior and communications between representatives of the city government and city residents, which gives every citizen a feeling of involvement in the life of the modern city [7].

New technologies (for example, virtual or augmented reality) contribute to more effective planning and involvement of residents in city development.

From a technical point of view, the Internet (Internet of things, people, energy, services) is used for the general exchange of information [8, 9]. From a systems point of view, cyber-physical or socio-cyber-physical systems are used [10, 11].

In the Smart City, the management of urban structures changes, moving away from standard dynamic plans to adaptive control algorithms that ensure coordination of territorial units [12, 13].

All elements of a Smart City can be represented by corresponding *Demand Agents* and *Resource Agents*, which interact with each other and represent all existing requests and resources [14, 15].

Such a multi-agent model, being a digital platform with a limited and time-varying amount of resources, contributes to the dynamic modification of the functioning of the Smart City (*Smart Resilient City*) [16].

The multi-agent approach is a view of the city as a digital platform and ecosystem of smart devices, where agents of people, things, documents, robots and other components can directly interact with each other, based on the “order-resource” principle and providing the most optimal management solution.

Such a platform creates a smart space and becomes the basis for the self-organization of individual citizens, their groups, and entire systems in conditions of sustainability and adaptability [17].

In the Smart City concept, an important role is played by the factor of interaction (interface) of technical systems of different categories of citizens (children, pensioners, youth, people with different levels of IT literacy, etc.) [18, 19].

To assess the Smart City, different methodologies are used, for example, the Smart City Index [20], which includes an assessment of the level of “digitalization” of various processes of urban subsystems (for example, security, energy management, heat supply management, public transport management).

The purpose and tasks of the research. The purpose of the article is to research and solve problems associated with the management of urban structures (the functioning of which is supported by appropriate transport support), when all elements of a smart city are represented by interacting demand agents and resource agents, which are elements of the corresponding intelligent multi-agent system, design, development and operation which is performed using ontological modeling.

Materials and methods of research. One of the promising approaches to the creation of intelligent systems is the use of multi-agent technologies [21, 22].

Multi-agent system of the modern city. A multi-agent system consists of autonomous software objects (agents) capable of perceiving a situation, making decisions, and interacting with other agents.

The design of intelligent multi-agent systems involves the use of parallel and asynchronous interactions of software agents of the system until the agents reach the so-called “competitive equilibrium”, which is interpreted as a kind of “consensus” (balance of interests), when none of the agents can improve their performance anymore.

This approach makes it possible to switch to a distributed solution of the problem in the modern city, where the interests of all participants (subjects) of planning and management of the modern city and his services can be presented and taken into the account.

In this case, the processes of planning and management in the modern city and his services can be considered as a non-deterministic process of self-organization of agents, since each agent makes the decision on its own to establish or break connections both with the system itself and with other agents of the system at an arbitrary point in time, eliminating possible conflicts with other agents.

Designing intelligent multi-agent systems requires a lot of efforts from developers both at the design and development stage, and at the stage of implementation and operation.

The basic principles of building multi-agent systems based on ontologies were formulated in [21, 22], which shows the structure of a typical multi-agent resource planning system, the data model of which is built on the basis of a project management ontology.

The presented work develops well-known principles in terms of creating basic ontology for planning and developing models and methods for making decisions in planning and management in the modern city and his services, as well as in implementing complex of software tools, in which ontologies allow not only expanding the set of restrictions, but also rebuilding scenarios for providing subjects of modern city with information resources of the system [23, 24].

A system is considered complex multi-agent if it has the following properties:

- openness;
- adaptability;
- the presence of many partially autonomous and interconnected components (agents);
- lack of centralized management.

The overall behavior of such systems consists of connections between constituent agents whose autonomy is limited by the factors imposed on them by the system to which they belong. Table 1 shows the classification of multi-agent complex systems.

Table 1. Classification of intelligent multi-agent systems

Random	Complex multiagent	Deterministic
Uncertainty = 1	$0 < \text{Uncertainty} < 1$	Uncertainty = 0
Full autonomy of agents	Partial autonomy of agents	Lack of autonomy for agents
Unorganized	Self-organization	Organized
Unpredictable behavior	Emergent behavior	Predictable behavior

Agent connectivity indicates the number of agents with which the original agent can interact.

Agent autonomy indicates the degree of freedom of behavior of the agent.

The *complexity* of the system increases as the autonomy of the agents increases. In extreme cases, when agents are given complete freedom, the behavior of the system becomes random.

Emergence indicates that a system has special properties that are not inherent in its individual elements. These properties appear as a consequence of the interaction of agents.

The property of *nonlinearity* is inherent in systems in which the connections between agents are nonlinear.

Disequilibrium is a property indicating the susceptibility of operations to the influence of unpredictable destructive events.

Self-organization is a property that manifests itself when disruptive events occur (receipt of an unexpected request, delay, falsification, attack, etc.), then the system urgently identifies the affected areas and is rebuilt to eliminate/reduce the effect of the disruptive event.

Self-organization can lead to self-development, as a result of which agents self-organize to improve the performance of the system.

Co-evolution is a property of multiagent systems that allows them to develop together with their environment.

Smart city is an adaptive, resilient and sustainable city that offers its guests and residents a high standard of living, work and entertainment with minimal impact on the environment.

Adaptability, stability in development and the ability to quickly recover are emergent properties of multiagent systems [25 – 27].

It follows from this that in order to transform a city into a smart one, it needs to go through “digitalization”, i.e. be based on technologies such as: multi-agent systems, artificial intelligence, Internet of things, social networks, etc., as well as a set of necessary sensors [19].

Problems of the modern city. The complexity of effective city management in new conditions is discussed in [20, 28]. Among the important problems of urban “space” we should, in particular, highlight:

- the presence of unorganized, environmentally harmful services provided to city residents;
- lack of adequate communication channels between city residents, guests and city administration;
- lack of monitoring of the quality of services and knowledge about effective city management in a complex environment [29];
- imperfect methods of strategic planning.

In a typical modern city, various types of services are provided, including:

- education;
- health services;
- social services;
- roads and transport;
- food supply;
- water supply;
- sewerage;
- waste management;
- economic development;
- urban planning;
- public safety;
- environmental health;
- tourism;
- entertainment;
- construction;
- housing services;
- tax collection.

Unfortunately, in our time, each important service is provided separately, and there is practically no coordination of services of the city.

This management method leads to a significant waste of resources, a significant threat to the environment and an increase in the number of diseases associated with its pollution. As a result, the number of unpredictable events increases (eg, policy changes, changes in service demands, unsuccessful use of resources, etc.).

Important factors in city government are, in particular, a rigid, departmental structure that interferes with the coordination of services, and the use of outdated technologies that cannot cope with the dynamism of city life. Due to the limited knowledge of individual subjects, none of the personal ontological and cognitive models can claim to be an exhaustive conceptual representation of problematic situations that arise when managing a city.

By exhaustive conceptual mapping we mean:

- identifying all, including the so-called “hidden” prerequisites for the emergence of a problem situation;
- knowledge and understanding of cause-and-effect relationships between factors separated in space and time that determine the symptoms of a problem situation.

Obtaining a description of a problem situation (its conceptual representation), which is recognized by all participants in the processes in the Smart City (in particular, the city administration, city services, city transport, transport infrastructure, vehicles that provide and support the work of city services, residents and guests of the city, etc.), involves the implementation of an iterative procedure based on solving the following interrelated tasks:

- formation on the basis of personal ontological models of individual subjects (participants in processes in the Smart City, especially transport that supports the functioning of all city services) of an ontological model of a problem situation;

- construction, based on personal cognitive models of individual subjects, of a cognitive model of a problem situation recognized by all interested parties.

During the implementation of the iterative procedure, the personal ontological and cognitive models of individual subjects (participants in processes in the Smart City) are adjusted.

The cognitive model of a problem situation serves as the foundation for the subsequent presentation of a problem situation in the form of a multi-connected control object, which makes it possible to formulate the specification of the corresponding intelligent multi-agent Smart City system using the formation of a conceptual space, strategy and agents of the system.

The reasons for the occurrence of problematic situations, in addition to errors caused by the mental activity of subjects, include, in particular:

- lack of knowledge about the true causes of these situations;
- limited conceptual representation of problem situations; insufficient potential of the models used to represent the PS in the form of a multi-connected control object.

The basis for developing a consolidated solution to resolve problem situations in the city is the identification (both of the situation itself and its components) based on formalization in the form of appropriate ontological and/or cognitive models.

The set of models of problem situations in the city creates the prerequisites for a better understanding of the content of these situations. Studying the properties of an object through modeling creates the basis for forming a consolidated opinion on approaches to resolving problem situations in the city.

One of the tools for constructing formal models of a Smart City is the apparatus of cognitive modeling, the apparatus of ontological modeling is focused on formalizing the weakly structured knowledge of subjects involved in resolving problem situations that arise, in particular, when:

- management of various Smart City services;
- solving problems related to infrastructure facilities of the Smart City.

Transforming the modern city into Smart City. Let's consider a city where there is a local government body – the city administration, responsible for serving citizens. This administration decided to improve the quality of services and reduce the costs of their operation.

A top-down approach to solving a problem, attempting to create a requirements specification for the entire city before work begins, is unacceptable in a dynamically changing urban environment, since the requirements become outdated even before they are completed.

The proposed evolutionary transformation method can achieve smooth transformation.

Frequently changing requirements dictate the use of the proposed method:

Consider all services (including both direct transport and those provided to city services) from the point of view of their priority (importance, value) for the city.

Create a specification of requirements to improve the quality of the selected service.

Develop and implement an adaptive scheduler only for the selected service.

Evaluate and update the solution demonstrating an increase in target indicators.

Select the next service and repeat steps 2, 3, 4, making sure that they cooperate/compete with existing service services.

As the number of changed services increases, it is necessary to constantly monitor and make changes directly to the Smart City.

At the same time, it is necessary to ensure continuous access to qualified specialists to maintain and improve the urban ecosystem, which will allow it to be supplemented with new services capable of self-service and self-improvement.

Note that complex adaptive systems can work effectively in complex conditions. The rigid structures of deterministic systems break down when placed in complex environments, as seen in many declining urban economies around the world.

At the same time, complex structures easily adapt to changes and are able to quickly recover/change under external influences, which makes them more stable. This implies the need to find a way to transform a modern city into a complex adaptive urban system.

The urban system is required to be sustainable [30]. The evolution of Smart City services can be illustrated using the example of urban transport using different types of energy carriers.

The increase in pollution from diesel vehicles in large cities is already critical. In this case, intelligent adaptive planning helps accelerate the transition from diesel to electric vehicles and initiates the expansion of electric vehicle charging points.

Multi-agent planners in Smart Cities are capable of ensuring the interaction of city services in order to maximize Smart City performance indicators.

A typical city service consists of:

- the Real World resources and needs;
- the Virtual World software agents-schedulers of the Real World resources in real time;
- knowledge base containing information about services that support the functioning of the city and its services;
- interfaces for transmitting information about events from the Real to the Virtual World, as well as instructions for transferring resources from the Virtual to the Real World.

Application of service concept in the Smart City system. Let's consider an example of the work of emergency response services (ambulance service, fire service, rapid mine clearance and response service, gas service, water utility services, power grid services, heating network services, police) in the Smart City.

One of the approaches to formalizing knowledge in the Smart City concept is based on the use of appropriate ontological models.

They can be presented in the form of corresponding ontographs with a description of the main entities of the subject area in the form of classes, attributes and relationships.

In this case, both a database (DB) and a knowledge base (KB) are used to adapt the support system for the Smart City concept to provide access to services [19].

The task requires:

- formalization of knowledge about all aspects of the Smart City;
- providing easy access to databases and knowledge bases for various services;
- supporting interaction on digital platforms and ecosystems [16].

A city model based on ontologies can identify major objects such as buildings, roads, transport, bus stops, traffic lights, energy sources, recreational areas and others.

These objects can also have a detailed description – the building can be the restaurant, the business center or the residential building with many properties – attributes (number of floors, date of construction, etc.).

The ontological model also describes people (their activities, requests, requirements and business processes in which they take part) [26, 27, 31, 32].

Formalized knowledge can be used by city services not only as a source of raw information, but also to adapt to the situation and adjust work, ensuring the sustainability of city development.

The use of ontologies (ontological models) is especially relevant when it is necessary to understand the essence and structure of the subject area under consideration (including knowledge and data describing the objects of this subject area). In the problem under consideration, this is the understanding of employees of the relevant city services and/or software agents of an intelligent multi-agent system.

Ontologies allow you to reuse knowledge about objects in the subject area when solving different classes of problems. Formally, the ontological model is specified by the set [5, 6]:

$$O=\{C, R, A\}, \quad (1)$$

where O is an ontology;

C is a set of objects in the subject area;

R is a set of relationships between the objects of the subject area;

A is a set of axioms (laws and rules that describe the laws and principles of the existence of objects in the subject area).

In the subject area under consideration:

$$O_{SS} = \{C_{SS}, R_{SS}, A_{SS}\}, \tag{2}$$

where O_{SS} is an ontology that shows such a subject area as the life of the city (all its services),

$C_{SS} = \bigcup_i C_{SS_i}$ – set of objects of each city service (C_{SS_i}),

$R_{SS} = \bigcup_i R_{SS_i} \cup \bigcup_{i,j} R_{SS_{ij}}$ – set of relationships between objects within each city service ($\bigcup_i R_{SS_i}$) and relations between objects of different city services ($\bigcup_{i,j} R_{SS_{ij}}$),

$A_{SS} = \bigcup_i A_{SS_i}$ – a set of rules and laws (including regulations) that determine the functioning of city services (C_{SS_i}).

For the design of ontologies, there is a special toolkit - ontology editors, which are tools for describing the formal model of the subject area, and also provide additional opportunities for ontology analysis and use the logical inference mechanism.

Protégé is the most popular freely distributed ontology editor, designed to which, in the form of plugins, you can connect visualization tools, build queries to the ontology, and obtain conclusions [32].

The metaontology for the example under consideration, implemented in the Protégé ontology editor [32], is presented on the Fig. 1.

Application of the proposed approach to the Smart City concept includes descriptions of ontologies (which are parts of the metaontology shown on the Fig. 1):

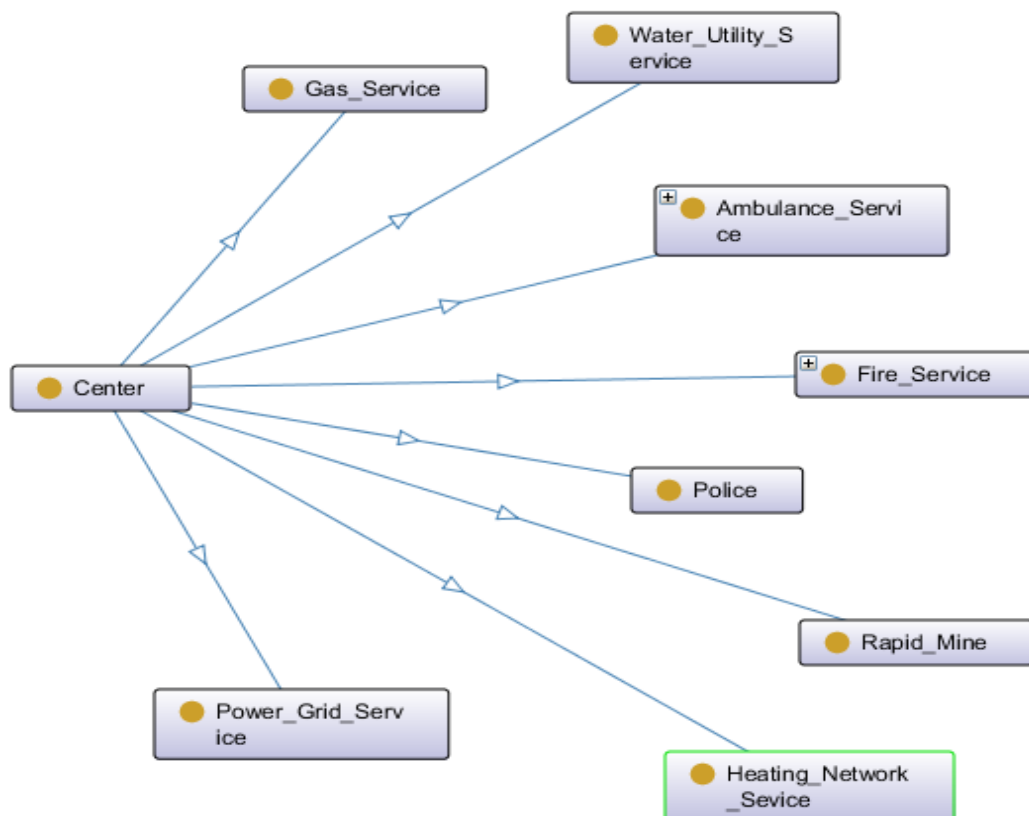


Fig. 1. Metaontology of the Smart City

- *ambulance service*, which includes:
 - object classes (ambulance, ambulance crew, crew member, medical equipment, route, road, hospital, patient, relative);
 - relationships (the crew belongs to the ambulance, the equipment belongs to the crew, the ambulance follows the route);
 - properties of object classes (for a crew member: identifier, qualification, availability);
- *fire service*, which includes:
 - classes of objects (fire fighting vehicle, fire fighting crew, crew member, fire extinguishing equipment, route, road, fire location, victims, rescued);
 - relationships (the crew belongs to the fire brigade, the equipment belongs to the crew, the fire brigade follows the route);
 - properties of object classes (for a crew member: identifier, qualification, availability);
- *rapid mine clearance and response service*, which includes:
 - classes of objects (demining service vehicle, demining service crew, crew member, equipment for rapid demining and response, route, road, location of detection of an explosive object, demining site (landfill), victims, rescued);
 - relationships (the crew belongs to the demining service vehicle, the equipment belongs to the crew, the rapid demining and response service vehicle follows the route);
 - properties of object classes (for a crew member: identifier, qualification, availability);
- *gas service*, which includes:
 - classes of objects (gas service vehicle, gas service crew, crew member, equipment for quickly eliminating gas pipeline depressurization, route, road, place where gas pipeline depressurization was detected, victims, rescued);
 - relationships (the crew belongs to the gas service vehicle, the equipment belongs to the crew, the gas service vehicle follows the route);
 - properties of object classes (for a crew member: identifier, qualification, availability);
- *water utility services*, which includes:
 - classes of objects (vodokanal service vehicle, water utility service crew, crew member, equipment for quickly eliminating a broken water supply pipe, route, road, location where a broken water supply pipe was detected);
 - relationships (the crew belongs to the water utility service vehicle, the equipment belongs to the crew, the water supply service vehicle follows the route);
 - properties of object classes (for a crew member: identifier, qualification, availability);
- *power grid services*, which includes:
 - classes of objects (energy network service vehicle, energy network service crew, crew member, equipment for quickly eliminating damage to energy networks, route, road, location of detection of damage to energy networks);
 - relationships (the crew belongs to the energy network service vehicle, the equipment belongs to the crew, the energy network service vehicle follows the route);
 - properties of object classes (for a crew member: identifier, qualification, availability);
- *heating network services*, which includes:
 - classes of objects (heating network service vehicle, heating network service crew, crew member, equipment for quick repair of heating network damage, route, road, location of detection of heating network damage);
 - relationships (the crew belongs to the heating network service vehicle, the equipment belongs to the crew, the heating network service vehicle follows the route);
 - properties of object classes (for a crew member: identifier, qualification, availability);
- *police*, which includes:

- object classes (police car, police crew, crew member, weapon for crime prevention/investigation, route, road, crime scene);
- relationships (the crew belongs to the police car, the weapon belongs to the crew, the police car follows the route);
- properties of object classes (for a crew member: identifier, qualification, availability).

The system under consideration is intended for planning, coordination and management of all city services based on information about objects and subjects of the subject area under consideration, related to the interests of various categories of users, and recommends to the user those resources of the intelligent multi-agent system that meet their information needs.

The considered intelligent multi-agent system uses the ontology representation language OWL and its processing tools [4, 34].

To represent knowledge, ontologies and thesauri of the subject area are used. In this case, the thesaurus is built by the user using the corresponding ontology independently.

The user of the system can access ontologies created by other users, revise them, set the context for obtaining an information resource based on them, copy the necessary fragments from them, but cannot change them.

The intelligent multi-agent system used in the Smart City provides a search for ontologies containing user-entered terms, as well as a search for ontologies similar to the ontology selected by the user.

An ontological model that describes the semantics of interaction between users and resources of an intelligent multi-agent system in the common information space of a Smart City provides knowledge for performing actions related to processes for solving the problems of a modern city and managing these processes.

On the Fig. 2 shows the ontograph [31, 32, 36] of the subject subdomain *Ambulance Service*.

At this stage, it is advisable to write scripts for agents, which will be stored in meta-ontologies and ontologies that describe subject sub-domains corresponding to specific services, and will be available to agents when there is a need to solve a specific problem.

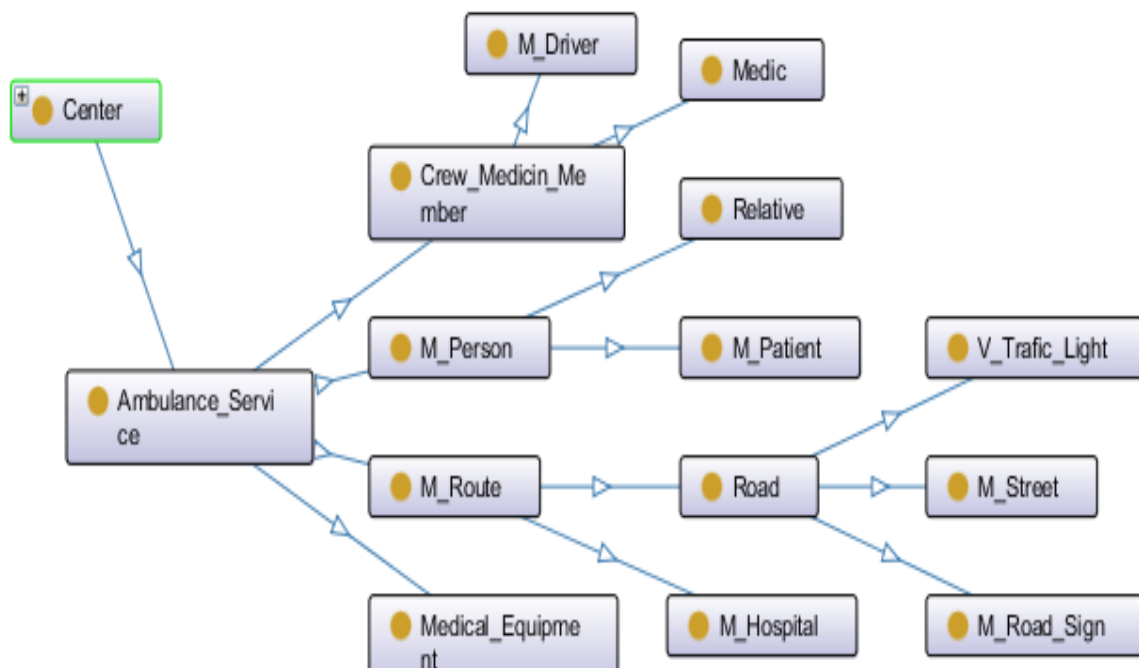


Fig. 2. Ontograph of Ambulance Service

All policies, rules and regulations governing the operation of services should also be stored in an appropriate ontology. In addition to the ontology, the knowledge base also contains all data about objects that are usually stored in client databases [34].

On the Fig. 3 shows the ontograph of the subject subdomain *Fire Service*.

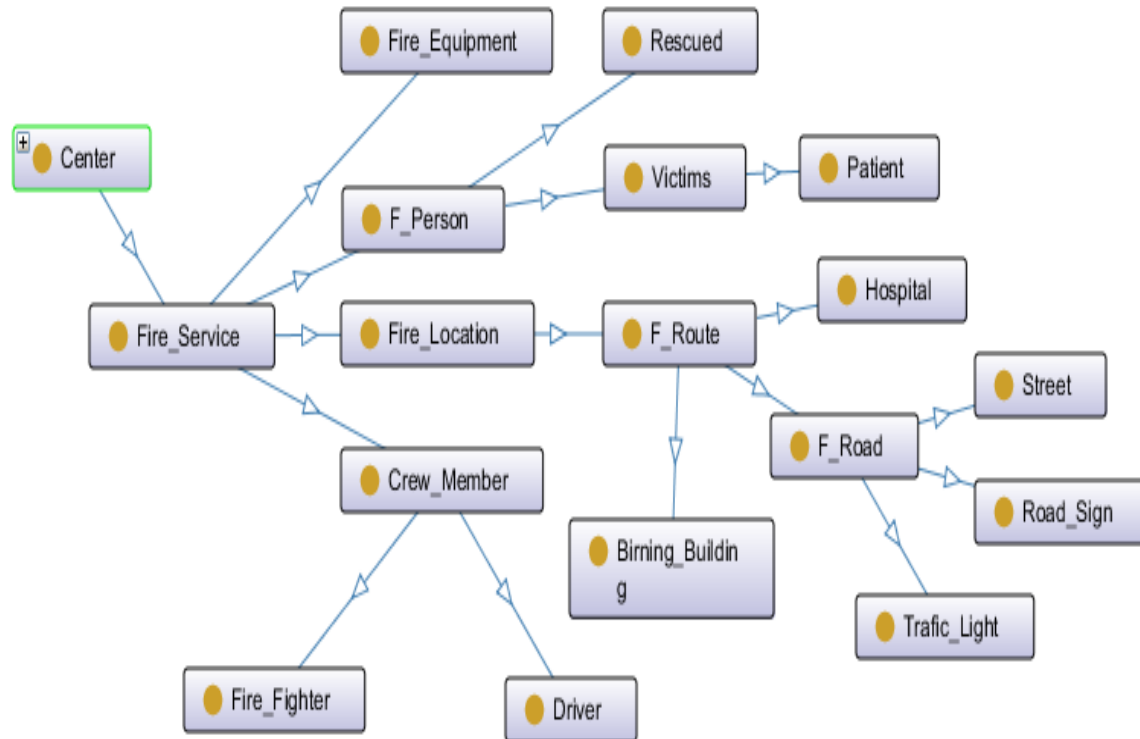


Fig. 3. Ontograph of Fire Service

Creation of virtual world of Smart City. The creation of a Virtual World involves the creation of a digital infrastructure that supports the exchange of information between numerous agents of the corresponding intelligent multi-agent system.

The Virtual World is a space in which agents determine conditions (“agree”) on the distribution of resources for certain requests.

In the Virtual World of the fire service, the interaction of crew members with each other or with other fire crews, as well as with hospitals, the interaction of roads with routes, patients with hospitals, etc. carried out by exchanging messages between the corresponding agents. Adaptability is achieved by agents matching resource requirements and capabilities.

If, for example, the road to the selected hospital is difficult due to traffic jams on a certain road, the agent of that road will immediately report the problem to the agents of other roads, which initiates an exchange of messages between them to determine a new route to the hospital or determine a route to another hospital. The described example demonstrates the advantage of multi-agency and ontological approach in solving Smart City problems.

Designing interfaces between the Real and Virtual Worlds Information about destructive events occurring in the Real World must be transmitted to the Virtual World, and all planning decisions made by agents in the Virtual World must be transmitted to the Real World.

Initially, information exchange can be carried out through the exchange of messages between people acting as operators (for example, drivers, fire fighters), using their smartphones or specially designed portable communication devices, and agents.

However, the most preferred method is the exchange of information between epyphysical Real World resources (for example, vehicles, robots, conveyors) and agents using Internet of Things technology.

Ambulance route planning is easily expanded, for example by adding doctors and facilities required by patients transported by fire transport.

This requires additional agents. The next step is to add agents to schedule the use of other hospital resources, such as equipment, operating rooms, etc. The design must proceed step by step and each step must be tested in practice before the next one is put into operation.

Conclusion. The transition from a city in the usual sense to a Smart City is extremely necessary due to the huge gap between the increased complexity of the political, social and economic environment of modern settlements and the already outdated administrative and technological infrastructure, unable to function effectively in the new conditions.

The article shows the need to rethink the key elements and general concept of the Smart City. The definition of a Smart City as a multiagent intelligent system is presented.

The method of evolutionary transformation of the activities of city services is described based on the use of an ontological approach, which, in particular;

- provides for the minimization of the so-called "manual" management of the activities of city services due to the connection to the management of artificial intelligence, which is supported by relevant intelligent multi-agent systems;
- ensures the smoothness of changes in the management of the city and its services;
- optimizes the activities of transport support of these services (in particular, due to the laying of optimal routes for the movement of ambulances, fire engines, etc.), ensures;
- supports the simultaneous work of several teams of specialists, avoiding the occurrence of possible conflicts associated with the duplication of some functions in different services of the city.

Currently, the method is used by the authors in a project aimed at developing Smart City – a digital ecosystem of services that allows achieving a synergistic effect between various subsystems (transport, ecology, energy, urban design, etc.).

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Моделювання та використання інтелектуальної мультиагентної системи в smart city: онтологічний підхід

У статті розглядаються проблеми використання інтелектуальних мультиагентних систем у вирішенні комплексу завдань управління та планування процесів у сучасному місті. Розглянуто концепцію побудови інтелектуальних мультиагентних систем, що підтримують концепцію Smart City (розумного міста) на основі використання онтологічного підходу (онтологічного багаторівневого моделювання). Запропонований підхід дає можливість побудувати формалізовані онтологічні моделі та гнучко налаштувати інтелектуальну мультиагентну систему для вирішення задач координації роботи всіх служб сучасного міста. Перехід від міста у звичайному розумінні до розумного міста (Smart City) є вкрай необхідним через величезний розрив між зростаючою складністю політичного, соціального та економічного середовища сучасних поселень та вже застарілою адміністративною та технологічною інфраструктурою, нездатною ефективно функціонувати в нових умовах. У статті показано необхідність переосмислення ключових елементів та загальної концепції Smart City. Наведено визначення Smart City як мультиагентної інтелектуальної системи. Описано онтологічний підхід, який передбачає мінімальне втручання в роботу міських служб, забезпечує плавні зміни та може здійснюватися паралельно кількома командами спеціалістів. Наразі метод використовується авторами в проєкті, спрямованому на розвиток Smart City – цифрової екосистеми послуг, яка дозволяє досягти синергічного ефекту між різними підсистемами (транспорт, екологія, енергетика, міський дизайн тощо).

Ключові слова: моделювання, онтологія, метаонтологія, інформаційна система, мультиагентна система, інтелектуальна мультиагентна система, Smart City.

Use of modified basalt fiber in transport construction

Basalt fiber is a promising material that can be used to create a new class of building materials. It has a number of advantages, including high strength, low weight and resistance to chemicals. One of the disadvantages of basalt fiber is its low alkali resistance. In an alkaline environment, the fiber is destroyed, which limits its use in building materials exposed to alkalis. The paper investigates the effect of heat treatment on the alkali resistance of basalt fiber. It was found that heat treatment at a temperature of 500 °C increases the alkali resistance of the fiber by 80%. This is due to the compaction of the fiber structure and the formation of iron-oxygen tetrahedra on its surface, which are resistant to alkalis. The authors of the article substantiate the feasibility of using heat-treated basalt fiber in transport construction. This material can be used to manufacture new types of building materials that are resistant to alkalis.

Keywords: *basalt fiber, transport construction, heat treatment, fiber structure, alkali resistance of fibers, X-ray diffraction patterns, spectra.*

Introduction. Among the characteristics of fiber-reinforced concrete, its flexural and compressive strengths are usually distinguished. The value of this indicator in fiber concrete exceeds the value of conventional concrete by 10...15%. Only fiber concrete or fiber and rod or wire reinforcement are used in structures. Domestic and foreign experience shows that fiber concrete is a versatile material and is increasingly used in the field of transport construction.

Analysis of recent research and problem statement. The length of the road network with cement concrete pavements in countries such as Germany is 31%, the United States – 35%, and Belgium – 41%. The average service life of cement concrete pavements is more than 20 years. Even in those countries where asphalt pavements have economic advantages over cement concrete pavements, in order to improve and develop a competing technology, government subsidies support the construction of cement concrete pavements at the level of 10...20 % of the total volume of road construction with capital types of pavements [1,2]. In the 70s, the Soviet Union began massive construction of cement concrete pavements using machines with sliding formwork on caterpillar tracks. However, the practice of operating such pavements in the Soviet Union revealed a number of significant drawbacks. Failures in temperature joints, peeling of the concrete surface layer, chipping of slab edges and corners, and the formation of potholes appeared. Premature damage to pavements was usually caused by violations of construction technology, a shortage of high-quality cements, the use of low grades of concrete, insufficient air entrainment in concrete, and excessive exposure to saline solutions at the early stage of concrete hardening [3,4].

Unlike the Soviet Union, in many countries of the world, the construction of cement concrete pavements continued in parallel with the construction of asphalt pavements. Stable transport and operational characteristics and high durability have proven their superiority over pavements built with organic binders.

Cement concrete pavements have a high distribution capacity, low abrasion wear, and a high coefficient of adhesion that is not highly dependent on the moisture content of the pavement. The

strength and deformation characteristics of cement concrete practically do not change with changes in temperature, humidity and loading rate. Vehicles driving on roads with such pavements consume about 5...10% less fuel than asphalt concrete roads. In addition, there are large raw material resources for the production of cement concrete pavements [5,6].

Modern technologies for the construction of cement concrete pavements involve full automation of the main processes for placing and compacting concrete mixtures, treating the concrete surface, arranging thermal joints and caring for concrete.

In recent years, there has been a trend toward the creation of road concrete with increased strength and durability. This is achieved by modifying the structure of concrete with chemical additives: plasticizing, air-entraining and gas-forming [7,6]. A new generation of high-quality concrete (High performance concrete) has been developed that has increased frost resistance, early strength (at least 35 MPa after 24 hours) and other high construction and technical properties. Such concretes are also used in our country, including at transport construction sites.

In industrialized countries (USA, Canada, Australia, Great Britain, Germany, Sweden, Norway, Spain and many others), the construction of road pavements made of rigid cement concrete mixtures compacted by rolling is expanding [8,9].

Rolled concrete means rigid cement concrete transported by heavy-duty dump trucks or concrete mixers to the construction site and compacted with rollers of various types. Such concrete can be used in the construction of dams and dam retaining walls. In Europe and North America, concrete is used in transport construction for pavement layers for roads intended for heavy vehicles (container ships, heavy military vehicles, forestry machinery); container terminals, parking lots access, rural, forest roads with high traffic loads; secondary roads and streets, local roads and highways, road accesses to airports, airfield runways; as a reinforcement layer for the reconstruction of old road surfaces [10].

The analysis of the technical and operational characteristics of all types of fibers currently used in road construction suggests that it is most advisable to use basalt fiber as a reinforcing element in cement concrete [11,12,13].

Given the shortage of funds, there is a need to develop a program for the construction of highways using fiber concrete in the structural layers of the pavement that is acceptable from a financial and technical point of view.

Modern conditions of road construction dictate the widespread use of industrial waste - slag, burnt shale from coal mine dumps, ash, as well as virtually inexhaustible resources - chalk deposits and igneous rocks (basalts), which are currently of little use in transport construction. Given the conditions and international experience, it is advisable to accelerate developments in the field of fiber concrete technology and calculation, to use fiber concrete structures more widely in the design of transport construction facilities, and to use materials that are optimal in terms of cost and volume of deposits in Ukraine as fiber.

Basalt fibers are one of the most effective modern materials, characterized by high physical and mechanical properties and can be used in a wide range of temperatures.

The production of fibrous concrete in modern construction based on basalt fibers is promising because they work in aggressive environments (resistance to acids and alkalis), have good operational, physical and mechanical characteristics. All these properties of basalt fibers make it important to create high-performance building materials and products for various areas of the construction industry. [14]

It has been established [15] that the fiber in solution during cement hydration is characterized by insufficient alkali resistance.






The purpose and objectives of the study. As noted earlier [15], prolonged storage of fiber in solution contributes to its dissolution. In this regard, it is relevant to develop methods for modifying the surface layer of basalt fiber that will provide high corrosion resistance.

The efficiency of using basalt fiber in cement concrete can be increased by heat treatment of the fiber.

Materials and methods of the study. To study the effect of heat treatment on fiber properties, the fiber was subjected to heating in the temperature range from 300 to 700 °C with a step of 100 °C. The

isothermal exposure was 30 minutes. Cooling took place at room temperature in an air environment (Table 1).

Table 1: Fiber modified by heat treatment gradient

Manufacturer	300 ⁰ C	400 ⁰ C	500 ⁰ C	600 ⁰ C	700 ⁰ C
Armbud					
	Normal color	Normal color	Lightened color	Changes in color – more red	Changes in color – more red

The temperature treatment time was chosen empirically and amounted to 30 minutes.

In the course of the research, a significant change in fiber color was noted depending on the processing temperature (Table 1). The probable explanation for this fact is the oxidation of iron in the fiber structure, which resulted in the fiber acquiring a red hue.

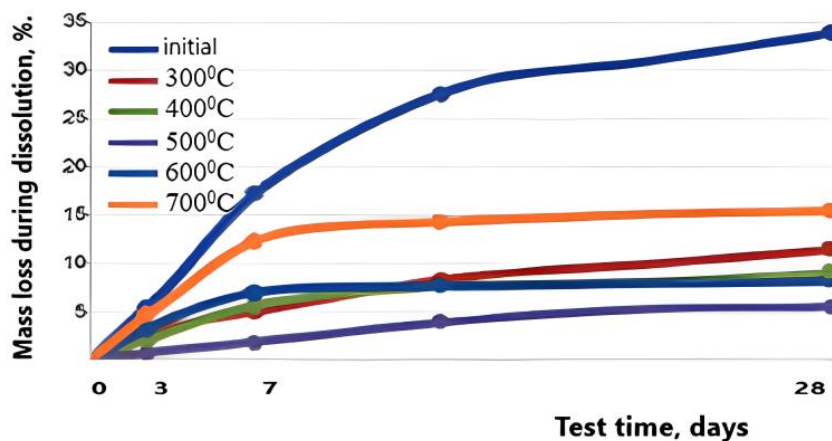


Fig. 1. Fiber weight loss during dissolution as a function of test time

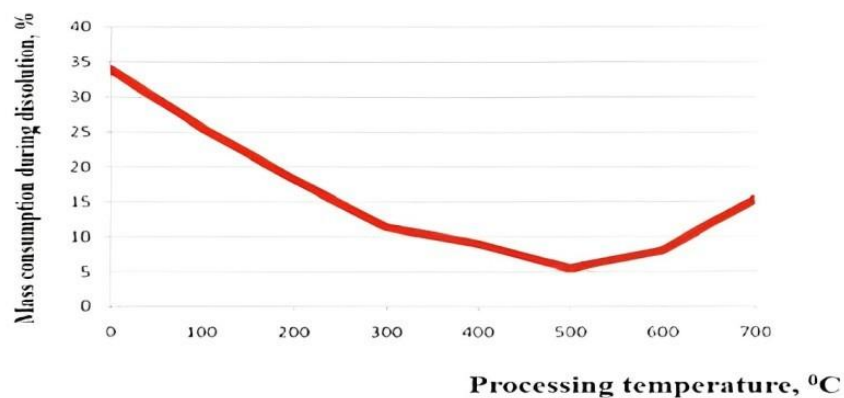
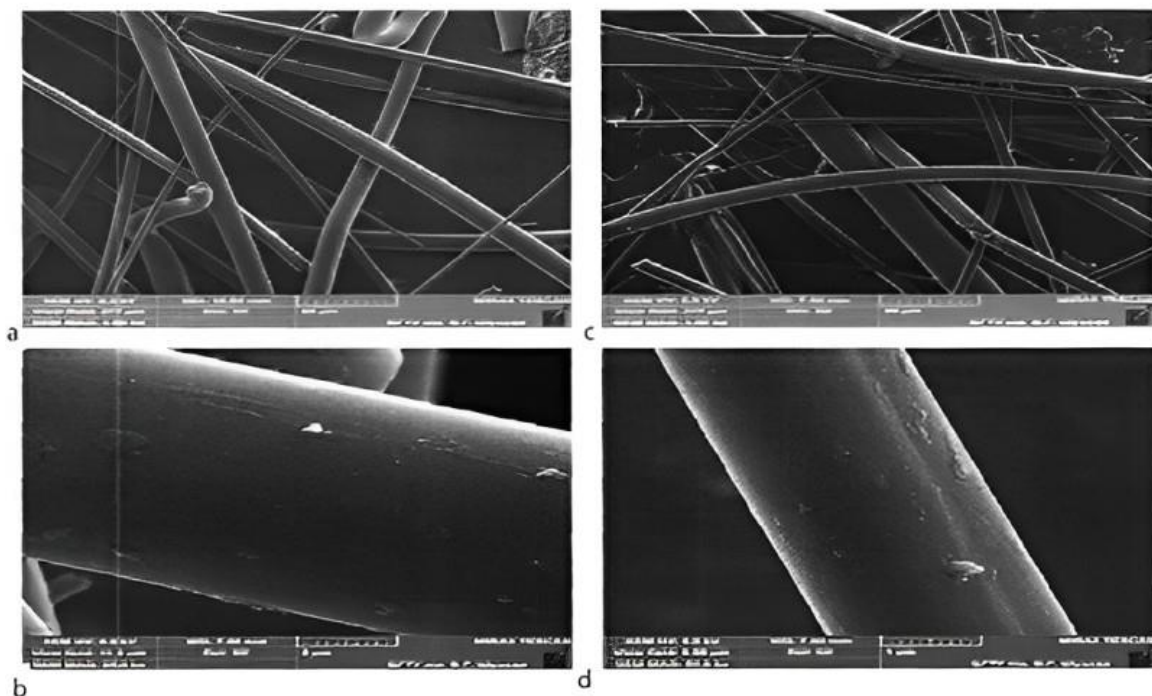


Fig. 2. Mass loss during dissolution depending on temperature treatment after aging in an alkaline environment for 28 days

As a result, it was found that an increase in temperature from 300 to 500 °C increases the alkali resistance of the fiber. The mass loss during aging in an alkaline solution after 28 days is about 5 %, while the original fiber loses more than 30 % of the fiber mass during this time. Further increase in the temperature of isothermal aging is not effective due to the decrease in alkali resistance of fibers and economic inexpediency.

When analyzing the microstructure of both the initial and heat-treated reinforcing component, there are no special changes (Fig. 3). This applies to both the size (diameter) (Fig. 3 a, d) and the surface of the fibers (Fig. 3 b, d). The diameter of the individual fibers varies in a wide range – from 2 to 30 microns. The surface of the fiber is quite smooth, but in some parts it is covered with globular formations, presumably carbonation products, up to 1 µm in size.

However, if the surface of the original fiber is highly coordinated (Fig. 4 (a, b), a-c), then after heat treatment it is covered with globular formations (Fig. 4 (b), d-f). The samples of the original anisotropic material have "eaten out" areas, longitudinal "furrows" in the direction of fiber elongation, which may indicate their internal structure (Fig. 4 (a, b), b, c). In this case, the destruction occurs along the weakest part - the interface, presumably, of individual fiber strands from aluminosilicate chains. If we consider the area of confirmed corrosion, it has a clear boundary (Fig. 4 (a), b) and a leaching depth of up to 400 nm (Fig. 4 (b), c). However, the actual amount of damage is greater due to corrosion of the entire surface layer of disordered aluminosilicate glass. There is a globular substance on the fibers themselves, which can be attributed to both X-ray amorphous calcium carbonate and alkali reaction products with the aluminosilicate material of the fiber itself.



*Fig. 3. Microstructure of basalt fiber:
a, b – initial; c, d – after heat treatment at 500 °C*

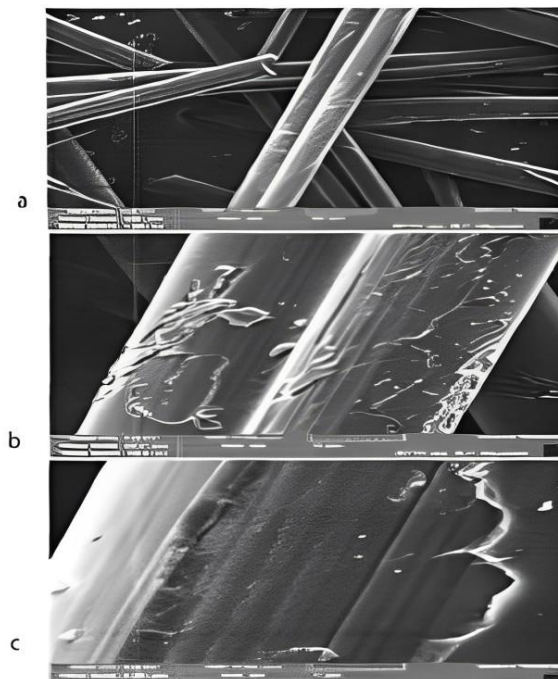


Fig. 4 (a). Effect of alkaline environment of the model system on the microstructure of basalt fiber: a...c – initial; d...e – after heat treatment at 500 °C

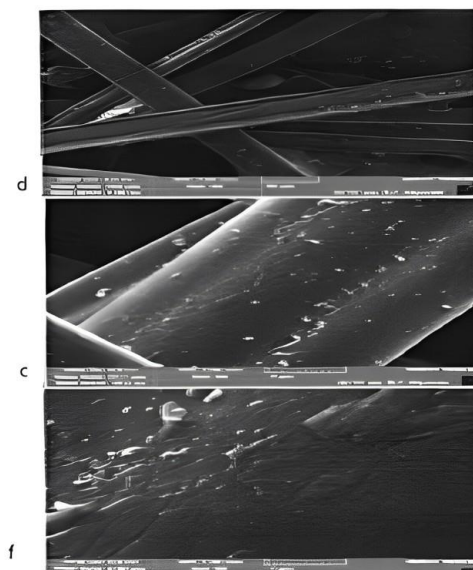


Fig. 4 (b). Effect of alkaline environment of the model system on the microstructure of basalt fiber: a...c – initial; d...e – after heat treatment at 500 °C

No obvious traces of leaching were found on the fibers after heat treatment (Fig. 4 (b), d-f). The absence of longitudinal «furrows» is noteworthy, which is a consequence of the high resistance of the modified basalt microfiber to alkaline environment. In general, it can be said that the surface morphology of the heat-treated fiber does not undergo serious changes under the influence of the aggressive environment of cement milk (Fig. 3).

The low alkali resistance of the original basalt fiber can be determined by several factors. As a result of the rapid cooling of the melt during the formation of fibers, a heterogeneous volumetric and surface loose high-temperature structure is fixed in them. At the same time, the fiber is characterized by surface defects (microcracks, micropores, bond breaks, etc.). All this together intensifies the process of dissolving the silicate framework.

During the heat treatment from 300 to 500 °C, defects are healed, the chemical composition and surface structure of the fibers change as a result of $\text{Fe}^{+2} \rightarrow \text{Fe}^{+3}$ oxidation and the formation of iron-oxygen tetrahedra $[\text{FeO}_4]\text{Na}$ with the involvement of alkaline cations on the fiber surface. The above processes are most active at 500 °C, a temperature close to the glass transition temperature (the transition from the solid to the plastic state).

At higher temperatures, structural changes associated with pre-crystallization processes (600 °C) and crystallization (700 °C) begin in basalt fibers, especially on their surface. Structural changes associated with crystallization are accompanied by the formation of various kinds of defects that make the material more chemically active and lead to accelerated interaction with alkali. At the same time, fiber weight loss increases.

To explain the processes occurring in the fiber structure during its heat treatment, X-ray diffraction patterns (Fig. 5) and spectra (Fig. 6) of the original and heat-treated fibers were obtained.

X-ray diffraction data were used to obtain an idea of the microstructural state of the initial and heat-treated basalt fiber.

The X-ray diffraction patterns of the basalt fiber are typical of structured amorphous materials with a characteristic broadened intensity profile in the region of angles around 30° (Fig. 5).

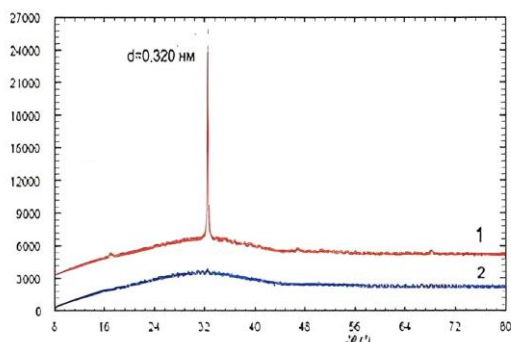


Fig. 5. X-ray diffraction pattern of basalt fiber before (1) and after (2) heat treatment

A characteristic feature of the fiber X-ray diffraction patterns is the presence of a single reflection 32.5°, with this reflection being most intense in the X-ray pattern of the initial fiber. Based on the general ideas about the rock-forming mineral phases of basalts and on the basis of XRD diagnostics performed using the diffraction database, this reflection can be attributed to $\text{Ca}(\text{Al}_2\text{Si}_2\text{O}_8)$.

The presence of this mineral in the X-ray diffraction patterns can be interpreted as a consequence of the finely plastic form of the crystallites. These nanoscale minerals on the surface of the fibers are attributed to newly formed phases during the drawing process. During heat treatment, they disappear from the fiber surface due to structural changes.

Comparison of the infrared spectra of basalt fiber before and after thermal modification showed a modification of the absorption band profiles of aluminosilicate groups in the region of 1000...300 cm^{-1} (Fig. 6).

In particular, the heat treatment causes a decrease in the intensities of the absorption bands 1019 and 1052 cm^{-1} , which are characteristic of the valence vibrations of Si-O-Si (Al) bonds in the anionic chain

groupings (Q^2) of clinopyroxenes. In view of this, there is an increase in the intensity of the bands of the framework structural fragments (Q^4) in the range of wave numbers 1084...1300 cm^{-1} .

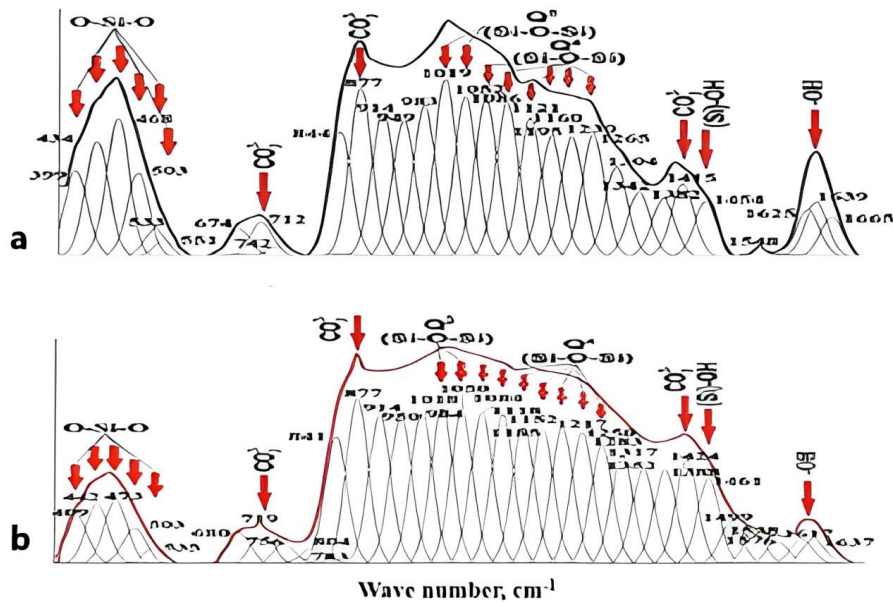


Fig. 6. Comparison of diagrams of normalized profiles of infrared spectra of the initial (a) and heat-treated (b) fiber

These circumstances indicate an increase in the level of polymerization, since an increase in the concentration of framework groups (Q^4) occurs due to a decrease in the number of chain fragments (Q^2). This results in a densification of the basalt fiber structure, which ultimately has a positive effect on the fiber's resistance to alkaline attack. Such structural shifts become possible due to the $Fe^{+2} \rightarrow Fe^{+3}$ transition as a result of heat treatment under oxidizing conditions, as noted by many researchers.

In order to select the basalt fiber most suitable for reinforcing the cement matrix, taking into account the wide geography of fiber application in the construction industry and the constantly growing volume of road construction in Ukraine, the fibers of the largest producers of basalt fiber were analyzed.

Based on a variety of initial properties, for a more accurate selection of basalt fiber, we analyzed the raw material composition, the ratio of geometric characteristics (length and diameter) of the fiber, as well as the methods of its production (Table 2).

Table 2: Properties of basalt fibers from different manufacturers

Company	Technology	Raw materials	Diameter, μm
Technobasalt - Invest LLC	Centrifugal dispersion	Basalt (SiO ₂ – 53%)	13...20
Plant of building materials and basalt products, LLC	Melt blowing by vertical air jet	Underlying basalt (SiO ₂ – 49%)	3...5
Basalt fiber & composite materials, LLC	Duplex process	Basalt (SiO ₂ – 53%)	1...3
Armbud, LLC	Centrifugal dispersion	Basalt (SiO ₂ – 52%)	1...3

One of the important initial parameters of a fiber is its composition. To increase the adhesion to cement stone, it is necessary that the fiber is characterized by a silicate composition, since concrete has an alkaline environment.

The elemental composition of basalt fiber (Table 3) from different manufacturers is characterized by slight variations in the elements.

Table 3: Composition of basalt fiber

Components	Technobasalt - Invest LLC	Plant of building materials and basalt products, LLC	Basalt fiber & composite materials, LLC	Armbud, LLC
	Fiber №1	Fiber №2	Fiber №3	Fiber № 4
Na	1,87	3,6	2,3	1,62
Mg	3,07	1,8	1,8	2,52
Al	5,331	6,4	6,9	5,41
Si	19,43	18,4	19,2	18,03
P	0	0,2	0,2	0,23
K	0,33	0,6	0,5	0,59
Ca	3, i	3,2	2,9	3,23
Ti	0,69	0,5	0,5	0,44
Mn	0	0,1	0	0
Fe	3,64	4,2	3,5	7,05
O	62,19	61	62,2	60,75
S	0,46	0	0	0,03

The resistance of basalt fibers in aggressive environments can be judged by the chemical composition of the raw material from which they are extracted. For example, alkali resistance increases with the introduction of structure-sealing oxides such as zirconium, aluminum, iron, tin, etc. Fiber resistance is also significantly affected by the technology and production method.

All this together can determine the possible submicron inhomogeneities associated with different Fe^{+2}/Fe^{+3} contents in the fiber, according to a number of researchers [11...12], determines the possible submicron inhomogeneities associated with the presence of iron outside the silicon-oxygen network, which in turn makes the fibers unstable to oxidation, and can also lead to crystallization at elevated temperatures.

As noted earlier, the geometric characteristics of the fiber are also important in the design of micro-reinforced materials. According to the literature, it is known that to achieve the optimal plastic-aggregate state of a micro-reinforcing component in a mixture, the initial components with an optimal length-to-diameter ratio of more than 10 should be selected [13...15]. The fiber produced by Armbud is characterized by the required ratio of geometric characteristics.

Cement milk was used as an aggressive medium, characterized by a sufficient alkaline environment ($pH = 12.9$). Fluffed fiber was introduced into the specified solution (Fig. 7). The concentration of basalt fiber in the solution was chosen taking into account the maximum fiber content in cement composites (3...12% by weight of the binder), established on the basis of literature data. The concentration was 7%.

The samples were aged at room temperature for 7, 14, 28, 72 days. After the exposure period, to remove the remaining cement component, the fibers were washed with a weak hydrochloric acid solution (0.1%) through filter paper. To remove impurities, the sample was further washed with 1 liter of distilled water. Then the basalt fiber was dried at room temperature. The solubility of the fiber was determined by the difference in masses before and after the experiment, as a dry residue as a result of exposure to alkaline medium. The mass loss was expressed as a percentage (Table 4). Possible fiber losses during washing (technological losses) were assumed to be comparable for each experiment.

Table 4. Results of the study of alkaline resistance of basalt fiber

№	Test time, days	Fiber weight before the experiment, g	pH initial	Weight after aging, g	Weight loss, %	pH after the experiment	Color
1	7	4,9	11,9	4,2	14,3	11,9	normal
2	14	5,2	11,9	3,6	30,7	11,5	normal
3	28	5,0	11,9	3,4	32,0	11,4	poorly lit
4	72	5,1	11,9	2,1	58,8	11,3	illuminated

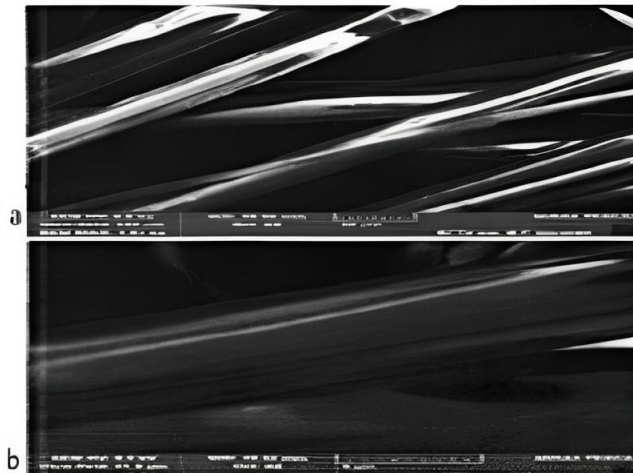
During the observation on day 7, a slight precipitation of white precipitate was detected on the surface of the fibers, probably due to the crystallization of CaO on the keratinized surface of the basalt.

In the period from 14 to 28 days, as a result of thinning of smaller fiber villi, the total mass of basalt fiber gradually crumbled with slow deposition of small fiber particles (up to 20%). On day 28, the amount of white sediment increased and covered more and more large fibers. Examination of the sample on day 72 revealed a change in the color of the fiber surface from lightly colored for small villi to gray for larger fibers.

It was found that the change in the pH of the cement mortar significantly depends on the time the fiber samples were in it. Thus, on day 7, no increase in pH was recorded, on day 14, a decrease of 2% was noted, and in the period from 28 to 72 days, a decrease of 4.3% was achieved relative to the initial one.

After 28 days of exposure to the solution, the weight loss was about 32%. Long-term storage of fiber (72 days) in solution leads to a mass loss of up to 59%.

The above facts are consistent with the results of microstructural studies of basalt fibers (Fig. 7). There is a significant leaching of the initial aluminosilicate materials after aging for 28 days in the alkaline environment of cement milk. This contributes to the appearance of characteristic traces of corrosion on the surface (Fig. 7 c, d), which negatively affects the reinforcing function of the anisotropic component of the cement matrix.



**Fig. 7. Microstructure of basalt fiber:
a, b - in the initial state; c, d - aged in an alkaline environment for 28 days**

When operating basalt fiber in real conditions in concrete, the degree of fiber dissolution will not be so significant, since the dissolution processes will subside as the cement stone hardens and hardens. Nevertheless, the chemical processes occurring in concrete during its service life, in which the fiber is

involved, should not be underestimated. In this regard, it is necessary to develop a method of fiber modification to increase its resistance in an aggressive alkaline environment.

Conclusions.

1. The expediency of heat treatment of basalt fiber at a temperature of 500 °C with subsequent cooling in an air environment at room temperature to increase its alkaline resistance has been substantiated. A model of modification of basalt fiber during heat treatment based on the $\text{Fe}^{+2} \rightarrow \text{Fe}^{+3}$ transition as a result of heat treatment under oxidizing conditions is proposed. The change in the coordination environment that occurs during this process initiates the formation of bonds between $(\text{Si}_2\text{O}_6)^{-1}$ and their transformation into a skeletal structural type with the formation of iron-containing plagioclase phases. These processes lead to the compaction of the fiber structure and contribute to the increase of its alkali resistance, which is confirmed by the morphostructural features of the surface of the heat-treated basalt fiber aged in cement mortar.

2. The analysis of the main fibers currently used in the production of building materials as a micro-reinforcing component, according to a number of variable criteria, made it possible to single out basalt fiber as the most rational in terms of its use in the production of fine-grained micro-reinforced cement concrete, including for road construction. A comparative analysis of fibers from 4 manufacturers by a set of indicators: geometry, chemical composition, physical and mechanical characteristics, made it possible to identify the fibers of Armbud, which most closely meet the requirements.

3. It was found that basalt fiber undergoes significant dissolution during aging in an aggressive and alkaline environment with a pH corresponding to the hydration of cement stone. At the same time, after 28 days of exposure to an alkaline solution, the mass loss is about 30%. Long-term storage of fiber (72 days) in solution leads to a mass loss of up to 59%. It becomes obvious that there is a need to develop a method to increase the alkali resistance of basalt fiber to increase its durability.

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Використання модифікованого базальтового волокна в транспортному будівництві

Базальтоне волокно - це перспективний матеріал, який може бути використаний для створення нового класу будівельних матеріалів. Воно має ряд переваг, включаючи високу міцність, низьку вагу і стійкість до хімічних впливів. Одним з недоліків базальтового волокна є його низька лугостійкість. У лужному середовищі волокно руйнується, що обмежує його застосування в будівельних матеріалах, які піддаються впливу лугів. У статті досліджено вплив термічної обробки на лугостійкість базальтового волокна. Було встановлено, що термічна обробка при температурі 500 °С підвищує лугостійкість волокна на 80%. Це відбувається в результаті ущільнення структури волокна і формування на його поверхні залізоокисневих тетраедрів, які стійкі до дії лугів. Автори статті обґрунтовують доцільність використання термічно обробленого базальтового волокна в транспортному будівництві. Цей матеріал може бути використаний для виготовлення нових типів будівельних матеріалів, які будуть стійкі до впливу лугів.

Ключові слова: базальтоне волокно, транспортне будівництво, термічна обробка, структура фібри, лугостійкості волокон, рентгенограми, спектри.

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Formation and management of safety culture in the railway industry: best practices and strategies

This article examines the current issue of safety culture in the railway industry, in particular, the formation and development of a safety culture on the railways of Ukraine. In the article emphasizes the uniqueness of the European model of railway safety culture. The purpose of the study is to comprehensively study the principles, methods and effectiveness of the formation and management of the safety culture in the railway industry. Recommended strategies include leadership commitment, staff engagement, training, communications, security audits, and technology use. A comparative analysis between the EU and Ukraine's railway system points to structural and regulatory differences, emphasizing the need for Ukraine to adapt European practices in the field of safety. The article also offers a structured approach to incident analysis and implementation of security practices, as well as the application of the Plan-Do-Check-Act cycle for systemic security management. These approaches aim to improve safety practices and ensure efficient transportation systems.

Key words: *Safety Culture, Railway Industry, Risk Management, Employee Education, Awareness, Technology, Safety Improvement, Organizational Safety.*

Introduction. Today, the safety of railways is a very important topic, which focuses a lot of interest in many countries of the world. Current aspects of railway security include the following topics: cyber security of railway transport; countering terrorism and vandalism; safety of passengers and employees; risk management and emergency preparedness; environmental safety and sustainable development. This article deals with the topical topic of the formation and development of safety culture in the railway industry of Ukraine.

To implement this practice in developed railway systems, a number of interrelated issues are resolved, the main aspects of which are shown in the diagram shown in fig. 1. This article examines these aspects and offers conclusions and strategies for the formation and development of a safety culture in the railway industry of Ukrainian railways.

Analysis of recent research and problem statement. A key and necessary condition for the sustainable development of the railway industry is to support and improve the level of safety at each railway transport enterprise and for the railway system as a whole.

Safety culture is a system that encompasses the attitudes of a particular group to risk, safety and threats, indicating the values that are considered key in this area.

Safety culture is the main prerequisite for the effective operation of the railway system. The safety and maintenance management system is based on a safety culture and is an important element in all railway organizations to maintain and improve safety.

A properly understood safety culture is based on a high level of trust and respect between employees and management, so it must be created and maintained by senior management.

The full definition of safety culture is contained in the European Railway Safety Culture Declaration: "Safety culture means the interaction between the requirements of the Safety Management System and

how people understand them based on their attitudes, values and beliefs and what they actually do, as seen from decisions and behaviour. A positive safety culture is characterized by the collective commitment of leaders and individuals to act safely at all times, particularly when faced with competing goals” [1].



Fig 1. Basic aspects of safety culture implementation in railway systems

According to the findings of European national accident investigation bodies, a poor safety culture on the railways has played a role in major rail transport accidents, including those in Great Britain and France. As part of the research conducted in the laboratory of the Lviv Scientific and Research Institute of Forensic Examinations of railway accidents that occurred on the railways of Ukraine, the need to implement an effective safety management system and the formation of a safety culture was also noted.

There are many approaches to assessing and improving safety culture in the railway industry [3-20]. The European Railway Agency (ERA) has defined important standards and developed a key model, taking into account the unique needs of the railway industry [1]. This model acts as a reference basis for evaluating and improving the safety culture, ensuring compliance with the highest standards of reliability and safety.

In turn, the International Union of Railways (UIC) provides guidance on safety culture, emphasizing a global approach to ensuring safety in different regions of the world [2]. These recommendations take into account the challenges and peculiarities faced by the railways of different countries, offering practical strategies and methods for improving the safety culture at all levels of management and interaction of the participants of the railway transport system.

These two influential organizations work together to establish high standards of safety and culture in the rail industry to ensure the efficient and reliable transportation of passengers and freight, reducing risks and improving the overall safety status of the rail system worldwide.

The European Union Agency for Railways (ERA) has introduced its "Safety Culture Model," which serves as a conceptual and evaluative framework for analysing and improving safety culture within railway organizations. The model is divided into three key components [1]:

Cultural Factors: these are levers that determine the development of organizational culture.

Behavioural Models: these are shared ways of thinking and acting that reflect the organizational culture.

Railway Safety Foundations: key principles that must be considered in behavioural models to achieve sustainable safety performance and organizational excellence.

These three components encompass four cultural factors and four fundamental railway safety principles, forming a total of 24 attributes. These attributes serve as a valuable tool for railway organizations to identify their cultural strengths and weaknesses, contributing to the development of a positive safety culture in the railway industry. Figure 2 shows the European Railway Safety Culture Model.

Considering the European integration vector of Ukraine, it is important to implement European practices in the field of security in the railway industry.

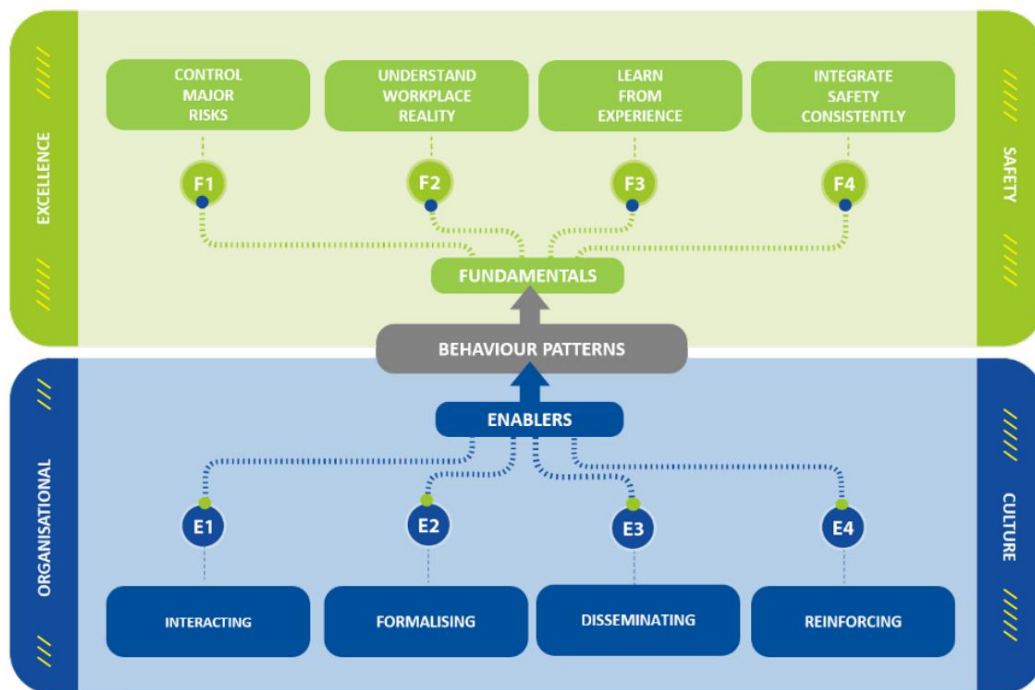


Fig 2. The European Railway Safety Culture Model

In order to ensure the safety and efficiency of operations in the railway industry, the availability of a skilled workforce with relevant competencies is a critical element. Employees of the industry daily perform such operations as inspection, maintenance and modernization of infrastructure and rolling stock. As demands on the rail network continue to grow, it is important that these industry workers receive ongoing training to ensure their skills and competencies are up to date with industry requirements.

The purpose and tasks of the study. The purpose of the study is to comprehensively explore the principles, methods, and effectiveness of forming and managing safety culture in the railway industry, with a focus on identifying best practices and developing strategic approaches. The research aims to contribute valuable insights into enhancing safety measures within railway operations.

The purpose of the study is a comprehensive study of the principles, methods and effectiveness of the formation and management of safety culture in the railway industry with an emphasis on identifying best practices and developing strategic approaches. The study aims to provide valuable information on improving safety measures during railway operations.

The tasks of the research include:

- study of the existing literature on safety culture in the railway industry;
- analysis of case studies, research articles and reports related to security practices;
- research on successful safety initiatives implemented by railway organizations around the world;
- determination of specific practices and strategies that have proven their effectiveness in increasing safety culture;
- assessment of the current state of safety culture in the railway industry;
- studying the effectiveness of existing programs and security policies;
- development of a strategy for the formation and improvement of safety culture based on identified best practices;
- comparison of the practice of safety culture in the railway industry with other highly reliable industries; comparison with international standards and recommendations.

- providing recommendations to railway organizations on strengthening the safety culture and improving the overall safety system.

Materials and methods of research. The formation of a safety culture in the railway industry requires a comprehensive approach, involving the engagement of personnel at all organizational levels and considering the industry's specifics. Best practices include:

1. *Leadership and Management Engagement:*
 - Prioritizing safety and demonstrating leadership commitment.
 - Leaders actively communicating with staff about the importance of safety rules and setting an example in following these rules.
2. *Training and Education:*
 - Regular training and reminders of safety rules.
 - Organizing seminars, training sessions, and other educational events on safety issues.
3. *Employee Involvement:*
 - Involving employees in decision-making processes related to safety.
 - Establishing feedback mechanisms for employees to report potential hazards and safety violations.
4. *Setting Safety Goals and Policies:*
 - Establishing specific safety goals and tracking their achievement.
 - Measuring safety indicators to assess the effectiveness of measures and risk management.
5. *Enhancing Communication:*
 - Ensuring effective safety information exchange across all organizational levels.
 - Encouraging open communication and reporting of incidents, even minor ones.
6. *Safety Audits and Evaluation:*
 - Conducting regular audits and evaluations of the safety management system to identify weaknesses and potential improvements.
7. *Compliance with Regulations and Standards:*
 - Ensuring compliance of all processes and procedures in the railway industry with established standards and regulatory requirements.

These practices contribute to creating a robust safety culture in the railway industry, ensuring the effectiveness and safety of railway transportation systems.

Managing safety culture in the railway industry requires a systematic and comprehensive approach aimed at forming and maintaining a safe working atmosphere. Here are some of the best safety culture management strategies in the railway industry:

1. *Leadership and Exemplification:*
 - Decisive top-down leadership prioritizing safety and actively embodying safety principles in all aspects of operations.
2. *Employee Engagement:*
 - Ensuring active participation of employees in shaping and implementing safety strategies.
 - Considering the opinions and ideas of employees for improving workplace safety.
3. *Training and Development:*
 - Conducting systematic safety training for all staff.
 - Providing opportunities for professional growth and skill development in the safety field.
4. *Communication and Feedback:*
 - Ensuring open and effective communication across all organizational levels regarding safety matters.
 - Establishing mechanisms for collecting and analysing feedback to improve the safety system.
5. *Safety Identification Building:*
 - Creating a specific organizational image where safety is a key component of corporate culture.
6. *Effective Use of Technology:*
 - Implementing modern technologies and innovations to enhance safety systems and operational efficiency.

7. *Monitoring and Analysis:*

- Regular monitoring and analysis of safety conditions, identifying issues, and taking appropriate measures for resolution.

8. *Recognition and Motivation:*

- Establishing a reward and recognition system for achievements in safety, encouraging employees to be more attentive to safety.

These strategies contribute to the creation of an effective safety culture in the railway industry, ensuring optimal protection for both employees and passengers.

Comparing safety culture across rail systems is challenging because of the different contexts, sizes, cultural differences, and management strategies. However, it is possible to highlight the main aspects for comparison, which are shown in Figure 3.



Fig 3. Key aspects for comparing safety culture in different railway systems

A comparison of the safety culture in the railway systems of the European Union (EU) and Ukraine is given in the Table 1.

Table 1. A comparison of the safety culture in the railway systems of the European Union (EU) and Ukraine

No	Indexes	EU	Ukraine
1	Structure and organization	The EU has an extensive rail transport system, including many member states, each of which has its own internal organization and management of railways	The railway system of Ukraine is centralized and owned by the state company JSC Ukrainian Railways (Ukrzaliznytsia), which is a monopoly operator
2	Regulations and standards	The European Commission and the European Railway Agency (ERA) set safety standards and regulations to ensure unity and a high level of safety in the EU rail industry	The Ukrainian State Transport Safety Service is responsible for regulating and overseeing safety in the transport industry, including railways
3	Safety standards and approaches	The European approach to safety includes strict standards and a high level of automation, technology and control over train traffic and infrastructure	Ukrainian safety standards also meet international requirements, but there is a problem of financial constraints and equipment obsolescence
4	Investments and development	European countries are actively investing in the modernization and development of railway infrastructures, in particular high-speed railways, and environmentally friendly vehicles	Ukraine also has plans to modernize its rail infrastructure and improve safety, but limited budget resources may affect the speed and scope of these reforms

Also, in the EU, great emphasis is placed on education and training of personnel in the field of safety and technical aspects of railway transport.

The development of a safety culture in railway transport in Ukraine is crucial to ensure the highest level of safety for both passengers and personnel. Important steps and corresponding actions of the strategy for the development of a safety culture in railway transport in Ukraine are given in Table 2.

Table 2. Important steps and corresponding actions of the strategy for the development of a safety culture in railway transport

№	Important steps	Actions
1	Regulatory Framework Strengthening	Enhance and enforce existing safety regulations and standards, ensuring that they align with international best practices. This includes oversight, monitoring, and audits to verify compliance.
2	Education and Training	Comprehensive training of railway employees at all levels on safety procedures, protocols, and emergency response. Encouraging continuous learning and skill development to keep employees up-to-date on the latest security measures.
3	Safety Communication	Promoting open communication channels where employees can freely report safety concerns, incidents, or potential hazards without fear of retaliation. Encouraging a reporting culture that emphasizes learning from mistakes
4	Safety Leadership	Leaders within the railway industry should set an example by demonstrating a strong commitment to safety. They should actively participate in safety initiatives, emphasize safety as a core value, and communicate safety expectations to all employees.
5	Involvement and Participation	Involvement of employees in safety decision-making processes, hazard identification, risk assessment, and development of safety procedures. Such participation increases a sense of ownership and responsibility for safety.
6	Risk Assessment and Management	Carrying out a thorough risk assessment of all aspects of railway operations. Identifying potential hazards and developing a risk mitigation strategy. Regularly review and update the risk assessment to adapt to changing circumstances.
7	Safety Performance Metrics	Establish clear safety performance indicators and regularly measure, monitor, and evaluate safety performance. Recognize and reward individuals and teams that contribute to maintaining a high level of safety.
8	Investment in Technology	Implement modern safety technologies such as advanced signalling systems, predictive maintenance tools, and automated control systems that can enhance safety and minimize the risk of accidents.
9	Collaboration and Partnerships	Foster collaboration and information sharing among railway companies, industry associations, government bodies, and international organizations. This can facilitate the exchange of best practices and innovative safety solutions.
10	Emergency Response Preparedness	Ensure that railway personnel are well-trained in emergency response procedures and conduct regular drills to enhance preparedness for various emergency scenarios.
11	Public Awareness and Education:	Educate the public about railway safety through campaigns, workshops, and school programs to instill safe behaviors and raise awareness about the risks associated with railway transport.
12	Continuous Improvement	Encourage a culture of continuous improvement by conducting regular safety reviews, learning from incidents, and implementing necessary changes to prevent similar incidents in the future.

A safety culture is a collective mindset, values, and behaviours within an organization that prioritize safety and encourage safe practices at all levels. By integrating these strategies and fostering a safety-oriented mindset at all levels of the railway transport sector in Ukraine, a strong safety culture can be developed, leading to safer operations and a reduced risk of accidents or incidents.

Identifying threats to train traffic safety is a critical step in ensuring a safe railway system. Threat identification involves recognizing potential risks, hazards, or factors that could compromise the safety of train operations. The following methods and approaches for determining threats to train traffic safety can be identified:

1. *Risk Assessments*. Conducting a comprehensive risk assessment and hazard analysis to identify potential threats. These assessments should cover various aspects, including infrastructure, equipment, operations, human factors, and environmental conditions.

2. *Safety Audits and Inspections*. Conducting regular safety audits and inspections of railway structures, tracks, stations, signalling systems, rolling stock and other critical components. Identification of any deviations from safety standards and their immediate elimination.

3. *Incident and Accident Analysis*. Analysis of past incidents and accidents in the rail system to identify recurring patterns, root causes and contributing factors. Learning from previous incidents can help in proactively addressing similar threats in the future.

4. *Safety Reporting Systems*. Implementing a robust safety reporting system that will encourage employees and stakeholders to report safety issues, incidents or unsafe conditions. Analysing these reports can help in identifying potential threats and taking preventive measures.

5. *Safety Meetings and Workshops*. Organizing regular safety meetings, seminars and brainstorming sessions with employees and stakeholders. These sessions can provide valuable insights and perspectives on potential threats and safety improvement opportunities.

6. *Job Safety Analysis (JSA)*. Conducting occupational safety analysis for various tasks and operations on the railway. This involves breaking down tasks into individual steps and identifying potential hazards and risks associated with each step.

7. *Human Factors Analysis*. Investigating human factors that may pose a safety risk, such as fatigue, distraction, lack of training or inadequate staffing levels. Addressing human factors is crucial to ensure safe train operations.

8. *Safety Surveys and Feedback*. Collecting feedback and information from employees, passengers, and other stakeholders through safety surveys. These surveys can help identify areas of concern and potential threats that might have been overlooked.

9. *Collaboration with Industry Experts*. Cooperation with safety experts, consultants, or external organizations with expertise in railway safety. Participate in security audits and consultations to identify threats and receive recommendations for improvement.

10. *Utilization of Advanced Technologies*. Implementation of advanced technology such as sensors, cameras, predictive maintenance tools and real-time monitoring systems. These technologies can provide real-time data and alerts to identify potential threats and safety issues promptly.

11. *Close Monitoring of Weather Conditions*. Keep a close eye on weather forecasts and conditions, as adverse weather such as heavy rain, snow or extreme temperatures can affect rail safety. Taking appropriate measures to mitigate the impact of adverse weather conditions on the operation of trains.

12. *Simulation and Scenario Planning*. Using simulation software to model and simulate various scenarios to identify potential threats and assess the safety implications of different operational situations.

By employing a combination of these methods, railway authorities can proactively identify threats to train traffic safety and take appropriate preventive and corrective actions to ensure a safe and reliable railway system.

Analysing the results of investigations into transport incidents on railway transport is crucial for understanding the causes, patterns, and potential impacts on safety. This analysis helps in identifying trends, improving safety measures, and implementing preventive actions. Table 3 provides a

recommended structured approach to rail incident analysis that organizations can use to identify critical safety issues and implement necessary improvements.

Table 3. A recommended structured approach to rail incident analysis

№	Hunting action	Recommended actions
1	Incident Data Collection	Gather detailed incident data including the date, time, location, type of incident, individuals involved, weather conditions, and any other relevant contextual information. Ensure data accuracy and completeness.
2	Root Cause Analysis (RCA)	Conduct a thorough root cause analysis for each incident to determine the underlying factors that contributed to the occurrence. Identify immediate, underlying, and systemic causes.
3	Categorization of Incidents	Categorize incidents based on their nature (e.g., collisions, derailments, signal violations, human error) and severity (e.g., minor, significant, catastrophic) to identify trends and patterns.
4	Frequency and Trend Analysis	Analyse incident data over a specific period to identify trends, patterns, and frequencies. Determine if the number of incidents is increasing, decreasing, or remaining constant, and identify any seasonal variations.
5	Identification of Common Factors:	Identify common factors across multiple incidents, such as equipment malfunctions, human error, maintenance issues, or inadequate training. Highlight recurring issues that need immediate attention.
6	Human Factors Analysis:	Evaluate the role of human factors in incidents, including factors such as fatigue, distractions, communication breakdowns, and inadequate training. Determine the impact of human performance on safety.
7	Equipment and Infrastructure Analysis	Evaluate the role of equipment malfunction, signalling system failures, track conditions, and overall infrastructure in incidents. Understand how these factors affect safety.
8	Regulatory Compliance Assessment	Evaluate incidents in the context of regulatory compliance to identify whether safety regulations and guidelines were followed. Assess the adequacy and effectiveness of existing safety protocols.
9	Safety Culture Assessment	Evaluate if there are indications of a poor safety culture within the organization by analysing incident reports and employee feedback. Consider factors like reporting culture, blame-free environment, and accountability.
10	Impact on Safety Measures	Assess how incidents have influenced safety measures, protocols, and procedures. Evaluate changes made post-incident to enhance safety and prevent future occurrences.
11	Lessons Learned and Recommendations	Summarize the lessons learned from each incident and provide recommendations for preventing similar incidents. Propose corrective actions, procedural changes, training improvements, or equipment upgrades.
12	Data Visualization and Reporting	Present the analysis findings through data visualization techniques such as charts, graphs, and dashboards. Create comprehensive reports summarizing the incident analysis and recommendations.
13	Implementation of Corrective Actions	Ensure that the recommendations are implemented effectively to improve safety. Monitor the progress and effectiveness of corrective actions.
14	Continuous Monitoring and Improvement	Establish a system for continuous monitoring, learning, and improvement based on incident analysis. Regularly revisit incident data, update safety measures, and conduct periodic safety reviews.

The Safety Management System (SMS) is fundamental for ensuring high levels of railway safety. Both railway operators and infrastructure managers share the responsibility for safety within the railway system. The SMS's purpose is to secure business objectives safely and adhere to safety obligations in the dynamic railway environment. Compliance with Directive (EU) 2016/798 is necessary for safety certificates or authorizations, involving a comprehensive Plan, Do, Check, Act (PDCA) cycle. A systematic approach considers individual requirements, their integration, and interfaces with other railway actors, emphasizing hazard identification, risk management, and accident prevention. Effective risk control involves three critical dimensions: technical, human, and organizational components.

The Plan-Do-Check-Act (PDCA) cycle can be applied to manage safety systems in railway transport. Figure 4 shows the application of the Plan-Do-Check-Act (PDCA) method for the management of railway safety systems.

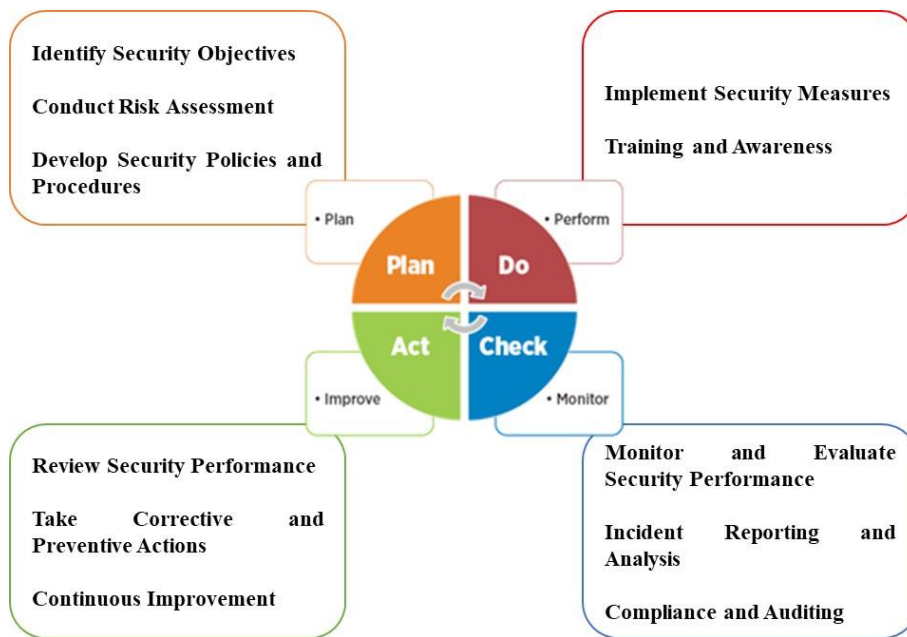


Fig 4. Application of the Plan-Do-Check-Act method to the management of the safety system in railway transport

Application of the Plan-Do-Check-Act method to the management of the safety system in railway transport.

1. Plan:

- *Identify Security Objectives:* Define security objectives, considering the unique security risks and challenges associated with railway transport. Objectives may include preventing sabotage, ensuring passenger safety, protecting critical infrastructure, and cybersecurity.

- *Conduct Risk Assessment:* Perform a thorough risk assessment to identify security risks specific to railway operations. Consider aspects such as potential terrorist threats, cyber-attacks, unauthorized access to tracks or stations, and safety hazards.

- *Develop Security Policies and Procedures:* Establish comprehensive security policies and procedures that address identified risks. Include guidelines for access control, emergency response, cybersecurity measures, employee training, and communication protocols during security incidents.

2. Do:

- *Implement Security Measures:* Put into action the security controls and measures outlined in the security policies. This may involve deploying surveillance systems, access control technologies, cybersecurity measures, security personnel deployment, and safety protocols.

- *Training and Awareness*: Conduct training programs and awareness campaigns for railway staff regarding security policies, emergency response procedures, and the use of security technologies. Raise awareness about the importance of security and reporting any suspicious activities.

3. Check:

- *Monitor and Evaluate Security Performance*: Continuously monitor security measures using a combination of surveillance systems, security audits, and feedback mechanisms. Regularly assess the effectiveness of implemented security controls against predefined key performance indicators (KPIs).

- *Incident Reporting and Analysis*: Establish an incident reporting system to capture security incidents or breaches. Analyse these incidents to understand the root causes, identify vulnerabilities, and develop strategies to prevent similar incidents in the future.

- *Compliance and Auditing*: Conduct regular compliance audits to ensure that security measures and practices align with the established security policies and relevant regulations. Address any non-compliance issues promptly.

4. Act:

- *Review Security Performance*: Review the data and insights obtained from monitoring, incident analysis, and audits. Evaluate the performance of the security system and identify areas for improvement.

- *Take Corrective and Preventive Actions*: Implement corrective actions to address identified security gaps and incidents. Also, proactively introduce preventive measures based on lessons learned and emerging security threats.

- *Continuous Improvement*: Integrate the lessons learned and recommended improvements into the security policies and procedures. Continuously update and adapt security measures to enhance the security posture of the railway transport system.

Conclusions. The article underscores the critical importance of safety culture in the railway industry, emphasizing its role in ensuring the safety of passengers, employees, and the overall railway system.

Drawing from global best practices, the article highlights the European Railway Safety Culture Model as a comprehensive framework. It discusses the role of influential organizations like the European Railway Agency (ERA) and the International Union of Railways (UIC) in shaping safety standards and promoting a positive safety culture worldwide.

The article identifies leadership, employee engagement, training, communication, safety audits, compliance, and technological advancements as key components of an effective safety culture. It emphasizes the need for a dynamic safety culture that adapts to changes over time.

A comparative analysis between the European Union (EU) and Ukraine's railway systems reveals distinctions in structure, regulations, safety standards, investments, and cultural emphasis on education and training. The article recognizes the need for Ukraine to align with European practices in enhancing railway security.

The article provides a set of comprehensive strategies for managing safety culture in the railway industry. These strategies encompass leadership commitment, employee engagement, continuous training, effective communication, safety audits, compliance with regulations, and utilization of technology.

The article outlines methods for identifying threats to train traffic safety, including risk assessments, safety audits, incident analysis, safety reporting systems, and collaboration with industry experts. It emphasizes the importance of proactive measures to ensure a safe and reliable railway system.

A recommended structured approach to rail incident analysis is presented, involving incident data collection, root cause analysis, categorization, frequency and trend analysis, human factors analysis, and continuous improvement. This approach aims to learn from incidents, improve safety measures, and implement necessary corrective actions.

The application of the Plan-Do-Check-Act (PDCA) cycle to the management of railway safety systems is illustrated. This cyclical approach involves planning security objectives, implementing

security measures, monitoring and evaluating performance, and taking corrective and preventive actions. The PDCA cycle is presented as a systematic method for continuous improvement in railway safety.

The suggested approaches and frameworks aim to guide the railway industry towards enhanced safety practices, ultimately ensuring the well-being of passengers and personnel while maintaining efficient and reliable transportation systems.

All organizations have their own security culture, regardless of whether they pay attention to it or explicitly manage this process. Various events and accidents that have occurred in various industries demonstrate that a low level of safety culture can lead to catastrophic consequences. Thus, companies and regulators in various fields recognize the urgent need to actively build a positive safety culture. This culture must not only be static, but also dynamic, constantly monitored, and ready to change or improve over time. Ensuring a high level of security requires organizations to be aware of and implement security principles and practices, thereby contributing to the safe and stable operation that is important to all participants in the process.

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Формування та управління культурою безпеки в залізничній галузі: найкращі практики та стратегії

У статті розглядається актуальне питання культури безпеки в залізничній галузі, зокрема, формування та розвитку культури безпеки на залізницях України. У статті підкреслюється унікальність європейської моделі культури безпеки на залізниці. Мета дослідження полягає в комплексному дослідженні принципів, методів та ефективності формування та управління культурою безпеки в залізничній галузі. Рекомендовані стратегії включають відданість керівництва, залучення персоналу, навчання, комунікації, перевірки безпеки та використання технологій. Порівняльний аналіз між залізничною системою ЄС та України вказує на структурні та нормативні відмінності, наголошуючи на необхідності для України адаптувати європейську практику у сфері безпеки. У статті також пропонується структурований підхід до аналізу інцидентів і впровадження практик безпеки, а також застосування циклу «План-Виконання-Перевірка-Дія» для системного управління безпекою. Ці підходи спрямовані на покращення практики безпеки та забезпечення ефективності транспортних систем.

Ключові слова: культура безпеки, залізнична галузь, управління ризиками, навчання працівників, обізнаність, технологія, підвищення безпеки, організаційна безпека.

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Surge suppressors for DC semiconductor switching devices

The research including the switching surges at semiconducting switches of commutation apparatus during the time of switching DC circuit. The target of this research is to develop a method for calculating the parameters of a switching surge which consists of series of parallel-connected varistors for using in semiconductor commutation devices. On the basis of researching the transient processes that can be in such surge restrictors of voltage in semiconductor switches at DC circuits. mathematical calculation expressions have been proposed for calculating the main parameters of the overvoltage regulator. In the issue, an engineering method allows the calculating the parameters of varistor surge regulators also for hybrid and contactless semiconductor apparatus of the DC circuits, and allows to choose lower level of surge admissible for this class of semiconducting devices. The results of the work make it easier high accuracy at a little time in choosing full controlled semiconductor switches with regard to the current and voltage in the design process of modern switching semiconductor apparatus that work in the DC circuits. That helps to solve the basic tasks of apparatus engineering. The voltage regulator that is proposed for DC semiconductor switching apparatus allows to limit effectively of switching surges in the power semiconductor devices to below several times by rated voltage level.

Keywords: *switching surge, voltage regulator, varistor, semiconductor apparatus, semiconductor device.*

Introduction. In the end of 20th century a new stage began in the designing of power electronics. It associated with the development of powerful full controlled semiconductor devices (SDs), in particular a double-gate turn-off (D-GTO) thyristor, a GCT-thyristor (gate commutated turn-off thyristor) and a high-speed power insulated gate bipolar transistor (IGBT-transistor). The high level electronic technology facilitates to organize a growing number of production of those devices in the type of compact integrated module structures as such as IGCTs (GCT-based thyristors) and IGBTs (BTIZ-based thyristors). These devices are characterized by high reliability and affordable price. The combination of semiconductor devices and control circuits for them in a single design with different degrees of integration has created excellent conditions to implement various laws of controlling of high level electric energy streams [1, 2].

The mentioned above devices have given a powerful incentive for further development of the hybrid and contactless switching power semiconductor devices (SDs) for the direct current (DC). This apparatus consist in their main circle new fully controlled semiconductor transformers (STs) as switches. The advanced devices have such operational qualities as high switching durability (up to several million cycles), an extremely high speed of performance (only several microseconds), absence

of highly expensive and unreliable systems of forced switching, improved functional features, and convenience of combinability with microprocessor devices, which make them really competitive on the world market despite their high cost [3, 4].

These refined DC semiconductor apparatus (SA), contactless [5, 6] and hybrid [7, 8], have switching surges continuously due to the energy stored in the network inductance and the load inductance during of commutation. But due to the fact that the circuits are switched off at a significant load during a very short time, the stored energy will be much higher, and dampening it will be more difficult than in earlier developed devices with the capacitive switching of the semiconductor switch. There where the switching capacitor combines its main function with the role of a voltage regulator [9].

In this case, it is rational to research the methods of limiting switch surges in these semiconductor devices and to make relevant calculations. The research may be interesting for the developers who professionals working in the electromechanical engineering.

Analysis of recent research and problem statement. In the DC semiconductor apparatus, damping of the switching surge caused by stored energy in the inductance of the electrical network and in the load at the moment of switch-off can be made by the following ways:

- by applying switching condensers [10];
- by using the same condensers which are shunted with linear resistors [10];
- by applying energy-intensive varistors [11, 12].

In all these methods for diffusion the energy accumulated in the inductive load, it is traditional to use a reverse diode or a reverse thyristor (in the case of a reverse system) which switch simultaneously with the load [13]. Transient electromagnetic processes in semiconductor apparatus have been treated in detail in sufficient [11]. Moreover, it should be noted that due to high energy accumulated in the inductive load at the switching moment, other methods are don't quite fit because it is impossible to use them them (usually the energy accumulated in the inductive load is too higher than the energy accumulated in the electrical network inductance) [14]. Thereby authors shall analyse the above mentioned methods, provided that it is necessary to dampen only the energy accumulated in the network inductance.

The use of capacitors to limit switching surges by transferring the energy accumulated in the circuit inductance into potential energy of the charged capacitors is a classic method implement in DC SA with compulsory capacitive switching of the primary semiconductor switch of the SA made on the basis of thyristors [10]. For obtaining an acceptable level of surge, it is necessary to make use of bulky, expensive impulse capacitors, with a limited temperature working range (it especially electrolytic pulse capacitors). This method can be valid when SA already have capacitive compulsory switching; but in modern SA, which are constructed using fully controlled STs, the implementation of this method is not be expedient [15].

The use of defensive capacitors with linear resistors that are enabled by a special scheme in parallel to the capacitors has allowed significant reduction of their size. Wherein, in addition to the problems connected with deficiencies of the special type of capacitors, there have appeared problems with involving the need to create the schemes for switching linear resistors. They would allow their switching on and off in due time [10]. In that reason this method is also impractical to use for reducing switching surges in modern SA.

Voltage regulators on the basis of the two mentioned above principles are analysed in detail in [10]. The research considers the methods of their calculation subject to constraining switching surges to a level acceptable for SA of the direct current.

In this time, due to the developing of energy-intensive varistors that allow to diffuse the energy of over the hundred kJ and that have suitable size and cost, sufficiently favourable conditions have been designed for their use in modern switching SA for the deffusing of stored energy in the circuit inductance at switching off the device [11, 16].

The mentioned above critical analysis of the different methods of damping switching surges in the power DC switching devices describes that while using DC SA in which STs are fully controlled it is advisable to limit the sharp increase of voltage to the level acceptable for this class of devices, less

than 2.5 nominal voltage value U_{nom} [17] by diffusing the energy accumulated in the inductive load by means of the voltage regulator (VR) VR1 on the basis of the feedback diode turned on parallel to the load, and the energy accumulated in the network inductance should be diffused by using VR2 which based on powerful varistors connected to the input circuit of the apparatus.

As are no methods used for calculating varistor VRs integrated into the DC SA using fully controlled power semiconductor devices, there is a need for a detailed researching of the electromagnetic transient processes that take part in the limiters of those devices in time of switching the load. According that, it is necessary to propose a method of calculating the parameters of varistor VRs that reduce switching sharp increase of voltage to the acceptable level for this class of devices.

The purpose and tasks of the study. The target of this study is to develop a method of calculating the parameters of voltage regulators which consists of the energy-intensive varistors at a given switching surge level in DC SA of the with full-controlled STs.

That is why, it is necessary to determine the following problems:

- to treat transients that occur in the voltage regulators for DC SA at the load switching,
- to solve the analytical expressions to calculate the basic parameters of VRs and to formulate them as the basis of an engineering method of calculation, and
- to propose the examples of calculating the parameters of VRs and switching surges for the most common types of DC SA.

Materials and methods of research. A calculating scheme of circuit of switching voltage regulator is shown in Figure 1.

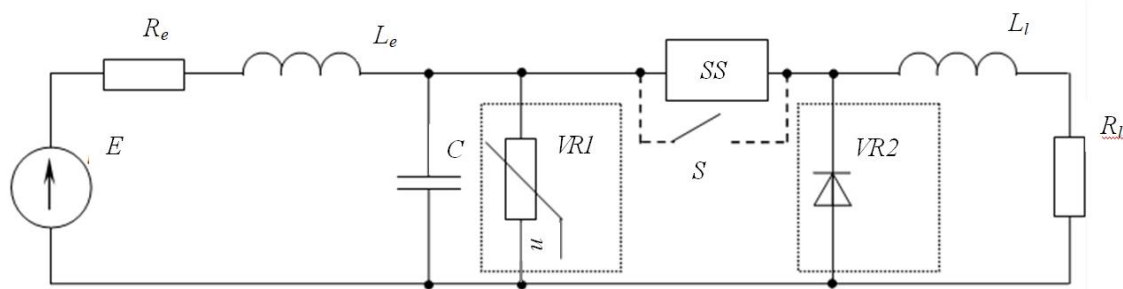


Fig. 1. An equivalent circuit of switching voltage regulators (SS is a semiconductor switch on fully controlled devices, S is a mechanical switch available only in hybrid apparatus, L_l and R_l are load inductance and active load resistance, whereas L_e and R_e are equivalent inductance and resistance in the circuit)

The parameters R_e and L_e are calculated in the short circuit mode in the apparatus circuit

$$R_e = \frac{U_{nom} \cdot 1.1}{I_{sc\ max}}, \text{ and } L_{sc} = L_e = \tau R_e, \quad (1)$$

where U_{nom} - the nominal value voltage in the network,
 $I_{sc\ max}$ - the maximum acceptable short circuit current, and
 τ - the constant of time of the short circuit current ($\tau=0.01$ s) [17].

In this scheme the capacitor C is the parallel connected to the VR1. That capacitor limits the speed of increase of the switching surge in STs of semiconductor apparatus at the break of the current. The value of capacitor's capacitance is determined by the following expression

$$C = \frac{I_{sl}}{\left(\frac{du_T}{dt}\right)_{crit}}, \quad (2)$$

where I_{SI} - the maximum acceptable switched current of the apparatus. (As example, a contactor and a modern high speed circuit breaker this value is usually, $I_{SI}=4 \cdot I_{nom.o}$) [4];

$I_{nom.o}$ - a nominal operating current, which is $I_{nom.o}=0.6 \cdot I_{nom}$ usually;

$\left(\frac{du_T}{dt}\right)_{crit}$ - a maximum acceptable speed of increase of the current in power semiconductor devices (PSDs).

The parameters of the varistors used in the VR1 have to comply with the math inequalities [4]:

$$\begin{cases} W_{c.max} < W_{c.adm} \\ I_{c.max} < I_{c.adm} \\ t_c < t_{adm} \\ U_{cl} \geq \frac{U_{nom}}{0.85} \cdot 1.1 \end{cases}, \quad (3)$$

where t_c - the current duration in the varistor;

$I_{c.adm}$ and t_{adm} - the acceptable amplitude and lasting of the current impulse in the varistor. Its energy W_c does not exceed the acceptable value of energy $W_{c.adm}$;

$W_{c.max}$ - the maximum value of energy diffused in the varistor;

$I_{c.max}$ - the maximum value of current in the varistor;

U_{cl} - a classified voltage of varistor.

For real parameters of the switching circuit of a DC SA, the values of I_c and W_c can be much higher than the acceptable $I_{c.adm}$ and $W_{c.adm}$. As example, for a contactor for $I_{nom}=630$ A, the maximum switched current I_{sc} in the circuit in the mode of occasional switchings is equal to $4 \cdot I_{nom.r}$. Therefore, at $I_{nom.o}=0.6 \cdot I_{nom}$, $L_e=0.5$ mHmH, the accumulated energy of inductance in the electric network is $\frac{L_e I_{SI}^2}{2} = 571$ J, while in varistors CH2-2, $W_{c.adm} \leq 150$ J, and in BC2-2 $W_{c.adm} = 350$ J [3].

Therefore, to increase the admissible energy for the VR1, the authors suggest series of parallel connection of a varistors, which is on Figure 2.

This VR consists of n parallel branches. Each of them is containing m serial linked varistors RU1-RUm and one ballast resistor R_b to equalize the currents in the parallel branches.

Computation of the maximum energy make in one varistor of the VR in Fig. 2, a is done for the limiting case of lopsided distribution of current in the parallel branches. It conforms to determining the minimum values of the parameters in an each n -th branch and the maximum values are determined in the other ones.

If current in the n -th branch will be the maximum, the currents in the other branches will be minimal. Clearly that the energy diffused in one varistor proportionally to the squared value of current will be maximal for the varistor that is connected in the n -th branch where is the maximum current.

The calculation of prinplice electric scheme of replacing the switching circuit of the VR1 (Fig. 2, a), which has a given distribution of the current, at the stage of limiting the surge looks like in Fig. 2, b (excluding the capacitor current C of the VR1, which has too small a capacity to have any actual effect on the current distribution in the VR1), where L_e is equivalent inductance in the switching circuit ($L_e=L_{sc}$; $R_e \approx 0$); $R_{emax}=m \cdot R_{dmax}+R_{bmax}$ and $U_{emax}=m \cdot U_{cmax}$ are equivalent maximum resistance and voltage in an $(n-1)$ -th branch with the minimum currents i_{cmin} ; $R_{emin}=m \cdot R_{dmin}+R_{bmin}$ and $U_{emin}=m \cdot U_{cmin}$ are equivalent minimal resistance and voltage in stabilizing the n -th branch with the maximum currents i_{cmax} ; R_{dmax} , R_{dmin} are the max and min dynamic resistances of the varistors; U_{cmax} , U_{cmin} are the max and min voltages in stabilizing the varistors; R_{bmax} , R_{bmin} are the maximum and minimum resistances of the ballast resistor; S1 is the switch simulating the operation of the VR1 (it switches off the branches with the currents i_{cmin} at the declining voltage in the VR1 u_{vr} below U_{emax}).

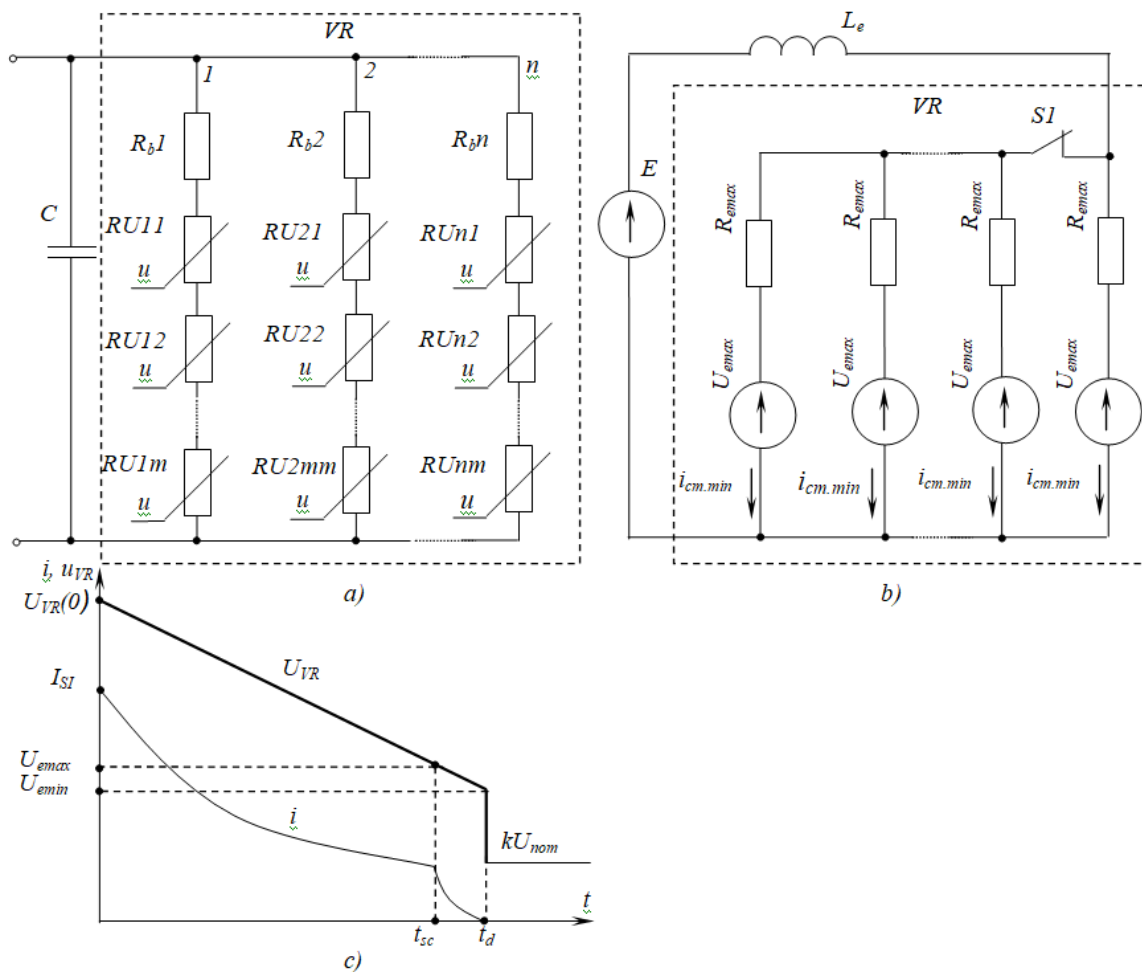


Fig. 2. The surge suppressor: *a* is a principle electric scheme of combination of parallel and serial connection of varistors, *b* is a calculation electric scheme of an equivalent switching circuit in the VR, and *c* is the dependency graph of the VR operation

It is necessary to rise the voltage u_{vr} to the value of U_{emin} for the flowing the current in the VR. Besides the switch $S1$ can be locked to allow to flow the current in all the n branches if the math inequality is like that

$$I_{SI} > (U_{e,max} - U_{emin}) / R_{e,min} \cdot \quad (4)$$

The practice of using varistors CH2-2 for diffusion big energy in them shows that it is recommendable to choose the varistor's value U_c as its I-V curve at the current of $I_{1,0}=1$ A. And its dynamic resistance is determined by the expression [4]:

$$R_d = \frac{U_{v100} - U_c}{I_{100}},$$

where U_{v100} - the varistor's voltage at $I_{100}=100$ A.

The voltage in the varistor U_v is determined by $U_v=U_c=I_c \cdot R_d$.

Analytical expressions to obtain the basic parameters of the VR and their implementation into the engineering calculation method. To satisfaction the inequality (3), the process in the circuit (Fig. 2, a, $0 \leq t \leq t_{sc}$) with the locked switch S1 must be in the time interval of $0 \leq t \leq t_{sc}$ (Fig. 2, c). This is described by the following equations [18]

$$\begin{cases} E = L_e \frac{di}{dt} + u_{vr} \\ u_{vr} = U_{e \min} + i_{c.\max} R_{e \min} = U_{e \max} + i_{c.\min} R_{e \max}, \\ i = i_{c.\max} + (n-1)i_{c.\min} \end{cases} \quad (5)$$

where u_{vr} - the value of voltage on the voltage regulator;

$E = k \cdot U_{nom}$ is the maximum admissible electromotive force (EMF) of the network ($k=1.1$).

The calculation of the parameters of the protection circuit is shown below.

The solution is subject to the initial condition of $i(0) = I_{SI}$:

$$\begin{aligned} i_{\bar{n}\min} &= \rho i_{\bar{n}\max} - I_{imb}, \\ i &= [1 + \rho(n-1)]i_{\bar{n}\max} - (n-1)I_{imb}, \\ i_{\bar{n}\max} &= A e^{-t/\tau_{sc}} - I_*, \end{aligned}$$

where $\rho = R_{e\min}/R_{e\max}$;

$I_{imb} = (U_{e\max} - U_{e\min})/R_{e\max}$ - an imbalance current;

$I_* = (U_{e\min} - E)/R_{e\min}$;

$U_{e\min} > E$

$A = I_* + [I_{SI} + I_{imb} \cdot (n-1)] / [1 + \rho \cdot (n-1)]$;

$\tau_{sc} = [(1 + \rho \cdot (n-1)) \cdot L_e] / R_{e\min}$.

The amplitude value of the max current in the varistor is

$$I_{\bar{n}\max} = i_{\bar{n}\max}(0) = [I_{SI} + (n-1)I_{imb}] / [1 + \rho(n-1)]. \quad (6)$$

The amplitude value of the limited VR voltage at the device input is

$$U_{v\max} = u_{vr}(0) = R_{e\min} I_{\bar{n}\max} + U_{e\min} \leq 2.5U_{nom}. \quad (7)$$

The duration of the locked state of the switch S can be found by solving the equation $u_{vr} = U_{e\max}$

$$t_{sc} = \tau_{sc} \ln \frac{\rho A}{I_{imb} + \rho I_*}. \quad (8)$$

Also the switch S1 is unlocked and the current i declines to zero at the time interval $0 \leq t \leq t_{sc}$ (Fig. 2, c). Meantime, the process in the equivalent circuit can be described by the equations [18]

$$E = L_e \frac{di}{dt} + u_{vr}, \quad u_{vr} = R_{e\min} i + U_{e\min}.$$

The solution is subject to the elementary condition of $i(0) = I_{imb}/\rho$:

$$i = -I_* + Be^{-t/\tau_{r.s.}},$$

where $B=I_*+I_{imb}/\rho$, $\tau_{r.s.}=L_e/R_{em}$.

The time of the unlocked mode of the switch S1 can be determined by the equation where $i=0$

$$t_{r.s.} = \tau_{r.s.} \ln \left(1 + \frac{I_{imb}}{\rho I_*} \right). \quad (9)$$

The current flow through the VR during the time:

$$t_d = t_{sc} + t_{r.s.}. \quad (10)$$

The maximum energy $W_{\bar{n}.max}$ diffused in one varistor in the n -th branch with the current of i_{cmax} is

$$W_{c.max} = \int_0^{t_{sc}} i_{c.max} (U_{c.min} + R_{d.min} i_{c.max}) dt + \int_0^{t_{r.s.}} i (U_{c.min} + R_{e.min} i) dt,$$

or

$$W_{c.max} = \int_0^{t_{sc}} (Ae^{-t/\tau_{sc}} - I_*) (U_{c.min} + R_{d.min} (Ae^{-t/\tau_{sc}} - I_*)) dt + \int_0^{t_{r.s.}} (-I_* + Be^{-t/\tau_{r.s.}}) (U_{c.min} + R_{e.min} (-I_* + Be^{-t/\tau_{r.s.}})) dt. \quad (11)$$

The maximum energy $W_{b.max}$ diffused in the ballast resistance in the n -th branch is:

$$W_{b.max} = \int_0^{t_{sc}} (Ae^{-t/\tau_{sc}} - I_*)^2 R_{b.min} dt + \int_0^{t_{r.s.}} (-I_* + Be^{-t/\tau_{r.s.}})^2 R_{b.min} dt. \quad (12)$$

The minimal energy $W_{\bar{n}.min}$ diffused in the varistor in the $(n-1)$ -th branch with the current of $i_{\bar{n}.min}$ is:

$$W_{c.min} = \int_0^{t_{sc}} \left[(Ae^{-t/\tau_{sc}} - I_*) \cdot \rho - I_{imb} \right] \cdot \left[U_{c.max} + R_{d.max} \cdot (Ae^{-t/\tau_{sc}} - I_*) \right] dt. \quad (13)$$

The following engineering method of calculation was suggested on the basis of the obtained expressions in this work.

1. It is initially necessary to select from the VR varistors the type whose main parameters correspond to restriction (3) and then to apply expression (2) to determine the value of the capacitance that shunts the VR.

2. The parameters are defined to calculate the VR operation, provided that the variation in the parameters $U_{\bar{n}}$, R_d and R_b is with the range of $\pm 5\%$, and $R_b \approx R_d$.

3. Formula (7) helps to determine $I_{\bar{n}.max} \leq I_{\bar{n}.adm.}$ (for the varistor CH2-2 $I_{\bar{n}.adm} \leq 120 \text{ A}$, $W_{\bar{n}.adm} \leq 150 \text{ J}$).

4. Expression (6) on the basis of the known $I_{\bar{n}.max}$ and I_{SI} helps to find out the number of the parallel-connected varistors n ; the n is rounded up to the next whole number. The values of $I_{\bar{n}.max}$ and $U_{v.max}$ are specified.

5. Expressions (8)-(10) define the time of the current flow through the varistor t_d .

6. Expression (11) determines the maximum value of energy diffused in the varistor.

7. If one of the varistor parameters does not meet the accepted confines, the calculation must to be repeated until all varistor settings satisfy the (3) and (7).

The results of calculations on a varistor VR are below. The switching surges determined by the proposed method for the case of using the VR in hybrid DC contactors (for 220 V), which consists common power switching SA.

Calculations were made in Mathcad on the basis of such data: $I_{nom.r}=0.6 \cdot I_{nom}$, $I_{SI}=4 \cdot I_{nom.r}$ (the maximum current switched by the apparatus in the mode of rare switching), and $I_{scmax}=10$ mA. In this case, the basic voltage regulating element of the VR is the varistor CH2-2 (330 V).

Table 1 contains the basic parameters for this type of the VR.

Table 1. The calculation parameters of the voltage regulator

The nominal contractor current I_{nom} , A	The number of the parallel varistors enable, items	The maximum current of the varistor I_{cmax} , A	The duration of the current flow through the varistor t_d , ms	The maximum switching surge U_{vmax}/U_{nom}	The energy in the varistor		C, μ F	R_b , Ω
					U_{cmin} , J	U_{cmax} , J		
100	3	103.60	0.32	2.22	3.71	6.94	1.0	0.68
160	5	105.32	0.50	2.23	6.33	11.56	1.6	
250	7	117.21	0.75	2.30	11.38	19.43	2.2	
400	12	113.37	1.20	2.07	17.90	30.97	3.0	
630	18	118.81	1.85	2.31	29.90	50.34	3.9	

The analysis of the calculation parameters in Table 1 illustrated that the use of inexpensive and compact varistors CH2-2 in creating a VR can limit the level of switching surges to below $2.5 \cdot U_{nom}$, the using hybrid DC contactors to switch currents equal to $4 \cdot I_{nom.r}$. In this case, even in the loaded contactor (with the effect of the stored circuit energy on the VR) when $I_{nom}=630$ A, the max energy diffused in the loaded varistor is three times less than the acceptable level, and the mass of the components of the VR is less than 0.1 kg and price is about 10 USD [4].

For example, in the previously developed hybrid contactor KP81-39 ($I_{nom}=630$ A), the resistive-capacitive VR has 14 parallel capacitors, type K75-17 (1000 V, 50 μ F, and the mass of 1.25 kg) [1]. Accordingly, the mass of the VR is at least 17.5 kg, which is bigger than the considered varistor VR. It should be added that the level of restricting voltage surges by this VR amounts to $4.5 \cdot U_{nom}$, which means that it exceeds the acceptable level for the existing switching devices.

Of course, a varistor VR may be based not only on varistors CH2-2. Other types of varistors and companies can be used if they comply with the requirements. For example, the varistor types SKP6.5.110SA and BYZ50A22.50K39 produced by Semicron. They are designed for $U_{cl}=6.5-110$ V, they should be enabled in the VR as in a parallel series connection, and the varistor, operating in the most adverse working conditions, must match to the restrictions (3).

Analysis of the research results on switching surges in power DC SA. The main result of the study is that it has developed an engineering method of calculating the parameters of varistor voltage regulators to contactless and hybrid DC SA and given for this devices acceptable surge levels. Also to be noted that the results of this research, as well as studies of the thermal mode of power semiconductor devices in SA [19], facilitate high accuracy at a short time in choosing full-controlled STs with regard to the current and voltage when designing modern switching DC SA. This facilitates to solve the basic

tasks of design stages.

But the worry findings in the study are researching only low-voltage SA (up to 1000 V), so it is difficult to extrapolate them onto SA for higher voltage. They have been made possible with the development of high-voltage STs based on silicon carbide [8]. It is expedient to continue research on this issue.

The practical recommendations following from the results of the study and the proposed calculation methods are being used by the developing company ENAS, Kharkiv, Ukraine, to modernize DC hybrid contactors of series KP81. This study refers to the stage of developing design documentation.

Conclusion.

1. The proposed VR with a series of parallel-connected varistors is a highly straight device that effectively limits switching surges in the circuits of power DC SA to below $2.5 U_{nom}$. It significantly surpasses such parameters as the dimensions, weight and cost of resistive-capacitive surge limiters previously used in semiconductor commutation apparatus. Moreover, it can reduce the class level of fully controlled PSDs that are used in switches of semiconductor devices for the voltage of 220 V from class 10 down to 6.

2. The proposed engineering method has been developed to compute the VR parameters of varistors in treated voltage regulator. In contrast to the previously researched cases, the present research has considered calculation for only the worst case of distributing varistors in voltage regulator with various deviations of their parameters. This facilitates to creating VRs on the basis of quite simple calculations to provide a suitable level of switching surges in DC SA in different operation modes, which is quite useful.

3. The calculation method has been proposed in the study can be further used in calculating surges in full-controlled PSDs that apply in an impulse mode as part of power electronic devices.

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Обмежувачі перенапруги для напівпровідникових комутаційних апаратах постійного струму

В роботі показано, що під час перемикання електричних кіл постійного струму на напівпровідникових ключах напівпровідникових апаратів виникають комутаційні перенапруги. Метою цього дослідження є розробка методики розрахунку параметрів обмежувача перенапруг на основі послідовно-паралельного з'єднання варисторів, що використовується в напівпровідникових комутаційних апаратах. На основі дослідження перехідних процесів, які відбуваються в таких обмежувачах перенапруги напруги в напівпровідникових пристроях при комутації кіл постійного струму, були віднадені аналітичні вирази для розрахунку основних параметрів регулятора напруги. У результаті була розроблена інженерна методика для розрахунку параметрів обмежувачів перенапруги в гібридних і безконтактних напівпровідникових комутаційних апаратах постійного струму. Такі обмежувачі підтримують перенапруги на заданому рівні, який допустимий для пристроїв такого класу. Методика, яка запропонована в роботі за результатами дослідження, забезпечує високу точність та швидкість розрахунку при розробці сучасних перемикаючих напівпровідникових пристроїв, які працюють з у колах постійного струму. Запропонований регулятор напруги для комутаційного напівпровідникового апарату постійного струму ефективно обмежує перенапруги комутації в напівпровідникових пристроях живлення нижче 2,5 від номінальної напруги.

Ключові слова: обмежувач перенапруги, комутаційна перенапруга, напівпровідниковий комутаційний апарат, напівпровідниковий прилад, варистор

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Effective method of evaluating the level of material damage under different loading conditions

The article analyses the known experimental results of the assessment of the level of damage of structural materials of various grades under the conditions of long-term, cyclic, static loading, and lubricated friction. The structural changes that occur in the materials during loading have been shown with correlate to the changes in the statistical scattering characteristics of the hardness measurement results. This enables prediction of the kinetics of damage accumulation in materials during operation and, therefore, prediction of their service life. This approach is relevant for the development of methods for the assessment of the current condition and residual life of structures in the railway and other transport industries. It is proposed to use this methodology to evaluate the level of damage to the microstructure of materials in the contact zone and its impact on the tribological characteristics of metal friction pairs. A new method is proposed for the performance assessment of lubricating compositions based on industrial lubricants that contain nano-additives of different chemical compositions for higher wear resistance of heavy-loaded steel friction pairs. The method is based on the joint analysis of the experimental data on the wear kinetics, variation of the relative hardness, and level of damage in the surface layers of the metal friction pairs. The structural damage of the materials in the contact zone is determined by employing the statistical parameters of scattering of the hardness values. The methodology has been approved for steel friction pairs where lubricants based on industrial oil and on nano-additives of copper, magnesium alloy, graphite, and two grades of medium-carbon steels, are used.

Keywords: *hardness, rail–wheel pair, statistical data processing, lubricating composition, friction and wear testing, wear resistance, tribological characteristics, damages.*

Introduction. The determination of the current condition and residual life of the structural elements and parts of machinery is considered to be one of the key challenges in modern-day mechanical engineering, since the physical-mechanical properties of a material change in the process of operation and the estimated life may prove to be unreliable. The relevance of these challenges is even greater for the structures and parts of the machinery used in the energy and transport sectors. Determination of residual life is based on the theoretical and experimental methods of assessment of the level of material damage of the structure as a result of mechanical, thermal, or other actions. The theoretical assessment may employ the methods of continuum damage mechanics (CDM) based on the phenomenological growth models of scattered defects, i.e. pores and micro cracks. These models assume that the number of defects in the elementary volume of the material is high enough for CDM modeling of the growth processes thereof as this type of modeling views damage as an additional thermodynamic parameter.

Active research efforts are currently being made to develop these models [1–4]. Some of the models have already been used in modern software packages for strength calculations [5, 6]. However, all the theoretical models require experimental determination of the parameters and functions present in the defining relations. Here, the aspects of determination of specific physical mechanisms of the degradation process of material mechanical properties and practical methods for assessing the damage level and the nature of its change during the operation of the component, need to be considered. The relevance of these aspects is also associated with the development of methods to improve the wear resistance and reliability of friction assemblies, as the wear of components caused by friction is known to be one of the main causes of failure and breakdown of machine parts and structural elements, particularly in the energy and transport sectors.

In this context, the interpretation of the term “damage” is fairly ambiguous. In material mechanics, damage is related to a decrease in resistance to a certain mechanical load or other external action leading to an increase in the number of defects in the material. In contemporary physics, it has already been proven that the loss of durability resulting from the failure process is the final stage of defect accumulation at all structural levels of the material. Therefore, it is critical to identify and use a comprehensive measure of damage that would be fairly simple to determine by experiment. This would enable the researchers to employ damage as a specific parameter (scalar, tensor, function, or functional) during the determination of the relationships between the theories of inelastic deformation that take into account material damage.

Background analysis of the recent studies and definition of the problem. Various methods for the assessment of the level of material damage have already been proposed in a number of research studies. The methods could conditionally be classified as either destructive or non-destructive. The classification is conditional, as the same methods are used in both cases. A comprehensive analysis of the methods would require a separate publication; therefore, only a few of them are briefly reviewed in the present paper.

Most destructive methods imply performing tests on material specimens cut from certain areas of the structural component. The investigations of the mechanical behavior or structural condition of the cut specimens provide the characteristics of the current damage of the material, $\Pi(T_i)$ where T_i represents certain parameters that characterise the level of operational load (e.g., time, passed tonnage, number of cycles, accumulated deformation, etc.). There is a certain initial damage Π_0 in any material; therefore, the same method is used for the determination of the damage level, while relative parameter $\frac{\Pi(T_i)}{\Pi_0}$ is used for the analysis of damage kinetics. These methods include, in particular, weight measurement methods for the determination of material density; determination of the transverse strain coefficient and Young’s modulus defect during uniaxial tension or compression of specimens [7]. The methods help assess the degree of material loosening or volumetric deformation that characterizes its damage. In laboratory conditions, the results of damage level assessments under the above methods agree fairly well with each other [7]. The methods of quantitative metallography and fractography are used to analyze the geometric characteristics of the specimen failure surfaces and to determine the number of defects of various types [8,9]. It should be noted that the procedures for determining the degree of damage using these methods are quite labor-intensive, and the efforts are made to automate them [10]. Recently, the method of pushing out of the disc micro-specimens cut from large structural elements has become widespread as it helps minimize the appearance of new defects that might result from this operation. The investigations using these methods allow to assess the degree of material damage caused by mechanical, radiation, thermal, and corrosive actions on the structure by the means of measurement of certain characteristics of the mechanical properties of the material [11–13]. The level of defectiveness of the material specimens could be determined using other methods of structural investigation and technical diagnostics, such as acoustic emission, ultrasound, X-ray, electron microscopy, and others [14–19]. In certain cases, these methods are also used for in-situ diagnosing of the material damage of structures, predominately thin-walled ones, due to certain physical limitations of these methods. The latter techniques require the use of special and often costly equipment.

The most common method of assessing material condition is probably the hardness method, which has quite a few variants at present [20–25]. In general, hardness is considered to be the property of a

material to resist the penetration of another, harder body (the indenter) into it. By its physical nature, hardness is assumed to be related to the mechanical characteristics of the material in the context of elastic-plastic deformation and failure.

The results of hardness measurement depend on the size, shape and material of the indenter; the method of application, value, and speed of the load; the capabilities of the equipment used for measuring the geometric parameters of impressions; the accuracy of calculation formulas, etc. In particular, as the load on the indenter decreases, the hardness indicators increase and the degree of the increase depends on the shape of the indenter. It should also be noted that most of mechanical characteristics are integral properties of the specimen of a certain shape, and the processes of restructuration of the microstructure on the surface versus those that take place in the middle of the specimen are different even at the stage of uniform deformation, let alone in the zones of its localization.

Currently, only approximate correlations between hardness indicators and some standard mechanical characteristics have been established [26, 27]. These correlations are considered purely empirical, since hardness is a local rather than an integral characteristic in relation to the sample size.

The simplest methods to measure hardness are the ball, pyramid, or cone indentation into a prepared surface of the part. These techniques are used to determine the macro-hardness of the material, as, contrary to micro-structure parameters, relatively large volumes of the material are subjected to deformation during the indentation. These methods are often used to assess the quality of parts after thermal treatment (e.g., rails and wheels of a rolling stock) [28, 29]. However, the methods are characterized by rather low sensitivity due to structural changes in the material arising from the accumulation of micro-defects [30–32].

Therefore, methods for determining micro-hardness are used for the quantitative and qualitative assessment of structural changes in the material. Determining micro-hardness as a notion implies a fairly large number of methods [22], which differ in the shape of the indenter, load application, and result recording techniques.

The micro-hardness methods are used to study the structural components of metals and alloys, analyze the anisotropy of mechanical properties of microcrystals, and to investigate changes in the mechanical properties of surface layers of parts caused by friction and wear, cavitation, corrosion, etc. The micro-hardness method has been found to be sensitive to changes in the phase composition of metastable materials, enabling the prediction of the kinetics of phase transformations under various conditions of thermo-mechanical loading of the parts made from this kind of materials [33]. This method is characterized by a fairly large scatter of micro-hardness indicator values, the main factors of which are the non-uniformity of the material, the measurement technique or the quality of specimen preparation, as changes in the surface micro-hardness are caused even by the mechanical cutting or grinding of the specimens. The dispersion of micro-hardness indicators largely depends on the indenter shape and value of the load acting on it, with the dispersion of data increasing at the decrease in the loading degree [22]. Nonetheless, the micro-hardness method is considered by many researchers to be a versatile method to investigate the mechanical properties of materials.

The neglect of the scale factor is a common weakness of all experimental methods for damage research using specimens made from the structural material. The damage accumulation process is very complex and takes place at all structural levels of the material. Hence, it depends on many factors, including the volume of the deformed material (this is related to the differences in the accumulation of elastic energy, conditions of dissipation of the thermal energy that builds up during deformation, statistical aspects of micro-defect distribution, etc.). Another factor is the complexity of modeling of the loading conditions of specimens in the experiment that would adequately represent the loading conditions of the structural material. In most structures, structural materials function under the conditions of non-uniform complex stress condition, and the transfer of research data from the laboratory to real structures should therefore be carried out with some caution.

The scatter in the mechanical properties of many materials is evidently associated with the specifics of their crystalline structure. Reducing errors associated with hardness measurement equipment and the so-called human factor (or an instrumental factor) and using modern automated testing devices could help establish correlations between certain characteristics of the structural state of the material and the parameters of the statistical law of distribution of the hardness measurement results.

Determining the nature of the scatter of mechanical properties of various structural materials and choosing adequate statistical laws for the mathematical description of experimental data has been a relevant problem in materials mechanics for many years. The need for research in this area is related to the necessity of accounting for the scatter of mechanical parameters used in the estimation of the strength and reliability of the structural elements. If the correspondence of the experimental data to a certain statistical distribution law is established, then the distribution parameters could be used to assess the level of damage in the structural material. At the same time, if certain criteria for assessing the value of these parameters are present, it would be possible to predict the durability of the structure and its residual service life.

Quantitative evaluation of a random homogeneous variable (for example, a certain characteristic X of the mechanical properties of a material, the value of which can be represented as a series X_1, X_2, \dots, X_n for control purposes n) is known to use dimensioned and dimensionless numerical characteristics, which have no direct relation to the form of the law of distribution of a random variable: arithmetic mean $\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i$; dispersion $D = \frac{1}{n} \sum_{i=1}^n (X_i - \bar{X})^2$; standard deviation $S = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (X_i - \bar{X})^2}$; coefficient of variation $v = \frac{S}{\bar{X}} \cdot 100\%$. Two more parameters, namely kurtosis $E = \frac{\frac{1}{n} \sum_{i=1}^n (X_i - \bar{X})^3}{S^3}$ and skewness $A = \frac{D}{S^4} - 3$, provide additional information about the shape of the distribution curve.

The scatter of values of mechanical properties within the totality with a sufficiently large n (theoretically at $n \rightarrow \infty$) is subject to the law of probability distribution, which is determined by the distribution function. Any finite set of values of these characteristics is a so-called statistical sample from the totality and provides only approximate representation of its characteristics. This circumstance is one of the main challenges when choosing a distribution law for a limited number of observation results (in particular, in the case of labor-intensive and relatively costly mechanical tests). According to the long-term studies, the results of which have been published in hundreds of scientific papers (for example, in certain observational papers [34–36]), the characteristics of mechanical properties mainly obey the normal or log-normal (the case where the logarithms of a random value correspond to a normal distribution law) laws. According to paper [36], the normal law is preferable for description of the parameters such as hardness or conditional tensile strength, while the log-normal or a variant of type III exponential distribution (two-parameter Weibull distribution) is preferable for the yield strength, threshold narrowing, and elongation. For the assessment of results of cyclic tests on strength limit, the three-parameter Weibull law is preferable, while for data on crack propagation velocity, the log-normal distribution is recommended. It should be noted that these conclusions apply to a limited group of materials and loading conditions. Significantly fewer publications provide the results on the dispersion of test data under complex stress conditions taking into account the anisotropy of materials, structural and phase composition, etc.

For smaller statistical samples typical for mechanical testing, it is generally recommended to use log-normal distribution or the two-parameter Weibull distribution law, as the latter only provides positive values of a random parameter, corresponding to the physical concepts of characteristics of mechanical properties.

Structural reliability is evidently linked to the number of defects that arise during its operation. The overwhelming majority of studies note that kinetic curves of damage accumulation $\Pi(T_i)$ are nonlinear functions of their arguments. For analytical approximation of these curves, the Avrami equation, which contains an exponential function of a certain type known as the sigmoidal function, is often used:

$$y(t) = 1 - \exp(-kt^n) \quad (1)$$

where k, n —parameters that are easily available where the experimental data are presented in double log plot.

This equation was originally used to describe topochemical reactions, such as isothermal phase transformations in metastable materials. Later, it was found to also be applicable to the modeling of other processes associated with structural transformations, such as crystallization and recrystallization, polymerization, accumulation of corrosive damage, etc. Studies [33, 37] have shown that changes in the

phase composition of metastable chrome-nickel steel under elastic-plastic deformation over a wide range of low temperatures, which could be described by a modified equation of type (1), correlate well with changes in the micro-hardness of the material.

In large-scale tests, the hardness value can be considered random. Assuming the scatter degree of values H is associated with the level of material damage $\Pi(T_i)$ and changes depending on two physically substantiated conditions $\frac{\Pi(T_i)}{\Pi_0} > 1$ and $\frac{\partial \Pi(T_i)}{\partial T_i} > 0$, in view of the above, it is reasonable to employ Weibull statistics with a distribution function as in (1). The Weibull distribution is often used in reliability theory (the weak-link model) and when describing the dispersion of certain characteristics of mechanical properties of materials and predicting the probability of brittle failure. A detailed analysis of the distribution, its mathematical justification, and other applications can be found in the book by H. Rinne [38].

For a two-parameter Weibull distribution, the probability coefficient $P(H)$ could be written down as follows:

$$P(H) = 1 - \exp\left(-\left(\frac{H}{k}\right)^m\right) \quad (2)$$

When the experimental data correspond to the theoretical distribution (2), then the parameters k, m could be determined by logarithmising both parts of the relationship (2) twice

$$m \cdot \ln(H) - m \cdot \ln(k) = \ln[-\ln(1 - P)] = \ln\left[\ln\left(\frac{1}{P}\right)\right]. \quad (3)$$

In coordinates $y = \ln[-\ln(1 - P)]$ or $y = \ln\left[\ln\left(\frac{1}{P}\right)\right]$ and $x = \ln(H)$, this is a straight line with the slope coefficient

$$m = \frac{\ln[-\ln(1 - P)]}{\ln(H) - \ln(k)} \quad (4)$$

Experimental data are plotted on the special probability plotting paper and the degree and nature of their dispersion relative to the theoretical line (3) are visually assessed. For a more precise estimation, the least squares method can be used.

In practice, due to the limited number of test results, a situation arises where the data only approximately correspond to the distribution (2), and there is certain dispersion of the data relative to the straight line (3). Currently, more than 20 approximate methods are known for the estimation of the values of the distribution parameters (2) [38]. To determine parameters k, m analytical, grapho-analytical, and numerical methods are used [38–40]. However, this paper does not focus on a detailed review and accuracy assessment. It should be noted, that a dedicated software is available for statistical calculations using the Weibull distribution [41, 42]. For the purpose of determination of the parameter in the further investigations, the methodology proposed by E.J. Gumbel [43] is used, as the damage accumulation method, developed by a team of researchers at the G.S. Pisarenko Institute for Problems of Strength of the National Academy of Sciences of Ukraine [44], has been used for the justification. The main idea behind the method is to determine a correlation between the statistical parameters, which are applicable to the estimation of the degree of scatter of hardness measurement results in large-scale tests, and the level of material damage of the structure. This method, which has been named as «LM-hardness method», was subsequently standardized in Ukraine [45]. According to this method, the results of n measurements of material hardness are presented as a series $lgX_1, lgX_2, \dots, lgX_n$, and the shape parameter m is determined by formula

$$m = 0,4343 d(n) \left[\frac{1}{n-1} \sum_{i=1}^n (\lg X_i - \lg \bar{X})^2 \right]^{-\frac{1}{2}} \quad (5)$$

Since the average value of a random parameter can be determined based on a number of observations n (i.e., for any sample), it therefore depends on n ; consequently, relationship (5) contains function $d(n)$ referred to as the standard deviation [43]. The values of this function were calculated by the Computational Laboratory of Columbia University and are provided in certain statistical guides. To generate the totality $d(n) \rightarrow \frac{\pi}{\sqrt{6}}$, if $n \rightarrow \infty$. The increase in data dispersion and the corresponding decrease in parameter m indicates an increase in material non-uniformity (therefore, in some works, this parameter is referred to as the homogeneity parameter). A higher value of the homogeneity coefficient corresponds to a low level of dispersion of micro-hardness characteristics and, accordingly, a better organization of the microstructure of the surface layers of the material.

It should be noted that a change in the structural state of the material is not necessarily a sign of its damage, i.e., a deterioration of certain operational properties.

The analysis of distribution parameters above shall be preceded by a procedure of elimination of gross measurement errors. In the standard mentioned above [45], a methodology based on the use of the Smirnov criterion is used for this purpose.

Experimental justification of the LM-hardness method. To substantiate the ideas outlined above, some results available in the literature and provided by the experiments on the specimens made from structural materials of different grades are reviewed. Primarily, it should be noted that the data of this kind are scarce and are not systematically organized. Due to the limited volume of the article and some important issues related to corrosion damage of various kinds and damage to welded structures, the present paper does not consider any examples of diagnosing real structures. The authors of the paper have anticipated to address these issues in subsequent publications.

The change in material hardness under tensile test conditions was used to assess the damage degree D in paper [20]: $D = 1 - \frac{\tilde{H} \sigma_y}{H \sigma_u}$, where H —hardness of the conditionally undamaged material (measured on the specimen before reaching yield strength σ_y), \tilde{H} —hardness of the most damaged material (measured on the specimen in the zone of deformation localization upon reaching the conditional failure threshold σ_u). It was assumed that the initial hardness and yield strength had a linear relationship.

In paper [46], an attempt was made to directly link the level of material damage to the degree of dispersion of standard mechanical characteristics (elasticity modulus, yield strength, Poisson's ratio, conditional strength limit), which was estimated by the value of the parameter m using formula (5). In tensile experiments, identical specimens of the length equal to five diameters, made from chromium steel (40X) and high-strength aluminum alloy (B95), were used. The impact of “instrumental” errors was minimized to a certain extent by providing identical experimental conditions, careful specimen selection, and control of the measurement of forces and deformations. As a result, the obtained data did not contain any systematic outliers (anomalous observations). The level of deformation was used as a development parameter. According to the test results, there was no correlation between the damage levels calculated on the basis of the scatter of mechanical characteristics. Furthermore, the damage level was the transition highest at the stage from elastic to elastic-plastic deformation, and as deformation increased further, the rate of accumulation of damage accumulation decreased.

This fact is considered in greater detail below, and an attempt is made by the authors to explain it, as similar results were obtained in other experiments.

In certain studies, the correlation coefficient ν was used as a parameter to evaluate the hardness data dispersion [47, 48]. Study [47] provides data (Fig. 1) on the level of threshold damage and the average hardness of two-phase ($\alpha + \beta$) alloy VT6 (Ti-6Al-4V) during the static long-term strength tests under uniaxial tension conditions at $\sigma = const$. Dependency $\nu(\sigma)$ was found to be close to linear. Assuming that long-term strength decreases at an increase in the load value, this is obviously associated with

greater damage in the material and, consequently, with an increase in the number of microstructural defects. This leads to a larger dispersion of micro-hardness values, as evidenced by the increase in the variation coefficient. At the same time, the average hardness (expected value) hardly changes. This indicates a lack of correlation between the scatter level of the hardness values and its average value.

Qualitatively similar dependencies were obtained by the authors of study [48] under the condition of cyclic pulsating loads at 0.3 Hz frequency on the specimens of heat-resistant steel 10GN2MFA (10ГН2МФА) commonly used in nuclear power sector (Fig. 2).

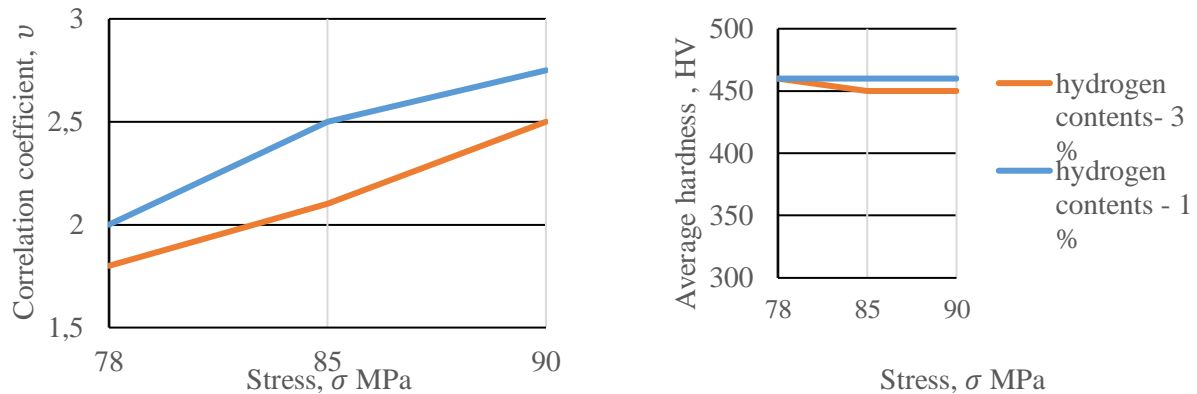


Fig. 1. Dependence of the correlation coefficient and on the stress level at different hydrogen contents.

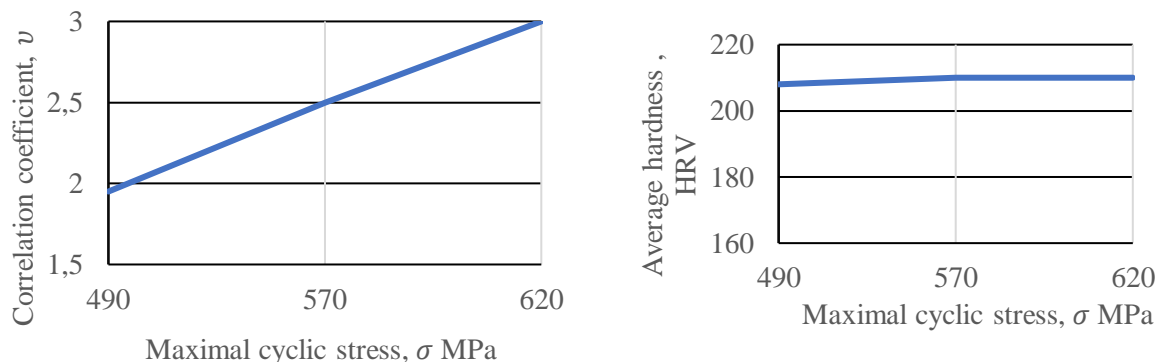


Fig. 2. Dependence of the correlation coefficient and average hardness on the maximal cyclic stress levels.

The results confirmed the presence of linear correlation between the maximum cyclic stress and the level of material damage, which was evaluated based on homogeneity parameter m , while hardness was determined in the zone of appearance of the first fatigue crack. This experiments also demonstrated that the previous impulse load affected the type of correlation, since the phase composition would change under the conditions of dynamic unbalanced processes, resulting in the physical and mechanical properties of materials. It has been concluded by the authors of the present paper that, in the absence of phase transformations, the homogeneity parameter could be used in structural-mechanical models for the assessment of cyclic durability.

The presented data provide evidence of validity of the main rationale behind the method, namely, that the dispersion of hardness measurement results increases with the increase in the operating time parameter. In the studies referred to above, the value of stresses was used for the latter, while dependencies $v(\sigma)$ and $m(\sigma)$ were close to linear for the studied load modes. It should be noted that, despite the difference in physical processes of damage accumulation for these loading processes (long-term and cyclic), there are certain similarities in terms of damage accumulation occurring in the surface

layers of the specimens, where cracks subsequently appear. A large number of microdefects leads to a significant increase in the correlation coefficient, which, in turn, indicates a decrease in the accuracy of determination of the parameters of statistical distribution. Regrettably, studies [47, 48] do not provide any data on the initial damage in the specimens, since it would require operating with relative values of the correlation coefficient in order to assess the degree of material damage.

An investigation [49] was conducted and provided results (Fig. 3) on the processes of damage accumulation in aluminum alloys D16ChATW and 2024-T351 under cyclic loading conditions (at 110 Hz frequency and 0.1 cyclic asymmetry coefficient).

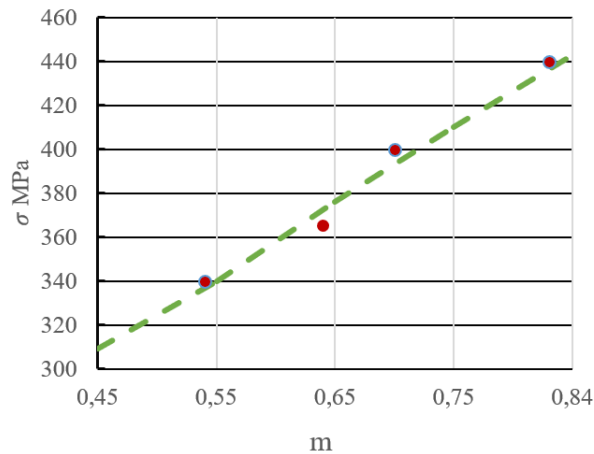


Fig. 3. Dependence of the damage level on the maximal cyclic stress.

It should be noted that the stress value is not a definitive estimate of the level of operating life of the respective loading modes. This is due to the potential accumulation of equivalent parameters at the long-term load, creep deformation, or time to failure, while under cyclic loading, the number of cycles to failure or cracking have the potential to accumulate.

In study [50], the results of investigation of micro-hardness distribution using the specimens made of different grades of structural materials (steel 45, steel 20K, steel 12Cr18N10T (12X18H10T), aluminum alloy D16T (Д16Т)) are presented according to the following test procedure: loading to the specified value of axial deformation; hardness measurement in 30 points of specimens; unloading of the specimen, registration of residual deformation, and repeated measurement of hardness.

Each material was subjected to four stages of testing, with the maximum deformation reaching approximately 1%. The evaluation of hardness measurement results was performed based on homogeneity parameter m (see (5)). The results of the experiments have suggested that the dispersion of hardness data is greater in a loaded state versus an unloaded state.

The results of evaluation of the scatter of hardness values in unloaded specimens presents on Fig. 4. The graphs are based on the data by study [50].

The degree of data dispersion clearly does not depend on the nature of strain hardening of the material when such an assessment is performed using the relative indicator $\frac{m}{m_0}$, where m_0 – value of homogeneity parameter m for the undeformed state of the material. It is noteworthy that for all the investigated materials, the greatest changes in indicator $\frac{m}{m_0}$ occurred at very small deformations, in the transition zone from elastic to elastic-plastic deformation.

The type of stress state also strongly influences the characteristics of the scatter of measurement results of micro-hardness for the specimens made from different materials. Study [51] has provided data from the experiments on thin-walled tubular specimens made of steel 45, copper M1, aluminum alloy D16T (Д16Т), and stainless steel 12Cr18N10T (12X18H10T) under conditions of uniaxial tension, compression, and torsion (Fig. 5). The materials differed by nature of strain hardening, with the greatest

hardening observed in medium carbon steel 45, the lowest – in copper M1. For all the investigated materials, the greatest scatter in hardness data was observed during torsion, while the lowest – during compression, and the difference value was influenced by the nature of strain hardening of the material. At the same time, there were hardly any changes in the average value.

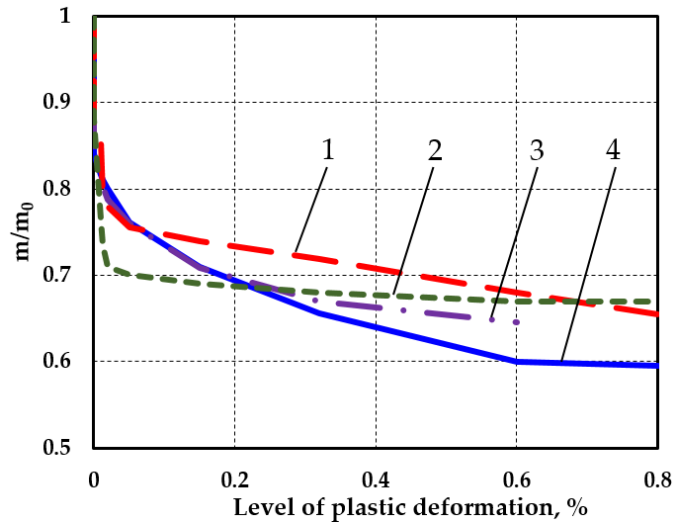


Fig. 4. Dependency between the degree of dispersion of hardness data and the level of plastic deformation (1—steel 12Cr18N10T (12X18H10T), 2—steel 20K, 3—aluminum alloy D16T (Д16Т); 4—steel 45).

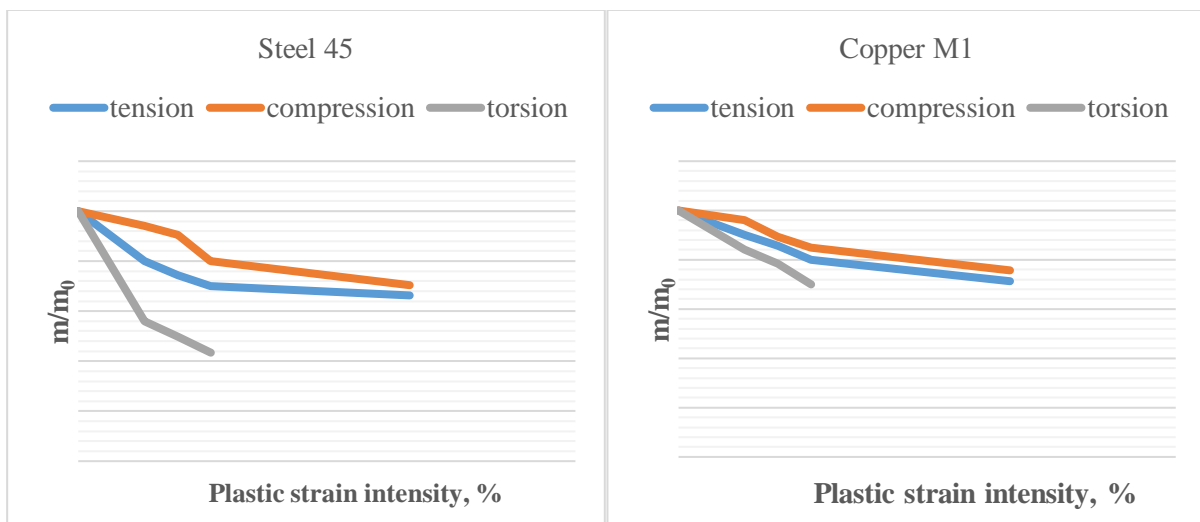


Fig. 5. Dependence of the homogeneity coefficient on the level of plastic deformation.

The main conclusion drawn from the experimental data analysis was that the scatter of the material hardness changed under the influence of any energy impact that led to structural changes in the material. However, the average hardness value changed insignificantly if there were no phase transformations or no changes in chemical composition or density of the surface layers of the material during thermo-mechanical loading.

Various types of thermal treatment are known to cause alterations in the mechanical properties of a material, including hardness. The degree of dispersion of micro-hardness data also depends on the heat treatment mode due to the change in the size of crystallites, development of residual stresses, potential emergence of new phases with different mechanical properties, etc. In view of the numerous factors that

may influence the nature of hardness data scatter, establishing a definitive relationship between the heat treatment mode and the parameters of statistical distribution would currently be challenging.

During static deformation of metallic materials caused by the heterogeneity of the crystalline structure and presence of initial defects, certain microstructural changes occur as early as during the elastic deformation stage (dislocation movement, point defects, atom movement along grain boundaries, etc.), accompanied by the appearance of plastic deformations in individual grains. The intensity of these processes depends on the initial homogeneity of the material, presence of phases with different mechanical properties, various inclusions, grain size distribution, etc. According to the experimental data and numerical simulation results, plastic deformation begins in stress concentration zones of the surface layers of the material as they are characterized by the lowest shear strength. Surface stress concentrators generate the deformation defects (dislocations, disclinations, meso-localized shear strain bands, point defects) on the surface of the specimen that subsequently propagate into its deeper layers, leading to the development of plastic deformation throughout the specimen volume.

As a result, the scatter of hardness in the elastic region increases, and the dependence of the homogeneity parameter on stress becomes close to linear (see Fig.4). Upon reaching its conditional yield strength σ_{ys} , the material becomes more homogeneous, as a large portion of the grains have already transitioned into a plastic state. Hence, the dispersion of micro-hardness decreases, and damage accumulation in the material slows down. This process of structural changes in the initial stage of material deformation should be considered when modeling damage accumulation processes in real structures.

Significant changes in the correlation coefficient or homogeneity parameter occur under cyclic and long-term loading conditions at low stress levels. Under these kinds of loading modes, damage accumulation also occurs primarily in the surface layers of the material. If the stress level does not exceed the static yield strength, a strong linear correlation is present between the statistical parameters of the micro-hardness data scatter and the level of maximum stresses. The nature of this relationship $\nu(\sigma)$ and $m(\sigma)$ is evidently influenced by the type of stress state and temperature.

Method for the performance assessment of lubricating compositions. One of the factors that affect the performance and service life of machine components is wear of the contact surfaces due to friction. The wear process of the friction surfaces is quite complex, and its intensity depends not only on the shape and nature of the mechanical interaction between the friction components. This process is affected by a variety of other factors, which can sometimes be challenging to formalize, such as the presence of moisture, dust, lubrication regime, lubricant type, etc. Therefore, the possibilities for a theoretical solution of this problem, for example, by mathematical modeling of the contact interaction between friction pair components, are quite limited.

Local plastic deformation is known to potentially cause changes in the hardness of the surface layers of components during the friction process of rough surfaces. This phenomenon is directly related to the intensity of wear. However, stable correlations between these processes have not yet been established, as experimental data are not available or have not been systematized [52]. The contact interaction of solid rough bodies is characterized by discreteness and stochastic distribution of surface forces and heat sources, as well as high gradients of stress, strain, and temperature. As a result, surface layers of the material have a high concentration of defects in the crystalline structure and exhibit specific phase transformations that are often accompanied by changes in chemical composition. Meanwhile, the presence of lubrication, additives, and lubricating materials in the contact zone significantly influences the course of these processes.

In view of the damages primarily to the surface layers of the material in the case of sliding friction, it would be reasonable to assume that the degree of their damage could be determined by referring to the degree of hardness dispersion. Specific correlation relationships can be established by a combined analysis of data on wear intensity, changes in surface hardness of the specimens, and parameters characterizing the level of structural damage to the material.

To improve the operational properties of traditional lubricants used for lubricating rails and wheels of a rolling stock, various additives have been used recently, in particular, additives containing various

nano-materials. The introduction of this kind of lubricating compositions into the friction zone can fundamentally change the nature and intensity of the processes of friction, wear, and defect formation. Natural metal-containing compounds (serpentine, dolomite, magnetite, aluminosilicates, etc.), polyvalent metal salts of fatty acids, nano-powders of various metals and alloys, as well as carbon-based materials of natural or artificial origin (graphite, diamond, graphene) are used as nano-additives. At present, there is no single opinion on the composition and method of manufacturing lubricants containing nano-additives, as their performance depends on the type of friction pair, operating conditions of tribounit, compatibility of lubricating materials and parts, etc. Therefore, performance assessment of a lubricant for improvement of the tribological characteristics of friction pairs should be based not only on the results of laboratory research but also on data from field experiments. However, in the case of wheel-rail friction pairs, the possibility of conducting field experiments is extremely limited due to a certain uncertainty in the conditions of power loads, the environmental impact, long duration, and the cost of work. Therefore, the choice of a specific lubricant from a variety of options should be made at the stage of laboratory research. One of the objectives of these experiments was to develop a method for performance assessment of a lubricant based on a combined analysis of data on changes in the main tribological (wear and friction coefficient) and strength (hardness value and damage parameter) characteristics during the experiment.

The choice of criteria for performance assessment of lubricants should be based on the assessment of the operating conditions of a specific friction pair. For many types of tribounit, the effect of a significantly increasing wear resistance is achieved only if there is a simultaneous significant reduction in the friction coefficient. Therefore, in practice, a simplified approach to the performance assessment of different types of lubricants is often used. Namely, a high-performing lubricant is considered to be one that provides a minimum friction coefficient and maximum stability of the lubricating film under certain temperature-force operating conditions of the friction pair. However, the value of the friction coefficient changes during operation/experiment as a result of deformations of the microrelief and damage accumulation, changes in temperature and physical-mechanical properties of the lubricating material and materials of the friction pair components.

The study [53] presents the results of hardness measurement and assessment of the level of damage to the surface layers of the specimens made of two grades of medium carbon steel. The experiment was conducted under sliding friction conditions using lubricating materials based on industrial lubricants with nano-additives of different chemical compositions. Application of this kind of lubricating compositions provides the possibility to control the tribological processes occurring in the friction zone to a certain extent. Therefore, one of the objectives of these experiments was to evaluate the effectiveness of lubricating compositions with nano-additives of different chemical compositions for improvement of wear resistance of steel friction pairs.

The shape of specimen, loading method and modes, measuring equipment, chemical composition of the steels and nano-materials, manufacturing method of nano-powders, as well as other details of the experiment, are thoroughly described in [53]. Average hardness $\bar{H} = \frac{1}{n} \sum_{i=1}^n H_i$ of the working surface of the specimens was determined based on the results of 30 measurements, in this case $d = 1.1124$. To assess the damage according to the methodology in [45], the hardness measurement data were presented as a series $lgH_1, lgH_2, \dots, lgH_n$, and according to the Smirnov criterion, these data were checked for gross measurement errors [45]. The average value of the series members $lg\bar{H} = \frac{1}{n} \sum_{i=1}^n lgH_i$ and the mean squared deviation were determined by $S = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (lgH_i - lg\bar{H})^2}$. The level of material damage was evaluated based on the homogeneity parameter by using formula (5), with an accuracy m of ± 0.05 .

The results were presented in relative values: $\Delta H = \frac{\bar{H} - \bar{H}_0}{\bar{H}_0} \cdot 100\%$ and $\Delta m = \frac{m_0 - m}{m_0} \cdot 100\%$, where index 0 corresponded to the initial (conditionally undamaged) state of the material.

Table 1 presents the main results of the experiments for different friction modes using lubricating materials based on Greaseline Lithium BIO Rail 000 industrial oil and nano-additives of copper grade

M2, magnesium alloy grade MA2, graphite grade GK-1, steel 20, and rail steel. Powdered nano-additives, particle size 100 to 300 nm were obtained by electro erosion dispersion [53].

Table 1. Key results of the experiment.

Specimen material	Friction mode, lubricating composition number	Maximum wear	Relative friction coefficient	Change of mean hardness	Change of homogeneity coefficient
		Δh , mm	f/f_0	ΔH , %	Δm , %
Rail steel	No. 1, pure oil	0.08	$\frac{0.7}{1.39}$	+9.8	+31
	No. 2, oil + rail steel powder	<0.001	$\frac{0.84}{0.87}$	+14.7	+29
Steel 20	No 3, pure oil	0.095	$\frac{0.92}{0.6}$	+13.9	+34
	No. 4, oil + powder GK-1 (ГК-1)	0.084	$\frac{0.91}{0.8}$	+1.3	+58
	No. 5, oil + powder M2	0.23	$\frac{0.91}{1.15}$	+4.2	+63
	No. 6, oil + powder MA2	0.0015	$\frac{0.92}{0.72}$	+31.6	+32
	No. 7, oil + steel powder 20	0.001	$\frac{0.9}{0.73}$	+16.4	+32

The coefficient of friction f (KOF) is an important indicator of the performance of friction pairs, with its value significantly affecting the energy efficiency of machines and mechanisms. A decreasing friction in the contact areas would evidently be expected to a decrease in wear. However, this pattern may be influenced by nano-additives. For different specimens, initial values f were slightly varied, which could be attributed to the presence of undeformed particles of nano-additives and possible differences in the surface roughness of the specimens. Therefore, for the purpose of analysis of the influence of different additives on the change in KOF, the experimental data are presented in Table 1 depicting relative values f/f_0 , where f_0 represents the initial value of KOF, and f – its values after 1 (upper value) and 3 (lower value) hours of operation.

According to Table 1, the greatest increase in average hardness, the lowest damage level, and the least wear were recorded for lubricating compositions No. 2, No. 6, and No. 7. This signals that these lubricating compounds possess certain corrective properties. Lubricating compositions No. 2 and No. 7 are produced on the basis of an industrial lubricant with additives of steel nano-powders used for friction tests. In these cases, the additives to lubricating materials do not further affect the oxidation of the specimen surfaces, unlike the magnesium alloy additive used in composition No. 6. Magnesium, as the main component of this additive, oxidizes due to high electrochemical potential relative to iron. Therefore, the properties of this kind of a lubricating compound are inherently unstable. Moreover, under the experimental conditions under consideration, the composition containing magnesium alloy as an additive provides a friction coefficient that is too low for lubricating wheels and rails.

Lubricating composition No. 2 has the best set of properties. It is based on industrial lubricant with the addition of rail steel nano-powder. It provides a moderate increase in hardness and minimal surface damage, virtually no wear, and an optimal friction coefficient value. In addition, this nano-additive is non-toxic, provides the lubricant with corrective properties, and cost moderately, since it can be produced from scrap metal resulting from the mechanical processing of rails. Hence, it can be recommended for lubricating rails and wheels of railway rolling stock.

Conclusions. In this study has investigated a prospective method of qualitative and quantitative assessment of lubricants containing nano-additives of different chemical compositions to improve the wear resistance of steel friction pairs. The method involves an aggregate analysis and kinetics of damage

accumulation during the change of mechanical and tribological characteristics in the course of friction, and the parameters are used to assess the level of material damage and the statistical distribution of hardness measurement results during mass tests. In particular, the correlation coefficient and the Weibull distribution shape parameter could be used as these statistical parameters.

An analysis of published works on the application of this method to assess the level of damage of structural materials of different grades has been carried out under static, cyclic, and long-term loads, as well as under friction conditions.

It has been demonstrated that, in cases of long-term, cyclic, and static loads, the degree of hardness data dispersion increases, thereby reducing the non-uniformity of the structure associated with material damage. An important conclusion from the analysis of the experimental data is the absence of correlation between the statistical parameters that characterize the scattering of hardness values and the average hardness value. Therefore, the average hardness cannot be considered a reference parameter for assessing damage. Furthermore, in view of multicycle the conditions of uniaxial loads and long-term loads, when the surface layers of the material are most damaged, the value of damage is proportional to the maximum stress. This indicates the possibility of using linear damage accumulation models under these kind of load conditions. It has also been shown that the kinetics of the damage accumulation process largely depends on the type of stress state.

The joined analysis of statistical characteristics of metal hardness scatter of friction pairs with the change in tribological characteristics during friction has allowed the authors of the present paper to evaluate the efficiency of lubricants with nano-additives of various chemical compositions. The proposed method allows identifying the corrective properties of lubricants with nano-additives at the laboratory research phase.

The method of this kind of comprehensive analysis, presented in this work, may be useful for an express assessment of the impact of lubricating materials on the wear resistance of friction pairs.

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Ефективний метод оцінки рівня пошкодження матеріалу за різних умов експлуатації

У статті проаналізовано відомі експериментальні результати оцінки ступеню пошкодження конструкційних матеріалів різних марок за умов довготривалого, циклічного, статичного навантаження та мастильного тертя. Показано, що структурні зміни, які відбуваються в матеріалах під час навантаження, корелюють зі змінами статистичних характеристик розсіювання результатів вимірювання твердості. Це дозволяє прогнозувати кінетику накопичення пошкоджень у матеріалах під час експлуатації, а отже, прогнозувати термін їх служби. Такий підхід є актуальним для розробки методів оцінки поточного стану та залишкового ресурсу конструкцій залізничного та інших транспортних галузей. Запропоновано використовувати цю методіку для оцінки рівня пошкодження мікроструктури матеріалів у зоні контакту та його впливу на трибологічні характеристики металевих пар тертя. Запропоновано новий метод оцінки ефективності мастильних композицій на основі промислових мастил, які містять нанодобавки різного хімічного складу для підвищення зносостійкості сталевих важконавантажених пар тертя. Метод базується на спільному аналізі експериментальних даних щодо кінетики зношування, зміни відносної твердості та рівня пошкоженості поверхневих шарів металів пар тертя. Порушення структури матеріалів у зоні

контакту визначають за допомогою статистичних параметрів розсіювання значень твердості. Методика апробована для сталевих пар тертя, де використовуються мастильні матеріали на основі індустріального масла та нанодобавок міді, магнієвих сплавів, графіту та двох марок середньовуглецевих сталей.

Ключові слова: твердість, пара рейка–колесо, статистична обробка даних, мастильний склад, випробування на тертя та зношування, зносостійкість, трибологічні характеристики, пошкодження.

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