Vol. 10, no. 1, 2026
eISSN 2541-9129
PEER-REVIEWED SCIENTIFIC AND PRACTICAL JOURNAL

Safety of Technogenic and Natural Systems

Technosphere Safety

Machine Building

Chemical Technologies, Materials Sciences, Metallurgy

www.bps-journal.ru
DOI 10.23947/2541-9129

Safety of Technogenic and Natural Systems
Bezopasnost' Tekhnogennykh i Prirodnykh Sistem

Peer-Reviewed Scientific and Practical Journal

eISSN 2541-9129

Published Since 2017

Periodicity – 4 issues per year

DOI: 10.23947/2541-9129

Founder and Publisher — Don State Technical University (DSTU), Rostov-on-Don, Russian Federation

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Registration:	Mass Media Registration Certificate ЭЛ № ФС 77 – 66531 Dated Jule, 21, 2016, Issued by the Federal Service for Supervision of Communications, Information Technology and Mass Media
Indexing and Archiving:	RISC, CyberLeninka, CrossRef, DOAJ, Index Copernicus, Internet Archive
Website:	https://bps-journal.ru
Address of the Editorial Office:	1, Gagarin Sq. Rostov-on-Don, 344003, Russian Federation
E-mail:	vestnik@donstu.ru
Telephone:	+7 (863) 2–738–372
Date of Publication No.1,2026:	28.02.2026

Безопасность техногенных и природных систем

Safety of Technogenic and Natural Systems

Рецензируемый научно-практический журнал

eISSN 2541-9129

Издается с 2017 года

Периодичность – 4 выпуска в год

DOI: 10.23947/2541-9129

Учредитель и издатель — Федеральное государственное бюджетное образовательное учреждение высшего образования «Донской государственный технический университет» (ДГТУ), г. Ростов-на-Дону

Создан в целях освещения результатов исследований и реальных достижений по актуальным вопросам машиностроения, техносферной безопасности, современной металлургии и материаловедения. В журнале освещаются проблемы развития фундаментальных исследований и инженерных разработок в ряде важнейших областей технических наук. Одним из главных направлений деятельности журнала является интеграция в международное информационное пространство.

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Регистрация:	Свидетельство о регистрации средства массовой информации ЭЛ № ФС 77 – 66531 от 21 июля 2016 г., выдано Федеральной службой по надзору в сфере связи, информационных технологий и массовых коммуникаций
Индексация и архивация:	РИНЦ, CyberLeninka, CrossRef, DOAJ, Index Copernicus, Internet Archive
Сайт:	https://bps-journal.ru
Адрес редакции:	344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1
E-mail:	vestnik@donstu.ru
Телефон:	+7 (863) 2–738–372
Дата выхода №1,2026 в свет:	28.02.2026

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Safety of Technogenic and Natural Systems. 2026;10(1):7–18. eISSN 2541−9129

TECHNOSPHERE SAFETY
ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

UDC 614.841.3
https://doi.org/10.23947/2541-9129-2026-10-1-7-18

Original Theoretical Research

Matrix of Fire Hazard Factors for Overhead Power Lines as a Basis for Risk Modeling

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Abstract

Introduction. Studies of fire risks associated with overhead power lines (OHPLs) consider combustible materials, terrain, and meteorological conditions. The mechanisms of fire occurrence and spread have been studied, and quantitative risk modeling is being developed based on incident statistics. However, these scenarios rely on arbitrary or poorly defined sets of initial factors, making it difficult to create unified risk management systems. This scientific work aims to fill this gap by creating a unified classification of fire hazard factors for overhead power lines that takes into account the causes, environment, and development of fires. A scenario-based risk matrix for OHPLs is built on this foundation.

Materials and Methods. The basis of the study was a method for assessing fire risk, which considers fire from overhead power lines as a result of the interaction between three key components: the ignition source, combustible medium and fire propagation conditions. Through an analysis of the relevant literature, these components were broken down, classified, and the principles for systematizing them were identified.

Results. Ignition sources, combustible medium, and fire propagation conditions were presented as axes in the scenario matrix of fire risk associated with overhead power lines. These factors were classified and structured using author-created diagrams. The first one included the types of short circuits, heating, and ignition mechanisms. In the second, four classes of materials were differentiated by their sensitivity to fire. The third one described three categories of fire propagation conditions. The risk level and critical ignition energy were mathematically represented. The final matrix aggregated four classes of material: high-sensitive, medium-sensitive, low-sensitive, and specific. Fire spread conditions were divided into favorable, moderate, and unfavorable. Taking into account the ignition sources (interphase and single-phase), the risk levels were determined: low, medium, high, and critical.

Discussion. The matrix combined 24 typical scenarios of the studied hazard (two groups of sources × four classes of materials × three categories of propagation conditions). Five scenarios (approximately 21%) were critical. As a rule, they occurred with a combination of high-energy emergency conditions, high- and medium-sensitive materials and adverse weather conditions. The matrix can be used in the transition from a qualitative description of OHPLs to a quantitative assessment of the probability of a fire and its consequences. This innovation will be beneficial for modeling OHPL incidents, refining safety measures, and improving risk assessment. Scenarios can be ranked based on importance, allowing for a more efficient allocation of resources for protective measures.

Conclusion. The new approach, in contrast to the traditional one, makes it possible to overcome the limitations of the fragmented hazard assessment and systematically analyze fire scenarios related to overhead power lines. This allows us to justify decisions on modernizing and strengthening the protection of individual network sections, i.e., to focus investments on infrastructure elements and typical situations that fire risks depend on to a greater extent. Future research in this area is expected to:
– supplement accident statistics and the amount of experimental data on the energy characteristics of ignition sources;
– provide a quantitative parameterization of the function that represents the risk level for each scenario;
– set numerical thresholds for four risk levels.

Keywords: overhead power line, OHPL, ignition source, flammable environment, fire propagation conditions, OHPL fire risk matrix

Acknowledgements. The authors would like to thank the Editorial board and the reviewers for their attentive attitude to the article and for the specified comments that improved the quality of the article.

For Citation. Ogurtsov DA. Matrix of Fire Hazard Factors for Overhead Power Lines as a Basis for Risk Modeling. *Safety of Technogenic and Natural Systems*. 2026;10(1):7–18. https://doi.org/10.23947/2541-9129-2026-10-1-7-18

Оригинальное теоретическое исследование

Матрица факторов пожарной опасности воздушных линий электропередачи как основа для моделирования риска

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Аннотация

Введение. Исследования пожарных рисков, связанных с воздушными линиями электропередачи (ВЛЭП), учитывают горючие материалы, рельеф и метеорологические условия. Изучены механизмы возникновения и распространения пожаров. На базе статистики инцидентов развивается количественное моделирование рисков. Однако сценарии опираются на произвольные или слабо формализованные наборы исходных факторов, что затрудняет формирование единых систем управления рисками. Представленная научная работа восполняет этот пробел. Ее цель — создание единой классификации факторов пожарной опасности ВЛЭП с учетом причины, среды и развития горения. На этой базе строится сценарная матрица риска для ВЛЭП.

Материалы и методы. Основа исследования — метод оценки пожарной опасности, при котором пожар от ВЛЭП рассматривается как результат взаимодействия трех ключевых компонентов: источника зажигания, горючей среды и условий распространения горения. Анализ литературы позволил провести декомпозицию этих элементов системы, классифицировать их и определить принципы систематизации.

Результаты исследования. Источники зажигания, горючая среда и условия распространения горения показаны как оси сценарной матрицы риска пожаров, связанных с ВЛЭП. Факторы классифицируются, структурируются и приводятся в виде авторских схем. Первая включает типы замыканий, нагрева и механизмы зажигания. Во второй четыре класса материалов дифференцируются по чувствительности к возгоранию. В третьей характеризуются три категории условий распространения огня. Математически представлены уровень риска и критическая энергия зажигания. Итоговая матрица агрегирует четыре класса материалов: высокочувствительные, среднечувствительные, слабочувствительные и специфичные. Условия распространения горения делятся на благоприятные, умеренные и неблагоприятные. С учетом источников зажигания (межфазные и однофазные) определяются уровни риска: низкий, средний, высокий и критический.

Обсуждение. Матрица объединила 24 типовых сценария исследуемой опасности (две группы источников × четыре класса материалов × три категории условий распространения). Пять сценариев (примерно 21%) — критические. Как правило, они возникают при сочетании высокоэнергетических аварийных режимов, высоко- и среднечувствительных материалов и неблагоприятных метеоусловий. Матрицу можно задействовать при переходе от качественного описания обстановки на ВЛЭП к количественной оценке вероятности пожара и его последствий. Новация будет полезна при моделировании инцидентов на ВЛЭП, доработке мер безопасности, улучшении оценки рисков. Сценарии можно ранжировать по значимости, что позволит более рационально распределять ресурсы на защитные мероприятия.

Заключение. Новый подход, в отличие от традиционного, позволяет преодолеть ограничения фрагментарной оценки опасности и системно анализировать сценарии пожаров, связанных с ВЛЭП. Благодаря этому можно обосновать решения по модернизации и усилению защиты отдельных участков сети, то есть ориентировать инвестиции на элементы инфраструктуры и типовые ситуации, от которых в большей степени зависят пожарные риски. В будущих исследованиях по этой теме предполагается:

– дополнить статистику аварий и объем экспериментальных данных по энергетическим характеристикам источников зажигания;
– представить количественную параметризацию функции, которая представляет уровень риска для каждого сценария;
– установить численные пороги для четырех уровней риска.

Ключевые слова: воздушная линия электропередачи, ВЛЭП, источник зажигания, горючая среда, условия распространения горения, матрица риска возгорания ВЛЭП

Благодарности. Автор выражает благодарность редакции и рецензентам за внимательное отношение к статье и замечания, которые позволили повысить ее качество.

Для цитирования. Огурцов Д.А. Матрица факторов пожарной опасности воздушных линий электропередачи как основа для моделирования риска. *Безопасность техногенных и природных систем.* 2026;10(1):7–18. https://doi.org/10.23947/2541-9129-2026-10-1-7-18

Introduction. For a long time, the issues of assessing and reducing fire risk for long linear electric grid infrastructure facilities, in particular overhead power lines (OHPLs), have been in the focus of researchers' attention. The urgency of the problem is due to the frequency and scale of wildfires. In addition, violation of the integrity of power lines is one of the basic vulnerabilities of power systems [1]. In this case, combustible materials, terrain, and meteorological conditions form a complex of dangerous factors that should be considered in detail, separately from the general models of landscape fires.

Abroad, in fire-prone regions, energy companies are forced to use preventive shutdowns [2] and other restrictions (including PSPS[1]), as well as promptly modernize infrastructure to reduce the probabilities of fires [3].

According to the Federal Forestry Agency, 132 fires[2] broke out in Russia in 2019 due to linear-type facilities (including power lines). In the first half of 2023, in the Far Eastern Federal District, the transition from linear-type facilities was identified as an independent cause of 6.2% of the number of fires (3.4% by area)[3].

During the fire-hazardous period (April – October) in 2018, 648 forest fires were registered in the Chelyabinsk region. Of these, 19 (2.9%) were connected to power lines [4].

Landscape fires often occur due to short circuits on power lines and spread rapidly due to heat and strong winds. Such a case was recorded by the Aerial Forest Protection in the Ust-Donetsk region of the Rostov region (a fire on agricultural land on August 15, 2022[4]).

The issues of fire safety of overhead power lines are addressed from several angles. Firstly, the mechanisms of fire initiation and propagation near power lines are actively studied. This includes considering the influence of tower design, wire and insulator characteristics [5], as well as operating conditions [6]. Secondly, weather and climatic factors that contribute to fire occurrence and intensity (high air temperatures, low humidity, strong winds, prolonged periods without precipitation) are assessed [7], along with their interaction with topography and vegetation cover [8]. Thirdly, quantitative risk assessment is developed, based on accident statistics [9]. This involves using probabilistic methods, scenario analysis, and various approaches for ranking overhead line sections by risk level [10].

In the domestic and international literature, various groups of risk factors have been identified. Ignition sources near overhead power lines have been classified and detailed, including:

- equipment defects,
- external mechanical influences,
- atmospheric phenomena,
- human factor.

Various approaches to fire hazard assessment of vegetation cover have been developed and applied. These include the index of burnability, phytomass, and degree of desiccation, among others [11]. In addition, models have been proposed that take into account the influence of terrain, woodlands, fire barrier lines, and distance to infrastructure facilities and settlements [12]. However, these and other factors are usually considered separately within the framework of specific tasks (for example, building fire hazard maps, predicting the spread of fire, or planning clearing measures), without integration them into a single system “ignition source (or initiating action) – combustible environment –fire spread conditions” (IS – CE – FSC).

A separate area of research relates to predicting the development of fire-hazardous situations along overhead power lines [13]. In such studies, a limited number of typical scenarios are usually identified, for which the probabilities of occurrence and possible consequences are analyzed. Examples include fires under wires when trees fall, fires from sparking on towers in conditions of high vegetation dryness, the spread of crown fires through clearings, etc. Scenario matrices, risk maps, and other visualization tools are used to aid management decisions in these cases. However, these scenario descriptions are often based on arbitrary or poorly formalized initial factors, making it difficult to compare and integrate them into unified risk management systems at the energy system or regional level.

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[1] Public safety power shutoff.

[2] *An Up-to-Date Summary of the Fire-Prone Period: 98 Percent of Forest Fires are Caused by Humans.* (In Russ.) URL: https://rosleshoz.gov.ru/news/federal/aktualnaya-svodka-pozharoopasnogo-perioda-98-protsentov-lesnykh-vozgoraniy-voznikayut-po-vine-cheloveka-n4696 (accessed: 18.12.2025).

[3] *Analysis of the Causes of Forest Fires in the Far Eastern Federal District.* (In Russ.) URL: https://rosleshoz.gov.ru/news/dfo/analiz-prichin-vozniknoveniya-lesnykh-pozharov-na-territorii-dalnevostochnogo-federalnogo-okruga-dfo-22041 (accessed: 18.12.2025).

[4] *A Forest Fire in the Ust-Donetsk Region of the Rostov Region Arose from a Landscape Fire on Agricultural Land.* (In Russ.) URL: https://aviales.ru/popup.aspx?news=7474 (accessed: 18.12.2025).

Thus, with a significant amount of empirical data, private classifications and models in the public domain, there is no single systematic classification of the factors determining the fire hazard of overhead power lines. The relevance of such a system, built in accordance with a three-component structure (IS – CE – FSC) and initially oriented towards the use in scenario analysis, is evident. Additionally, a standardized approach to creating a risk matrix for scenarios has not yet been established, in which IS, CE, and FSC would be presented as a set of typical factors reflecting the most likely and hazardous situations. Meanwhile, elements of classification, scenario description, and quantitative modeling remain fragmented and dispersed in the literature. The authors focus on, for example:

– ignition sources [14],
– characteristics of the combustible medium [15],
– fire spread conditions [16],
– methods of probabilistic assessment and ranking of OHPL sections [17].

At the same time, there is no holistic methodological framework that includes the classification of factors, the logic behind their combination in a given scenario, and the relationship between scenarios and a quantitative risk assessment. This scientific work aims to fill this gap by creating a unified classification of factors that affect the fire hazard of overhead power lines. The classification is described in terms of the initiating effects, the combustible environment, and the conditions for fire development. Another innovation of the proposed solution is the construction of a formalized scenario risk matrix for power line sections. To achieve this goal, several tasks were completed:

– analysis of approaches to the description and classification of fire risk factors (mainly near overhead lines);
– classification of factors into three groups (IS, CE, FSC) with an indication of their interactions;
– identification of parameters and classification of the combustible environment in the area of potential exposure to the ignition source;
– definition and classification of ignition and fire spread conditions (FSC);
– generalization of classification results into a limited number of representative states;
– creation of a scenario risk matrix.

Materials and Methods. The basis of this research is the method of fire hazard assessment. In this approach, the occurrence of a fire caused by OHPLs is considered as a result of the interaction between three key components: IS, CE, and FSC. This is a generally accepted approach to assessing complex threats. Thus, multi-criteria solutions are used to determine the reliability of power lines under conditions of multiple natural disasters. For example, methods of hierarchy analysis and entropy weighting coefficients (AHP[5] – EWM[6]) [18]. Another example of a complex methodology is TOPSIS[7]. This approach is applied primarily to the ranking of risks that various types of natural disasters pose to power transmission lines. Let us mention that the method is useful for resource management based on statistics of consequences, rather than causes [9].

The methodology of the work consisted in the sequential decomposition and classification of the components mentioned above. The key principles of systematization have been identified for groups of factors.

For ignition sources, the classification was based on the analysis of their physical nature, causes of occurrence, and aggregated by key physical mechanisms of thermal effects on the combustible environment.

The classification for the combustible medium was based on its pyrological properties and location relative to the structural elements of the overhead line.

The concept of the “fire behavior triangle”, recognized in world pyrology, was used to determine the conditions of fire spread. This article focuses on weather, topography, and characteristics of combustible materials.

Results. To achieve the goal of the study, a literature review was conducted, which allowed us to organize and present the findings in the form of author-created classification schemes for ignition sources, combustible environments, and fire spread conditions. Each of these factors became the axis of the final scenario risk matrix.

Ignition sources classification. Let us mention the variety of causes of fires associated with overhead power lines. These include violations of the rules of operation of electrical networks (wear and tear, human factors) and probabilistic phenomena (climatic conditions). However, for quantitative risk modeling, the root causes of events (for example, a falling tree or a breakdown of an insulator) are less important than the physical characteristics of the ignition process itself. Therefore, from a scientific point of view, a system based on the dominance of physical heat transfer mechanisms and the nature of energy effects is considered to be of better quality.

In the proposed classification, ignition sources belong to one of two classes corresponding to emergency modes of operation. It concerns short circuits between phases (SCPs) and single-phase line-to-ground short circuits (LGSCs). Other types of emergency modes of operation (overloads or unbalanced modes) usually lead to distributed heating of conductors along their entire length, rather than concentrated and high-temperature energy release at one point, which is sufficient to ignite combustible materials.

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[5] analytical hierarchy process.
[6] entropy weighting coefficient method.
[7] technique for order preference by similarity to ideal solution.

This classification makes it possible to clearly distinguish ignition sources by type and heating mechanism (Fig. 1).

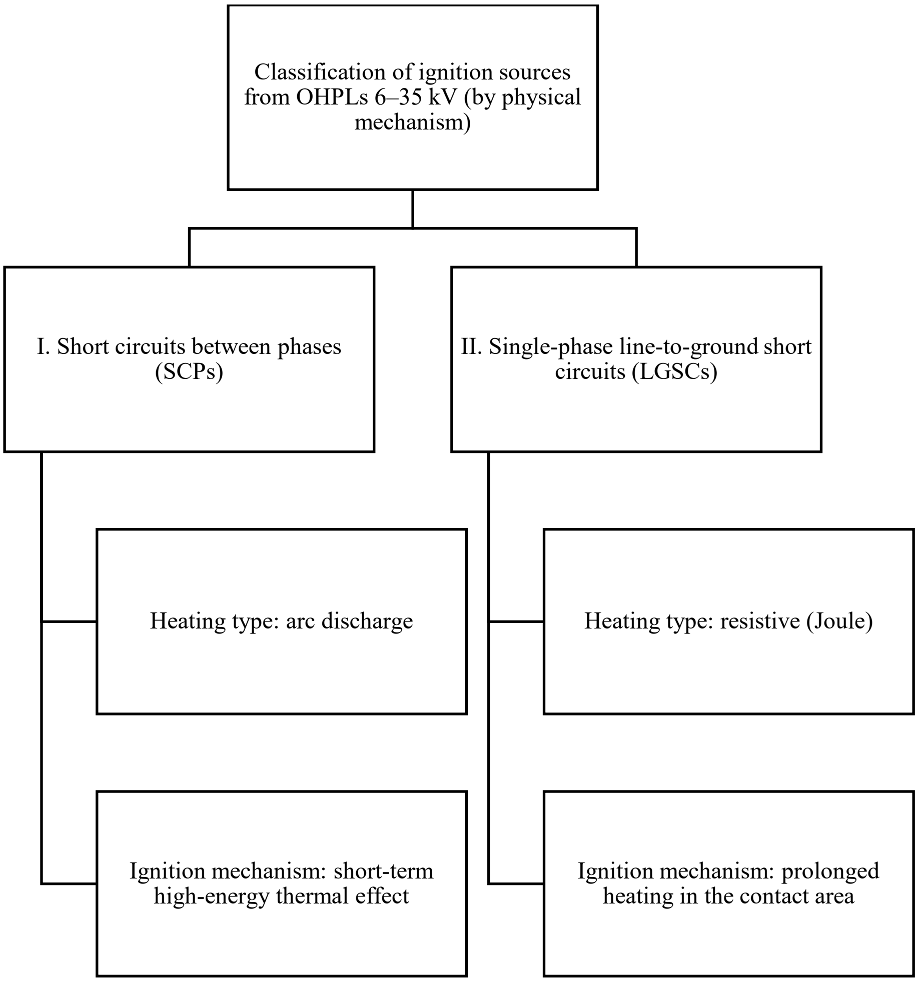

Fig. 1. Classification of fire hazard sources of overhead power lines

I. Short circuits between phases occur under the following circumstances:

– wires colliding due to wind,
– wires icing,
– trees and other objects falling on wires.

In such cases, intense heating is recorded up to 4,000–10,000°C and above. The current strength increases dramatically by 10–100 times compared to the rated mode [7]. In this case, an electric arc is formed — a plasma channel with high temperature and intense heat generation. A short-term but extremely powerful release of energy generates secondary ignition sources — incandescent metal droplets. This circumstance causes a high probability of ignition of dry forest floor or grass.

The risk of wire snapping in high winds can be quantified using models based on nonlinear equations of conductor oscillations. Such systems make it possible to determine the probability of a dangerous phase convergence in real time [8].

At the same time, the level of fire hazard directly depends on current strength and short circuit duration: low, medium or high [5]. Experimental studies confirm that there are specific ranges of fire-hazardous short-circuit currents for non-insulated aluminum wires. Thus, a wire with a cross-section of 25 mm^2 corresponds to a range of 120–180 A [13]. The same class includes double line to ground faults (DLGFs) that occur when wires of two or three different phases fall to the ground. Despite the fact that the current goes through the ground, this mode is electrotechnically equivalent to a short circuit between phases, as it is characterized by high short-circuit currents. The physics of ignition in this mode is identical to SCP: powerful electric arcs occur at the points of contact of the wires with the ground. As a result, the metal melts, and the red-hot droplets ignite combustible materials.

II. Line-to-ground short circuits cause a stable thermochemical effect on combustible materials. This is the most common and main cause of fires. The emergency mode is characterized by prolonged and, as a rule, uncontrolled release of thermal energy.

In 6–35 kV networks operating with an isulated neutral, the LGSC currents are insignificant (usually up to 10 A) [6]. They do not cause instant destruction of elements and equipment, which makes it possible to operate the network in emergency mode for a long time (several hours) without power cuts. During this time, damage is detected and repaired.

This class combines all scenarios in which the conductor of an overhead power line (OHPL) comes into prolonged contact with a grounded combustible object.

There are two types of ground faults in the literature [14]. The first one is metal. We are talking about cases of direct connection of conductors to the ground with negligible resistance at the point of contact. For example:

– wire breakage and fall on the crossarm,

– fall on the transformer substation housing and other metal objects in the protected area of the power line.

Short circuits due to high transient resistance (second type) occur when wires fall on dry grass, as well as if a broken wire touches a tree or wooden support. The same type includes contact through a damaged or contaminated insulator.

The mechanism of thermal action at the phase contact point is the same for both types of LGSCs. At the point of contact with the ground, resistive (Joule) heating occurs due to the passage of a capacitive short-circuit current through a transient resistance at the point of contact. This process is slower than in resistively compensated networks because there is no high-energy arc discharge. Nevertheless, the resulting conductive heat transfer from the heated conductor to the surrounding combustible materials ensures their gradual heating to the ignition temperature, i.e. causes the risk of fire. The earth fault current near the damage site creates local heating zones, which also contributes to the occurrence of a fire. In this case, heat dissipation is determined by the product of the square of the current and the resistance according to the Joule–Lenz law.

For metal circuits, typical transient resistance values range from 0.1 to 10 ohms, whereas for high-resistance circuits, such as when a wire falls on dry grass or contacts wood, the resistance can reach hundreds or even thousands of ohms. With relatively small LGSC currents, the level of transient resistance becomes the main factor determining heat dissipation. When the resistance increases by hundreds of times, the heating power also increases proportionally, creating local zones of intense heat that can ignite combustible materials, even at moderate short-circuit currents.

Thus, the entire variety of root causes has been grouped into two typical physical mechanisms, which will become the first dimension (axis) in the final scenario risk matrix.

Combustible environment (CE) classification. As it has been established earlier, one of the three mandatory fire conditions during the operation of overhead power lines is a combustible environment (CE). This is a combination of:

– combustible materials of natural and anthropogenic nature within the protected overhead line zone;

– overhead line structural elements that can ignite from thermoelectric ignition sources.

When quantifying the probability of ignition, we take into account the key pyrological parameters that determine the sensitivity to ignition. Thus, the minimum critical ignition energy Q_{ign}, which is determined by the heat balance equation, directly depends on the type and moisture content of the combustible material:

$$Q_{ign} = m \cdot c_p \cdot \left(T_{ign} - T_0\right) + m_{moist} \cdot L_{evap}, \tag{1}$$

where m — mass of the heated material, kg; c_p — heat capacity of combustible materials, kJ/(kg·K); T_{ign} — ignition temperature; T_0 — initial temperature; m_{moist} — moisture mass in the material, kg; L_{evap} — heat of water evaporation.

As the moisture content increases, the ignition energy conditions increase significantly. Experimental studies show that with an increase in the humidity of natural combustible materials (NCMs) from 10% to 30%, the required minimum thermal load increases from 20 kW/m^2 to 35–40 kW/m^2, which corresponds to an increase in the critical ignition energy by about 1.75–2 times [15].

An additional factor contributing to the increase in the energy barrier is the energy expenditure on moisture evaporation. The specific heat of evaporation for water is 2.26 MJ/kg. For living vegetation with moisture content of 100–300% relative to dry mass, ignition does not occur at heat fluxes below 35 kW/m^2.

Thus, when compared to dry finely dispersed materials (moisture content 10–15%), the ignition energy barrier for moistened and living NCMs increases approximately 3–10 times, which is consistent with experimental data on the effect of moisture content on the flammability of plant materials [16].

Based on this information, a classification of the combustible medium can be proposed (Fig. 2).

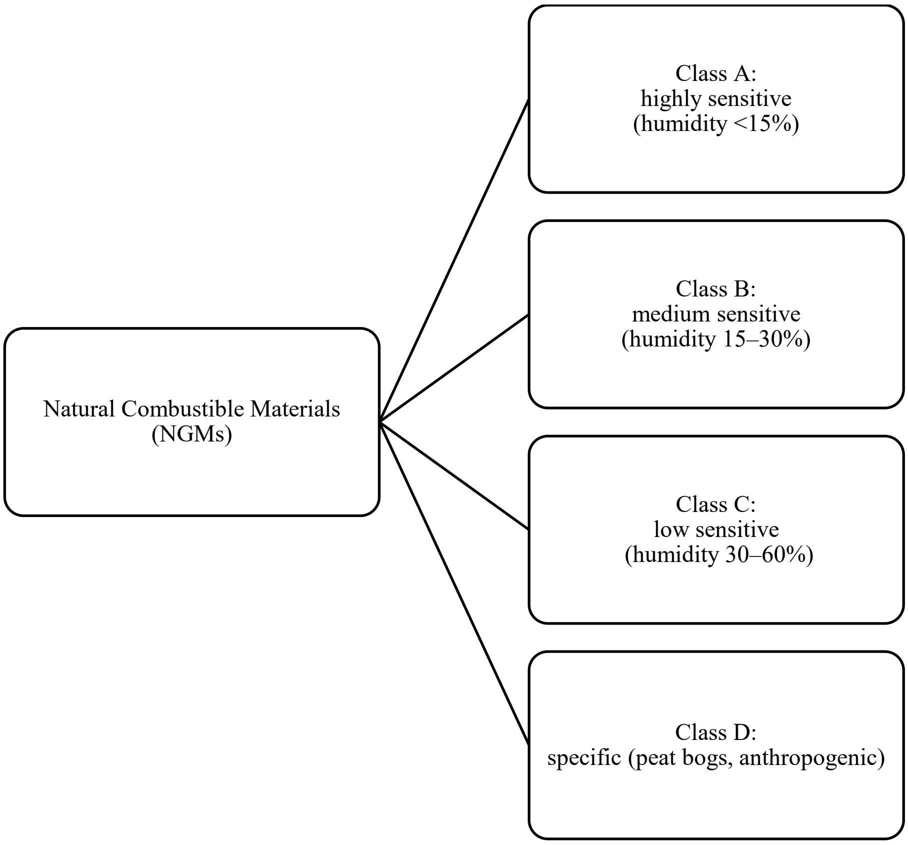

Fig. 2. Classification of combustible materials in OHPL area

Class A. Highly sensitive NCMs. This class is characterized by minimum moisture content (less than 15%) and, as a result, low critical ignition energy (less than 1 kJ). This group includes the most fire-hazardous materials: dry grass and needles (fallen this year), mosses during prolonged drought, as well as organic accumulations on insulators (droppings, down) and materials from bird nests.

Class B. Medium sensitive NCMs. This class combines materials with a moderate moisture content (15–30%), which increases the required ignition energy to 1–10 kJ. Examples: forest floor with moderate humidity, long-fallen needles from previous years, dry branches up to 5 cm in diameter, and support wood with a humidity of 20–30%.

Class B. Low sensitive NCMs. They contain 30–60% moisture. According to equation (1), in this case, high energy (10–50 kJ) is needed for ignition. Low sensitive NCMs are moist forest litter, live needles and foliage in tree crowns, coniferous undergrowth and support wood with a humidity of 30–50%.

Class G. Specific combustible materials. The fire hazard of peat bogs, structural wood, and combustible debris is determined not only by the moisture content (as in classes A, B, and C), but also by specific properties: structural features, chemical composition, and the ability to self-sustaining combustion.

The elements of this class are qualitatively heterogeneous and demonstrate high susceptibility to thermal effects — prolonged during LGSC and short-term from drops of red-hot metal. This is due either to the low ignition energy (flame retardant-soaked wood, dry debris), or the ability to self-sustaining combustion after ignition (peat bogs). As a result, despite the heterogeneity, such materials are taken together for the purposes of scenario risk modeling.

This classification, based on pyrological properties and sensitivity to thermoelectric influences, allows us to move from the generalized concept of "combustible environment" to four classes. This is necessary to build a scenario risk matrix and allows you to quantify the probability of ignition (P_{ign}) in various emergency modes, depending on the current state of CE

Fire spread condition (FSC) classification. Let us consider the situation with such an initial event as the occurrence of a fire from an overhead power line. The damage and the scale of the consequences are determined by the fire spread from the source. The conditions that regulate this process form the third key component of the fire hazard system.

In the framework of this study, the FSC is understood as a set of environmental factors that determine the speed, intensity, trajectory of the fire front and the possibility of its transition between different tiers of the combustible environment. It is important to note that the probability of ignition and spread of fire depends on a number of factors (for example, wind, and humidity). However, in this section they are considered from the point of view of the impact on an existing, developing fire. The FSC classification is necessary for modeling fire scenarios and assessing potential damage.

A model called the triangle of fire behavior is widely used in pyrology. Within the framework of the presented study, the concept is adopted according to which the nature and dynamics of fire spread are determined by the interaction of three groups of factors: weather conditions, topography and characteristics of combustible materials [11]. This takes into account:

– wind speed and air humidity,
– ground form,
– volume of combustible material, its horizontal and vertical location (Fig. 3).

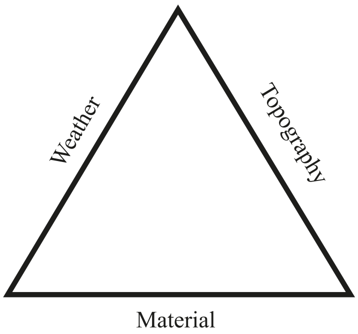

Fig. 3. Fire behavior triangle

For a specific section of overhead line, the topography is taken into account during the design and does not require inclusion in the scenario matrix as a variable. For critical areas (steep slopes), increasing risk factors are used. The characteristics of the materials are also reflected in the classification of the combustible medium:

– Class A materials ensure a high rate of grass-roots fires,
– Class B materials form a “ladder” for crown fires.

Only the weather is changing dynamically, and it requires an operational assessment. Wind and humidity have the maximum predictive potential and are easy to measure.

The fire hazard class (FHC) according to weather conditions is an integral indicator. In Russia, the Nesterov complex indicator is used with a gradation from I (absence of danger) to V (extreme danger). FHC is directly related to the moisture content of small combustible materials. Thus, with FHC V, humidity decreases to 10–15% (class A of the combustible environment), with FHC III, it is 20–30% (class B).

Wind speed of about 10 m:

– increases the probability of emergency modes (whipping of wires at SCP, contact with vegetation at LGSC);
– increases heat generation during ignition;
– determines the velocity of the front during propagation.

Wind speed is a consistently measured and predicted parameter. A threshold value of 5 m/s has been set for scenario analysis. Below this indicator, the fire spreads due to radiation heating at a moderate rate. The higher velocity causes convective heat transfer with flame tilt, spark transfer, and secondary foci [12].

Thus, the system of factors of the fire behavior triangle is reduced to two key dynamic parameters — FHC and wind speed. This reduction is justified physically, statistically and practically.

The fire hazard class (FHC) according to weather conditions determines the pyrological readiness of natural combustible materials. This integral characteristic reflects their ability to ignite and maintain fire. It depends on the type of material, its moisture content and thermal properties.

The wind speed, in turn, determines the dynamics of flame propagation and the formation of secondary foci.

From a statistical point of view, both parameters are reliable indicators of fire danger, and from a practical point of view, their use is justified by the high availability and predictive reliability of meteorological observations.

The FHC and wind speed determine the nature of fie spread conditions (FSCs) for the scenario matrix (Fig. 4).

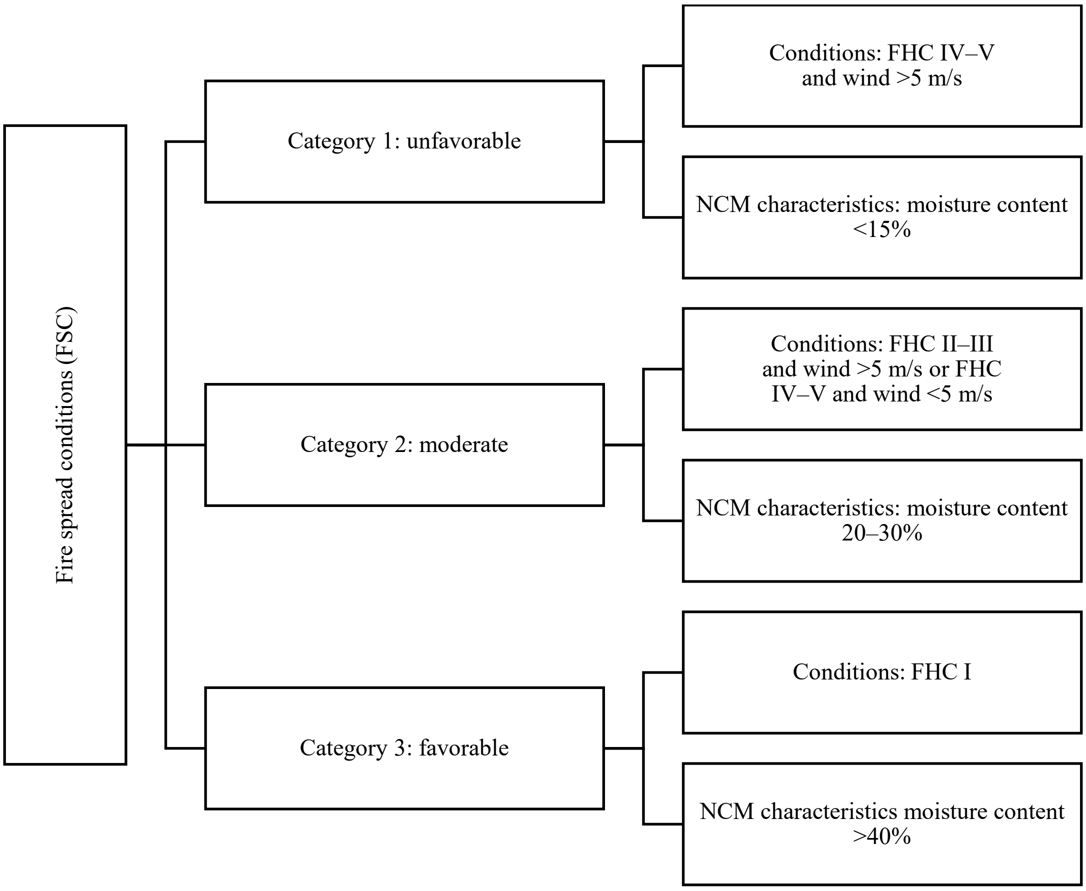

Fig. 4. Fire spread conditions

Fire spread conditions can be described as favorable, unfavorable, or moderate, and the level of threat can be low, medium, or high.

Fire risk scenario matrix. A scale of risk levels is needed to quantify each fire hazard scenario for OHPLs. The analysis of risk assessment methods became the basis for the proposed four-level classification.

Low risk *(R*1*)*. The probability of ignition is minimal or there are no conditions for the development of a fire. It is typical for combinations of: weak ignition sources + CE with high moisture content + unfavorable FSCs (FHC I–II, lack of wind).

Average risk *(R*2*)*. Moderate risk of ignition and limited potential for fire spread. It is typical for combustible materials with moderate pyrological readiness (class B), transitional weather conditions corresponding to FHC III, with wind speeds up to 5 m/s.

High risk *(R*3*)*. High probability of ignition and significant potential for fire spread. It is formed at FHC IV–V and (or) wind speeds of more than 5 m/s in combination with combustible materials of high or moderate pyrological readiness (classes A, B) and ignition sources of increased energy capacity.

Critical risk (*R*4). Maximum risk of ignition and rapid fire development. The risk is generated by powerful ignition sources (SCP, LGSC arcs) in combination with dry fine materials under extreme weather conditions (FHC V, wind >5 m/s).

Risk level *R* for each scenario can be represented as function *f*. It determines qualitative correspondence of input parameters and risk categories *R*1–*R*4 based on an expert assessment of two parameters:

$$R = f\left(P_{\text{вз}}, T_{\text{п}}\right). \qquad (2)$$

Here $P_{\text{вз}}$ — probability of catching fire, determined by a combination of IS type and CE class. $T_{\text{П}}$ — severity of consequences. It is determined by the CE class and the FSC category. The speed and scale of distribution are taken into account.

In this paper, the risk levels are qualitatively determined by the characteristics established in the previous sections. The quantitative parameterization of function (2) and the establishment of numerical thresholds for risk levels R1–R4 are the subject of further research.

The above analysis of the three key components (IS, CE and FSC) allows us to form a final scenario matrix (Table 1).

Table 1

Fire risk matrix

IS	Material class	Fire spread conditions		
		Favorable	Moderate	Unfavorable
LGSC	A. Highly sensitive	*R*2 — average	*R*3 — high	*R*4 — critical
	B. Medium sensitive	*R*1 — low	*R*2 — average	*R*3 — high
	C. Low sensitive	*R*1 — low	*R*1 — low	*R*2 — average
	D. Specific	*R*2 — average	*R*2 — average	*R*3 — high
SCP	A. Highly sensitive	*R*3 — high	*R*4 — critical	*R*4 — critical
	B. Medium sensitive	*R*2 — average	*R*3 — high	*R*4 — critical
	C. Low sensitive	*R*1 — low	*R*2 — average	*R*3 — high
	D. Specific	*R*2 — average	*R*3 — high	*R*4 — critical

Discussion. The matrix combined all 24 typical scenarios of fire hazard (two groups of ignition sources × four classes of combustible materials × three categories of fire conditions). The principles of assigning risk levels in the scenario matrix are provided below.

Class D of combustible materials in all scenarios is characterized by the minimum allowable risk level *R*2, even under favorable conditions of fire spreading. Assigning the *R*1 level in this case is impractical for the following reasons:

– the specific properties of such materials, including the ability to smolder and low humidity of structural and flame retardant-impregnated wood,

– the presence of combustible debris prone to sustained combustion.

SCPs with higher thermal impact energy tend to increase the risk level by one category compared to LGSCs with the same class of combustible materials.

Unfavorable fire spread conditions (FHC IV–V at wind speeds of more than 5 m/s) in combination with Class A combustible materials in all cases form critical *R*4 risk level regardless of the type of ignition source.

Approximately 21% of the total number of scenarios are critical (*R*4). They are formed mainly by the following combinations:

– high-energy emergency modes (interphase faults and individual single–phase scenarios),

– highly sensitive and medium-sensitive combustible materials,

– adverse weather conditions.

As you can see, the matrix is a solution that provides a transition from a qualitative description of the situation on the overhead line to a subsequent quantitative assessment of the probability of a fire and its consequences.

Let us list practical application options for this matrix:

– modeling the occurrence and spread of fires on OHPLs,

– refinement of safety measures for specific sections of the network,

– improvement of fire risk assessment in electrical networks.

The matrix allows you not only to identify the presence of increased danger, but also to rank scenarios by importance, which opens up the possibility of a more rational allocation of resources for protective measures.

Conclusion. The main physical and spatial factors determining the fire hazard of overhead power lines are highlighted. Based on them, classifications of ignition sources, combustible environment and fire spread conditions have been developed, reflecting the features of the linear infrastructure and the surrounding area.

The key result of this study is the creation of a risk matrix of 24 scenarios for the occurrence and development of fire on overhead power lines. Unlike the traditional approach focused on the analysis of individual factors, the proposed solution takes into account the interaction of ignition sources, combustible environment and fire spread conditions. The research results allow us to move from a fragmentary assessment of fire hazard to a systematic analysis of specific scenarios. Thanks to this approach, it is possible to justify decisions to modernize and strengthen the protection of individual sections of the network. This makes it possible to focus investments on infrastructure elements and typical situations, on which fire risks depend to a greater extent [10].

Let us note that the results require further development. There are certain limitations associated with an expert assessment of the relative importance of scenarios, which affect the objectivity of assigning risk levels. The lack of accident statistics and experimental data on the energy characteristics of ignition sources prevent a full-fledged quantitative parameterization of scenarios. Overcoming these limitations is a priority area for future research, including the collection and analysis of incident statistics.

In addition, in the future, we will need to develop function *f* that represents risk level *R* for each scenario. Specifically, we plan to quantify the parameters of the function and set numerical thresholds for the four risk levels discussed in this article

A separate area of development for overhead line fire safety systems is the rapid detection of fires. In this context, it is promising to combine a scenario-based approach to risk assessment with neural network computer vision technologies designed to detect smoke and flames in real time [19].

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Conflict of Interest Statement: **the author declares no conflict of interest.**

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Конфликт интересов. **Автор заявляет об отсутствии конфликта интересов.**

Автор прочитал и одобрил окончательный вариант рукописи.

Received / Поступила в редакцию 17.11.2025
Reviewed / Поступила после рецензирования 23.12.2025
Accepted / Принята к публикации 15.01.2026

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UDC 614.841.4:622.276
https://doi.org/10.23947/2541-9129-2026-10-1-19-31

Original Empirical Research

Integrated Management of Fire and Occupational Risks at Enterprises

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Abstract

Introduction. Ensuring fire safety at oil and gas enterprises is a crucial aspect of occupational health and safety management system. These facilities are known to have a high concentration of flammable and explosive materials. According to statistics from the Federal Service for Environmental, Technological and Nuclear Supervision (Rostechnadzor), approximately 38% of accidents at oil and gas facilities are related to fires and explosions. The introduction of a new method for calculating fire risk values and requirements for the occupational safety and health management system necessitates an integrated approach to fire risk management. The scientific problem is the lack of a comprehensive methodology linking fire risk assessment procedures with occupational risk management processes within a single system. The purpose of this research is to create an integrated fire risk management system that aims to enhance the effectiveness of occupational safety in oil and gas industry.

Materials and Methods. The research methodology was based on a systematic approach to integrating fire risk assessment procedures in accordance with Order No. 533 of the Ministry of Emergency Situations of Russia and Occupational Health and Safety Management System (OHSMS) processes. The research base consisted of data from 12 oil and gas industry facilities: four gas treatment units, three compressor stations, three oil pumping stations, and two gas distribution stations. The main facility was a gas treatment unit located in the Yamalo-Nenets Autonomous Okrug (YNAO). Initial data were collected over a period of at least three years, and a group of experts, including fire safety specialists, occupational safety engineers, and process specialists, was involved in determining the OHSMS correction factors. Expert evaluation was conducted using the Delphi method, with consistency analysis using the Kendall's coefficient of concordance ($W = 0.82$). As part of the research, a mathematical model with correction factors and an integrated hazard matrix was developed. At the first stage, identification and classification of hazards were carried out in accordance with Article 9 of Federal Law No. 123-FZ "Technical Regulations on Fire Safety Requirements", dated July 22, 2008. At the second stage, logical event trees were built and integrated metrics were calculated using JupyterNotebook (Python, Pandas, Scipy, NumPy libraries), and compared with traditional methods.

Results. An integrated fire risk management system was developed, which included five interrelated processes: hazard identification, risk assessment, development of management measures, monitoring and continuous improvement. A mathematical model for calculating potential fire risk was proposed, introducing the OHSMS integration coefficient, which allows for the consideration of the impact of organizational and technical occupational safety measures on fire likelihood and consequences. Within the integrated approach, 47 types of hazards were identified compared to 35 using the traditional methods, indicating more detailed risk source identification. The fire risk was reduced by 22–26% when using the integrated system compared to the baseline level.

Discussion. The use of an integrated approach to occupational risk management can increase its efficiency by 25–30%, due to a synergistic effect that has been confirmed by a comparative analysis of traditional and proposed risk assessment methods at oil and gas facilities. This effect is achieved through the integrated consideration of OHSMS measures, which affect the frequency and severity of fire-related incidents, while taking into account the limitations of the methodology, such as dependence on the completeness and representativeness of accident data (at least three years of observations) and focusing mainly on objects with continuous technological processes. The results obtained are consistent with international research on safety system integration, which has shown that similar approaches can improve hazard identification accuracy by 20–35% and enhance the quality of risk assessments.

Conclusion. The results of this study can be used to improve safety management systems at oil and gas enterprises. This includes the introduction of a mathematical model with OHSMS coefficients to reduce fire risks by 22–26%. The proposed integrated system contributes to the development of scientific foundations for risk management in industry. It opens up prospects for further research on adapting this approach to marine facilities, as well as permafrost and other extreme climates. It is recommended to use the model to optimize resource allocation in OHSMS. This should take into account the results of expert evaluations and regular revisions of parameters as more statistical data becomes available.

Keywords: fire safety, oil and gas industry, occupational health and safety management system, occupational risks, fire risk, hazard identification, mathematical modeling, integrated management system, industrial safety, OHSMS

Acknowledgements. The authors would like to thank Elena V. Glebova, Dr. Sci. (Eng.), Professor, Head of the Department of Industrial Safety and Environmental Protection at the Gubkin Russian State University of Oil and Gas (National Research University), for her assistance in obtaining data that made this research possible.

For Citation. Fomichev LYu, Minaeva IA, Sukharsky SP, Batmanov SV, Kuznetsov YaM. Integrated Management of Fire and Occupational Risks at Enterprises. *Safety of Technogenic and Natural Systems*. 2026;10(1):19–31. https://doi.org/10.23947/2541-9129-2026-10-1-19-31

Оригинальное эмпирическое исследование

Комплексное управление пожарными и профессиональными рисками на предприятиях

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Аннотация

Введение. Обеспечение пожарной безопасности на предприятиях нефтегазовой отрасли является одной из самых важных задач в системе управления охраной труда, поскольку такие объекты характеризуются высокой концентрацией пожароопасных и взрывоопасных веществ. Согласно статистическим данным Федеральной службы по экологическому, технологическому и атомному надзору (Ростехнадзор), около 38 % аварий на объектах нефтегазового комплекса связано с пожарами и взрывами. Вступление в силу новой методики определения расчетных величин пожарного риска, а также требований к системе управления охраной труда обусловливает необходимость формирования интегрированного подхода к управлению пожарными рисками. Научная проблема состоит в отсутствии комплексной методологии, которая бы увязывала процедуры оценки пожарного риска с процессами управления профессиональными рисками в рамках единой системы. Целью данного исследования является разработка интегрированной системы управления пожарными рисками, ориентированной на повышение эффективности обеспечения безопасности труда на предприятиях нефтегазовой отрасли.

Материалы и методы. Методология исследования основана на системном подходе к интеграции процедур оценки пожарного риска согласно приказу МЧС России № 533 с процессами управления охраной труда (СУОТ). Базу исследования составили данные с 12 объектов нефтегазовой отрасли: четыре установки подготовки газа, три компрессорные станции, три нефтеперекачивающие станции и две газораспределительные станции. Основной объект — установка подготовки газа в Ямало-Ненецком автономном округе (ЯНАО). Исходными данными служили материалы по авариям за период не менее трех лет. Для определения поправочных коэффициентов СУОТ привлечена группа экспертов: специалисты по пожарной безопасности, инженеры по охране труда и технологи. Экспертная оценка проводилась методом Дельфи с анализом согласованности по коэффициенту конкордации Кендалла (W = 0,82). В рамках исследования разрабатывались математическая модель с поправочными коэффициентами и интегрированная матрица опасностей. На первом этапе были проведены идентификация и классификация опасностей согласно ст. 9 Федерального закона № 123-ФЗ от 22.07.2008 «Технический регламент о требованиях пожарной безопасности». На втором этапе построены логические деревья событий, расчет интегрированных показателей с использованием JupyterNotebook (Python, библиотеки Pandas, Scipy, NumPy) и сопоставление с традиционными методиками.

Результаты исследования. Разработана интегрированная система управления пожарными рисками, включающая в себя пять взаимосвязанных процессов: идентификация опасностей, оценка риска, разработка мер управления, мониторинг и постоянное улучшение. Предложена математическая модель расчета потенциального пожарного риска с введением коэффициента интеграции СУОТ, который позволяет учесть влияние организационных и технических мер охраны труда на вероятность и последствия пожаров. В рамках интегрированного подхода выявлено 47 видов опасностей против 35 при использовании традиционной методики, что свидетельствует о более детализированной идентификации источников риска. Установлено снижение пожарного риска на 22–26 % при применении интегрированной системы, по сравнению с базовым уровнем.

Обсуждение. Применение интегрированного подхода обеспечивает повышение эффективности управления профессиональными рисками на 25–30 % за счет выраженного синергетического эффекта, подтвержденного сравнительным анализом традиционных и предлагаемых методов оценки рисков на нефтегазовых объектах. Указанный эффект формируется благодаря комплексному учету мероприятий СУОТ, влияющих на частоту возникновения и тяжесть последствий пожароопасных сценариев, с одновременным учетом ограничений применения методики, таких как зависимость от полноты и репрезентативности данных по авариям (не менее трех лет наблюдений) и ориентация преимущественно на объекты с непрерывными технологическими процессами. Полученные результаты согласуются с международными исследованиями по интеграции систем безопасности, где аналогичные подходы демонстрируют повышение точности идентификации опасностей на 20–35 % и улучшение качества последующей оценки рисков.

Заключение. Результаты исследования могут быть использованы для совершенствования систем управления безопасностью на предприятиях нефтегазовой отрасли, включая внедрение разработанной математической модели с коэффициентами СУОТ для снижения пожарных рисков на 22–26 %. Предложенная интегрированная система вносит вклад в развитие научных основ управления рисками в промышленности, открывая перспективы дальнейших исследований по адаптации данного подхода к морским объектам, а также к условиям вечной мерзлоты и других экстремальных природно-климатических зон. Рекомендуется применение модели для оптимизации распределения ресурсов в СУОТ с учетом результатов экспертной валидации и регулярного пересмотра параметров по мере накопления статистических данных.

Ключевые слова: пожарная безопасность, нефтегазовая отрасль, система управления охраной труда, профессиональные риски, пожарный риск, идентификация опасностей, математическое моделирование, интегрированная система управления, производственная безопасность, СУОТ

Благодарности. Авторы выражают благодарность заведующей кафедрой промышленной безопасности и охраны окружающей среды Российского государственного университета нефти и газа (национального исследовательского университета) им. И.М. Губкина, доктору технических наук, профессору Елене Витальевне Глебовой за помощь в получении данных, позволивших провести исследование.

Для цитирования. Фомичев Л.Ю., Минаева И.А., Сухарский С.П., Батманов С.В., Кузнецов Я.М. Комплексное управление пожарными и профессиональными рисками на предприятиях. *Безопасность техногенных и природных систем.* 2026;10(1):19–31. https://doi.org/10.23947/2541-9129-2026-10-1-19-31

Introduction. Ensuring fire safety at oil and gas industry enterprises is an important task, especially in light of current global trends towards occupational safety and health. Many countries are adopting increasingly strict norms and standards for environmental protection and worker safety, which presents additional challenges for the oil and gas sector. The absence of adequate fire safety measures can lead not only to catastrophic consequences for the health of employees, but also to significant financial losses, including compensation for victims, costs of facility restoration, and fines for legal infringements. Ignoring fire safety issues can cause devastating environmental consequences with massive leaks of hazardous substances. This, in turn, can lead to a negative perception of the industry as a whole. Thus, the urgency of developing and implementing effective fire risk management systems in the oil and gas industry is becoming indisputable, and the urgent need for an integrated approach to solving this problem in the context of global change requires immediate action. An analysis of statistical data on oil and gas industry facilities for the period 2019–2023 reveals that, despite the ongoing safety measures, significant losses from fires and explosions continue to be reported. The implementation of a new methodology for calculating fire risk values and requirements for occupational safety and health management necessitates an integrated approach to fire risk management. However, so far, no comprehensive methodology has been developed to link fire risk assessment procedures with occupational risk management processes within a single system.

According to statistics from Rostechnadzor, between 2019 and 2023, approximately 38% of accidents at oil and gas facilities involved fires and explosions. This emphasizes the urgency of developing effective fire risk management systems. Figure 1 shows data on emergencies in the oil and gas industry for 2019–2023. Figure 2 shows the number of accidents at oil and gas production facilities over the same period.

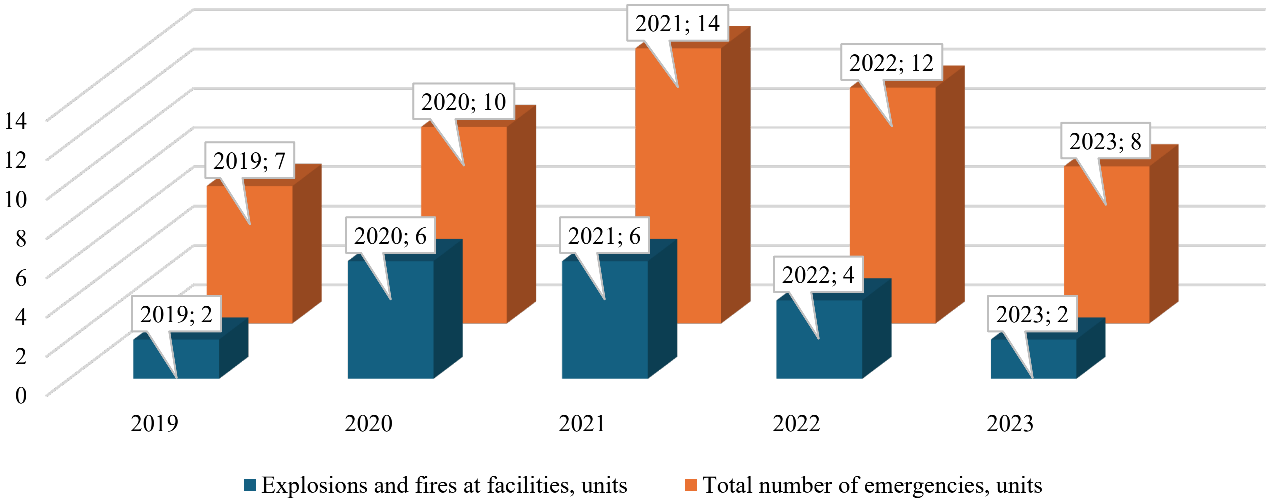

Fig. 1. Number of emergencies at oil and gas production facilities in 2019–2023

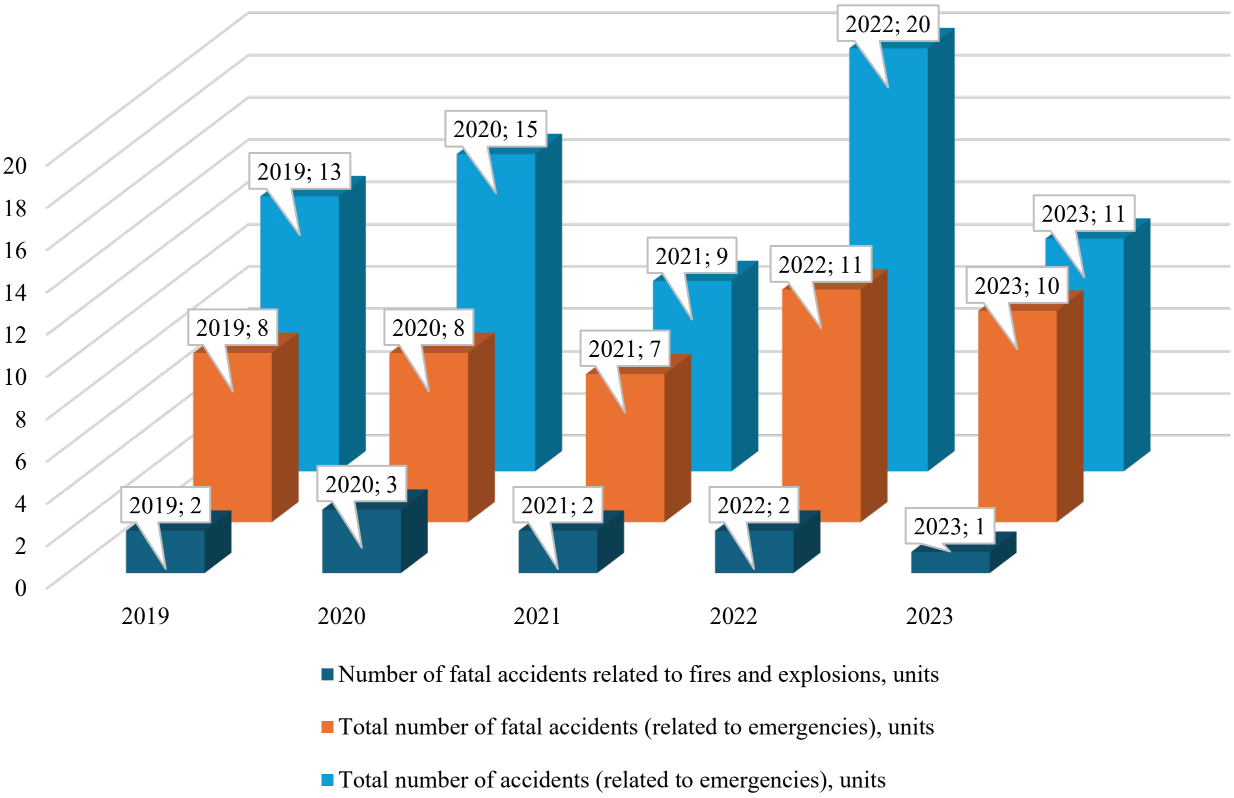

Fig. 2. Number of accidents at oil and gas production facilities in 2019–2023

The graphs show the dynamics of accidents and related consequences at oil and gas industry facilities in 2019–2023. During this period, the share of emergencies among all incidents varied in the range from 25 to 60%, with an average of 38%. The minimum number of emergencies was recorded in 2023, which indicated the effectiveness of the measures taken to manage industrial and fire safety. Similarly, the accident rate decreased from 25% in 2019 to 10% in 2023, and the five-year average was 23%. The average proportion of accidents related to fires and explosions remained at about 24%, demonstrating a steady downward trend.

Fatal accidents related to fires at the facilities under consideration remained at a relatively low level, which confirmed the effectiveness of integrated industrial and fire safety management systems, as well as ongoing preventive measures [1]. The identified trends emphasized the need for further improvement of approaches to ensuring integrated safety at oil and gas industry enterprises and the urgency of continuing work to reduce risk levels, frequency of severe and group incidents and scale of their consequences [2].

The new methodology for determining calculated fire risk values at production facilities, which entered into force on January 1, 2025 (EMERCOM of Russia Order No. 533 dated June 26, 2024)[1] and the current Approximate Regulation on the Occupational Health and Safety Management System (Ministry of Labor of Russia Order No. 776n dated October 29, 2021)[2] require the development of an integrated approach to fire risk management within the framework of the general occupational health and safety management system. The new methodology of the Russian Ministry of Emergency Situations maintains a comprehensive list of fire hazards as defined in Article 9 of Federal Law No. 123-FZ, while also clarifying criteria for human injuries and approaches to simulating fire scenarios and assessing associated risks. Main changes relate to details of calculation procedures and requirements for analyzing initial events and justifying initial data, rather than adding new hazardous factors. At the same time, the requirements of the occupational health and safety management system include regular identification of hazards and assessment of occupational risks. This forms the methodological basis for integrating fire risk assessment procedures into the overall occupational health and safety management system [3].

An analysis of modern scientific research reveals that in most studies the issues of fire safety and occupational safety are considered separately, without sufficient elaboration of their relationship [4]. However, the specific nature of the oil and gas industry necessitates the implementation of an integrated approach [5], which focuses on recognizing the mutual influence of different types of occupational and fire hazards, as well as their combined effect on the safety of production [6].

The aim of this research is to develop an integrated fire risk management system based on the requirements of the current methodology of the Russian Ministry of Emergency Situations, as well as the principles of occupational safety management systems, in order to improve the efficiency of occupational safety at oil and gas industry enterprises and reduce the probability of dangerous events.

Materials and Methods. The research methodology was based on a systematic approach to integrating fire risk assessment procedures in accordance with Order of the Ministry of Emergency Situations of Russia No. 533 and occupational risk management processes within the OHSMS in accordance with Order of the Ministry of Labor of Russia No. 776n. The research included the development of an integrated hazard matrix that linked primary and associated fire hazards (according to Federal Law No. 123-FZ) with occupational risks for various categories of personnel. Experts in fire safety and labor protection participated in validating the methodology. Methods of expert assessment and statistical analysis were used.

The research was conducted based on data from 12 oil and gas industry facilities located in the Yamalo-Nenets Autonomous Okrug and part of a large joint-stock oil and gas production company. To ensure the representativeness of the sample, we used the following criteria: the presence of a certified occupational health and safety management system in accordance with GOST R ISO 45001; the availability of information on industrial accidents for at least the last five years; the presence of data on inspections by regulatory bodies in the field of industrial safety and labor protection; and the variety of technological processes and equipment used. The sample included four gas treatment units with a capacity of 15 to 45 million m^3/day and an operating pressure of up to 25 MPa, three step compression compressor stations with a capacity of 40–80 million m^3/day with a total capacity of 12–32 MW and an injection pressure of up to 10 MPa, three oil pumping stations (oil pipeline) with a capacity of 8–25 million tons per year and with a supply pressure of up to 6 MPa, two gas distribution stations with a reduction pressure of 2.5 to 1.2 MPa and a capacity of up to 3.5 million m^3/day. The following data was collected and analyzed for each facility: acts and protocols of inspections of supervisory authorities in the field of industrial safety and labor protection for 2018–2023, registers of industrial incidents, including cases of pipeline integrity violations, hydrocarbon leaks, equipment failures and personnel injuries, results of hazard analysis conducted by the company (HAZOP, analysis of the types and consequences of failures), equipment parameters from technical documentation and plant data sheets, data on fire scenarios, calculated using models in software packages (PHAST, ALOHA or equivalent), information on occupational safety and fire safety measures, incident reports and disability sheets related to occupational risks. The database on violations of fire and industrial safety requirements was compiled on the basis of open registers of supervisory authorities and internal registers of the company.

Technosphere Safety

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[1] *On Approval of the Methodology for Determining Calculated Fire Risk Values at Production Facilities.* Order of the Ministry of the Russian Federation for Civil Defense, Emergencies and Elimination of Consequences of Natural Disasters No. 533 dated 26.06.2024. (In Russ.) URL: http://publication.pravo.gov.ru/document/0001202409030008 (accessed: 18.12.2025).

[2] *On Approval of the Approximate Regulations on the Occupational Health and Safety Management System.* (In Russ.) URL: https://normativ.kontur.ru/document?moduleId=1&documentId=409457 (accessed: 28.10.2025)

The proposed integrated system included the following interrelated processes. The first process was the identification of fire hazards as part of the overall process of identifying occupational risks according to OHSMS. The second was the assessment of fire risk using Methodology of the Russian Ministry of Emergency Situations No. 533. The third was the development of integrated risk management measures. The fourth was the monitoring and control of the effectiveness of the measures taken. The fifth was the continuous improvement of the risk management system [7].

Mathematical model of integrated risk assessment contained a calculation of the potential fire risk within the integrated system and was determined by the formula:

$$P_{int}\left(a\right) = K_{OHSMS} \cdot \sum\nolimits_{j=1}^{J} Q_j \cdot Q_{\partial ij}\left(a\right), \tag{1}$$

where K_{OHSMS} — coefficient of integration with OHSMS, which takes into account the effectiveness of the occupational safety management system; J — number of fire scenarios; Q_j — frequency of implementation of the *j-th* fire scenario, year^{-1}; $Q_{\partial ij}(a)$ — conditional probability of human injury during implementation the *j-th* scenario.

Coefficient of integration with OHSMS is determined by the formula:

$$K_{OHSMS} = K_{ident} \cdot K_{train} \cdot K_{cont} \cdot K_{impr}, \tag{2}$$

where K_{ident} — coefficient of effectiveness of hazard identification (0.8–1.2); K_{train} — coefficient of effectiveness of personnel training (0.7–1.1); K_{cont} — coefficient of effectiveness of control (0.8–1.3); K_{impr} — coefficient of continuous improvement (0.9–1.1).

To determine the values of the coefficients and validate the model, a group of 15 experts was involved: five fire safety specialists with work experience from 8 to 25 years, five occupational safety engineers with experience from 6 to 20 years, and five process specialists with experience from 10 to 30 years. The criteria for the selection of experts were higher professional education, at least five years of work experience at oil and gas facilities, certificates in the field of industrial safety, as well as the absence of a conflict of interest with the facilities. Expert evaluation of coefficients K_{ident}, K_{train}, K_{cont}, K_{impr} was conducted using the Delphi method in three rounds in the form of an anonymous questionnaire: in the first round, experts gave individual estimates (within predefined acceptable values); in the second round they were provided with an aggregative summary of the group (median and interquartile range for each coefficient) with a suggestion to clarify the answers; in the third round, the confirmation of the agreed values was performed. The consistency was controlled by the Kendall's concordance coefficient (W = 0.82). The final values of the coefficients were determined as the medians of expert estimates, and the interval values (ranges) were set by the boundaries of the interquartile range (25th and 75th percentiles), followed by rounding to values convenient for practical use.

The values of the coefficients in formula (2) were determined based on an expert assessment using the Delphi method and statistical analysis of Kendall's consistency. The ranges were selected taking into account data from similar studies [6–10]: K_{ident} reflected the variability of hazard detection depending on the completeness of databases; K_{train} — impact of staff training on reducing the frequency of incidents; K_{cont} — effectiveness of monitoring equipment based on historical accident data; K_{impr} — contribution of iterative improvements in OHSMS to long-term risk reduction.

The Kendall's concordance coefficient (W = 0.82) and ANOVA analysis were used to determine the significance of differences between groups. Pearson correlation analysis was used to identify relationships between parameters as statistical processing methods. The calculations were performed in the Jupyter Notebook development environment using Python and the Matplotlib, Pandas, Scipy, and NumPy libraries.

Table 1 shows an integrated hazard matrix developed based on the analysis of the requirements of Order of the Ministry of Labor of Russia No. 776n (Occupational Risk Management System) and Methodology of the Ministry of Emergency Situations of Russia No. 533 (Fire Risk Assessment), taking into account the classification of fires according to Art. 8 of Federal Law No. 123-FZ (classes A–F) and an exhaustive list of fire hazards according to Art. 9 (primary factors: flames and sparks, heat flow, elevated temperature, toxic products, low oxygen concentration, reduced visibility; collateral: fragments, radioactive/toxic substances, high voltage, explosion factors, exposure to extinguishing agents). The matrix provides a comprehensive identification of hazards, linking them with occupational risks for oil and gas facilities, where classes B (flammable liquids), C (gases) and E (live electrical installations) prevail.

When creating a matrix for each hazard, we recorded the corresponding fire hazard factor (primary or collateral), the association with occupational risk, the criteria for assigning the risk level set through the probability range of the scenario (year^{-1}), and the expected severity of the consequences for personnel (such as burns, poisoning, or electrical injury).

The matrix was used to qualitatively rank hazards and select priority management measures, as well as an input for logical event trees. At the same time, the values of correction coefficients K_{ident}, K_{train}, K_{cont}, K_{impr} were determined separately according to the expert procedure (Delphi method) and then substituted into formula (2).

Table 1

Integrated hazard matrix at oil and gas facilities

Hazard group (Order No. 776n)	Hazard (an example for the oil and gas industry)	Hazard factor (Art. 9 123-FZ)	Hazard type	Connection with occupational risk (Order No.776h)	Risk level	Assignment concept
Mechanical	Depressurization of gas pipelines	Fragments from equipment destruction	Collateral	Risk of injury during maintenance	High	Probability > 0.01 year^{-1} + >50 staff
Thermal	Ignition of hydrocarbon vapors	Flames and sparks, heat flow	Primary	Burns and heat injuries	High	Probability > 0.001 year^{-1} + severe burns
Chemical	Release of toxic gases in case of fire	Increased concentration of toxic products	Primary	Poisoning/Occup. disease	Average	Probability —0.0001–0.001 year^{-1} + toxicity zone
Explosion and fire-hazardous	Gas-air mixture explosion	Explosion hazards	Collateral	Shock wave, injuries	High	Probability > 0.001 year^{-1} + shock wave
Electric	Short circuit in electrical installations	Electric shock, electric arc injury	Collateral	Electric shock	Average	Probability —0.0001–0.001 year^{-1} + electrical injury
Toxicological	Smoke from the burning of insulation	Reduced visibility, reduced O_2 concentration	Primary	Suffocation, disorientation	High	Probability > 0.01 year^{-1} + suffocation/disorientation
Physical	Increased temperature in the compressor room	Increased temperature	Primary	Heat stress	Average	Probability —0,0001–0.001 year^{-1} + heat stress

The expanded matrix took into account the classification characteristics of fire hazards according to Federal Law No. 123-FZ, providing full coverage of primary and related manifestations. Integration with Order No. 776n made it possible to systematically identify hazards in the OHSMS, minimizing occupational risks (injuries, diseases) at facilities with a high fire risk. Validation of the integrated hazard matrix was performed by an expert group as part of an expert procedure (Delphi method): The experts assessed 1) the completeness of coverage of fire hazards according to Art. 9 of Federal Law No. 123 FZ (the presence of primary and collateral factors), 2) the correctness of assigning hazards to groups by Order of the Ministry of Labor of the Russian Federation No. 776n, 3) the validity of the "hazard — occupational risk" relationship for categories of personnel, 4) the unambiguity of the wording of the matrix lines, and 5) the validity of assigning the risk level according to the criteria given in the corresponding column "Assignment criteria". Based on the results of the analysis of the experts' comments, the formulations of individual lines and criteria for assigning risk levels were clarified, and the final version of the matrix was recognized as applicable to oil and gas facilities within the framework of the proposed approach.

The logical event trees were constructed taking into account the impact of the occupational health and safety management system on the development of fire-hazardous situations. The integrated risks were calculated using correction factors reflecting the effectiveness of the occupational health and safety management system.

To account for the impact of OHSMS on the frequency of fire-hazardous situations, a modified formula was used:

$$Q_{j,mod} = Q_{j,base} \cdot \prod_{k=1}^{n} \left(1 - E_k \cdot P_k\right), \qquad (3)$$

where $Q_{j,\text{base}}$ — base frequency of the j-th scenario; E_k — effectiveness of the k-th OHSMS event; P_k — probability of triggering k-th event; n — number of applicable OHSMS events [11].

To quantify the potential fire risk on the territory of the gas treatment facility, five control points (A–E) were selected, characterizing various zones of potential exposure to fire hazards. Point A corresponded to the compressor equipment area (high pressure and high concentration of process equipment). Point B corresponded to the gas drying unit area. Point C corresponded to the gas-handling equipment area. Point D corresponded to the administration and amenity area. Point E corresponded to the border of the sanitary protection zone of the facility.

The initial data for the development of the integrated system were collected from 12 oil and gas industry facilities that were included in the sample. At the same time, the gas treatment plant in the Yamalo-Nenets Autonomous District was used as the basis for detailed testing and calibration of the calculation procedures. This facility included various types of technological equipment for the full cycle of natural gas drying and purification. Based on the results of data processing from these facilities, a database of violations of fire and industrial safety requirements was created [12].

Results. The integrated approach identified 47 types of hazards, of which 23 related to fire hazards, 18 — to general occupational hazards, and 6 — to combined hazards requiring special consideration (Table 2).

Table 2

Results of integrated hazard identification

Hazard type	Number of identified hazards	Critical risk level	Required management measures
Fire	23	8	Technical and organizational
Occupational	18	5	Mostly organizational
Combined	6	6	Comprehensive measures

Table 3 provides the results of comparing different approaches to risk management.

Table 3

Comparison of the effectiveness of different approaches to risk management

Indicator	Traditional approach	Integrated approach
Number of identified hazards	35	47
Accuracy of risk assessment	0.75	0.92

The results of calculating the potential fire risk based on control points (A–E) are presented in Figure 3. The analysis of the potential fire risk values calculated using the traditional method and the proposed integrated approach showed that the integrated method provided a more conservative assessment of risk at all control points in the facility. The largest difference was observed at point A, where the integrated assessment exceeded the traditional one by 17%. This was due to additional factors that affected the development of fire-hazardous situations. This difference in estimates confirmed the need for an integrated approach to obtain a more accurate assessment of fire risks at oil and gas facilities.

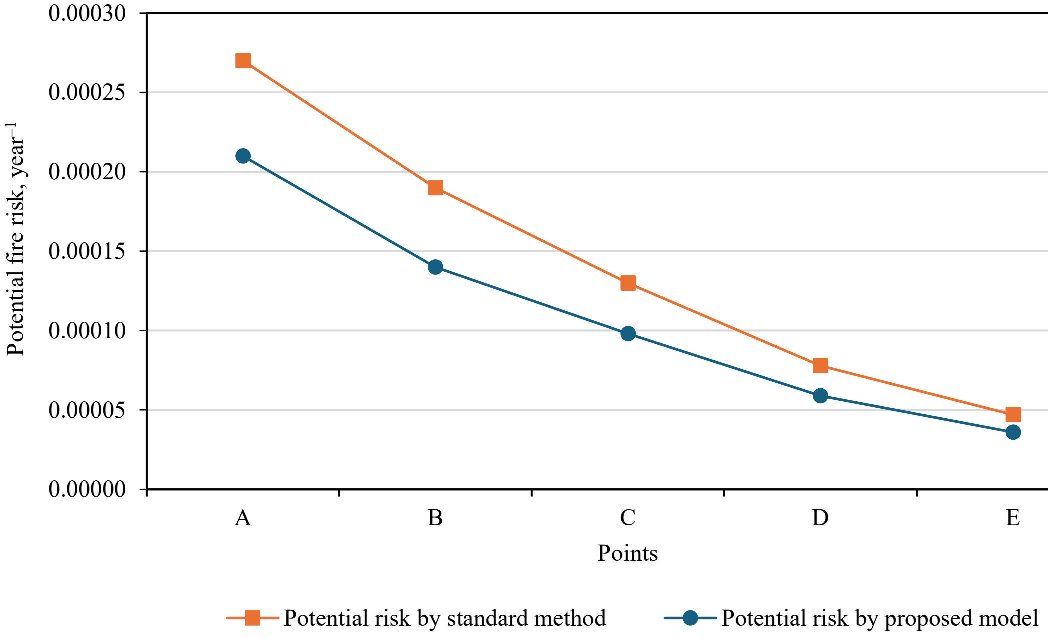

Fig. 3. Comparison of potential fire risk by control points

Table 4 presents the calculation results for potential fire risk, considering integration with the OHSMS.

Table 4

Values of integrated potential fire risk

Point	Traditional method, year^{-1}	Integrated approach, year^{-1}	Risk reduction, %
A	2.7×10^{-4}	2.1×10^{-4}	22
B	1.9×10^{-4}	1.4×10^{-4}	26
C	1.3×10^{-4}	9.8×10^{-5}	5
D	7.8×10^{-5}	5.9×10^{-5}	24
E	4.7×10^{-5}	3.6×10^{-5}	23

A comparative analysis of the results confirmed that the integrated approach reduced the estimated values of potential fire risk at all control points (A–E), compared to the traditional method. The greatest decrease was observed at point B (26%), while the smallest decrease was at point C (5%), reflecting differences in the technological loads and conditions that contribute to the formation of fire hazardous scenarios in the respective areas of the facility.

The comparative analysis of individual fire risk for different categories of workers is presented in Figure 4. The graph clearly illustrates the differences in risk levels according to the traditional methodology and the proposed integrated model for all categories of personnel. The highest risk values were typical for operators of technological installations, due to their direct contact with fire-hazardous equipment and substances. The integrated model showed an increase in estimated risk of 22–29% for all categories of employees, compared to the standard methodology. This difference was especially important for operators and maintenance staff, since their risk was approaching the maximum allowable value of 10^{-4} year^{-1}, established for production facilities with specific functioning of technological processes in accordance with Order of the Ministry of Emergency Situations of Russia No. 533.

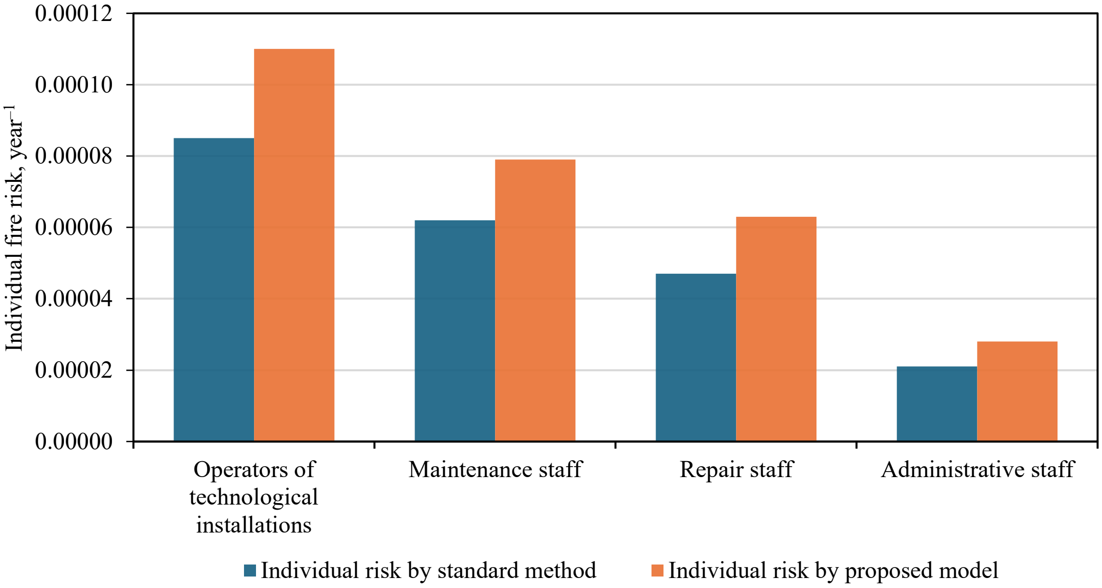

Fig. 4. Individual fire risk by employee category

To assess the contribution of various OHSMS elements to reducing fire risk, an analysis of the effectiveness of individual measures was conducted. The study found that monitoring the condition of equipment had the greatest impact on reducing fire risk. This was due to the importance of maintaining the equipment's technical condition in order to prevent depressurization and leaks. Training for staff was the second most effective measure (with an 18% reduction in fire risk), and it had the best efficiency-to-cost ratio. By analyzing the efficiency and cost ratios, it was possible to optimize resource allocation for OHSMS implementation.

The dynamics of changes in individual fire risk during the phased implementation of the integrated system is shown in Figure 5. The graph demonstrates a gradual reduction in risk for all categories of employees as each OHSMS element was implemented. The most significant decrease in risk occurred at the stage when the control system was implemented, confirming the critical importance of monitoring equipment condition and compliance with safety regulations. Operators of technological installations, who were most exposed to risk, showed the largest absolute decrease in risk — from 1.1×10^{-4} to 6.3×10^{-5} year^{-1}. The full integration of all OHSMS elements ensured the achievement of targeted risk levels for all employee categories.

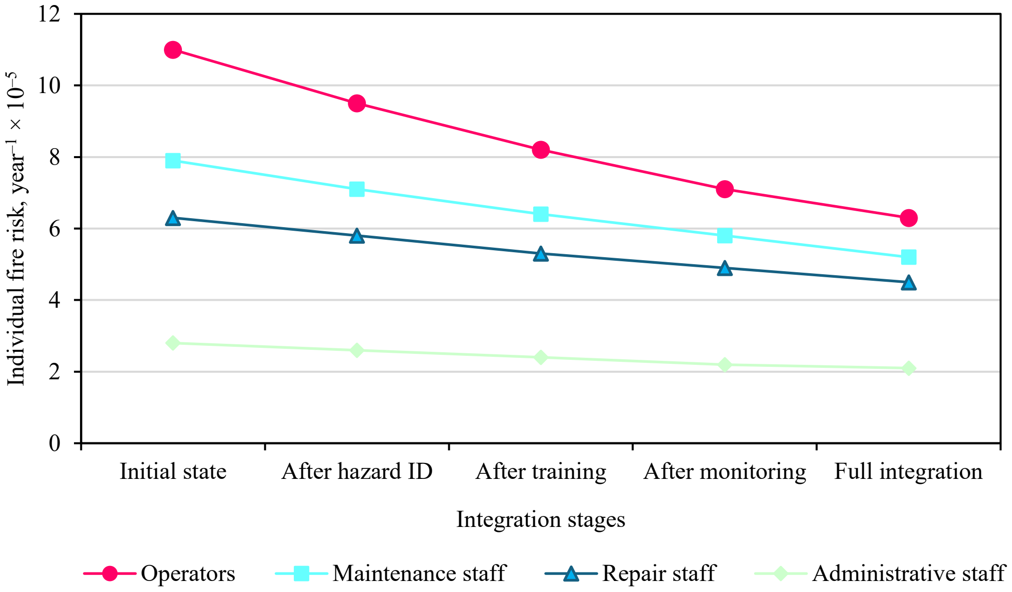

Fig. 5. Dynamics of reduction of individual fire risk when implementing an integrated system

Discussion. The integrated probabilistic statistical risk assessment model, which incorporates the elements of the occupational health and safety management system (OHSMS), allows us to quantify the dynamics of risks during the phased implementation of measures. Its use at oil and gas industry facilities has confirmed its suitability for analyzing the impact of both technical and organizational solutions on fire and industrial safety levels. The results have shown that the initial (baseline) risk values without the effects of OHSMS elements could be significantly higher than traditionally accepted estimates due to the consideration of a large number of scenarios and failures, as well as the human factor. However, the step-by-step implementation of measures provided by the management system has ensured a noticeable reduction in both potential and individual fire risks, bringing them to acceptable targets. This emphasizes the importance of transitioning from a purely formal approach to fulfilling requirements to a more quantitative-based approach in management.

Of particular importance are the system for monitoring the technical condition of equipment, timely maintenance, and staff training. Modeling has demonstrated that these elements have the greatest effect in reducing the frequency of triggering events and erroneous actions, while being characterized by a favorable efficiency-cost ratio. Considering their influence in the integrated model makes it possible to justify priorities in planning activities and allocating resources.

Comparison with international standards has shown that the proposed methodology largely meets modern requirements in the field of industrial and occupational safety management. It can be considered a practical tool for adapting existing management systems to current regulatory requirements and increasing the transparency of decisions. The developed methodology is consistent with the requirements of GOST R ISO 45001–2020 and modern approaches to risk-based safety management. The implemented approach ensures compliance with most of the provisions of the standard than using the traditional approach. Integration with elements of HAZOP analysis improves the quality of hazard identification compared to using standard procedures.

However, the developed methodology has some limitations in its application. It is designed for facilities with continuous processes and requires a database of incidents for at least three years, as well as a specific set of technological processes to ensure the accuracy of the assumptions. The effectiveness of this approach decreases when there are fewer than 50 employees. Additionally, the methodology does not account for the unique characteristics of offshore facilities or those located in permafrost conditions, which requires careful consideration when applying the developed model to different operating environments.

According to the research results, the Federal Intellectual Property Service has registered the computer program "Program for Analyzing the State of Industrial Safety" [13], which expands the possibilities of its use at various production facilities. This includes automation of calculations and the generation of accounting documentation.

Conclusion. The conducted research has shown that the integration of fire risk assessment procedures in accordance with the EMERCOM of Russia Methodology No. 533 and occupational risk management processes into the occupational safety management system (Order of the Ministry of Labor of the Russian Federation No. 776n) is an effective means of improving occupational safety in the oil and gas industry. This integrated approach enables us to consider fire safety and occupational safety as components of a unified risk management framework.

An integrated hazard matrix has been developed, taking into account the classification according to Federal Law No. 123-FZ and linking it to the occupational risks of oil and gas facilities. This matrix has increased the number of identified hazards from 35 to 47, including combined hazards that require special comprehensive measures. This confirms a more comprehensive identification of risks.

A mathematical model of integrated fire risk assessment has been developed with an integration coefficient with the OHSMS and a modified formula for the frequency of occurrence of fire-related scenarios, taking into account the effectiveness of OHSMS measures. Validation using expert estimates and statistical methods (Kendall concordance coefficient, ANOVA, correlation analysis), have shown that the coefficients are sufficiently consistent and valid.

Practical testing at oil and gas industry facilities has demonstrated an increase in the accuracy of risk assessment from 0.75 to 0.92 and a reduction in fire risk levels with the step-by-step introduction of elements of the OHSMS, especially systems for monitoring the technical condition of equipment and personnel training.

The prospects for future research include adapting the methodology for facilities with special operational modes and increased risk, expanding the list of scenarios under consideration, as well as a more detailed integration of aspects of the human factor and digitalization of monitoring: the use of online monitoring systems, intelligent diagnostics, and big data analysis.

In general, the proposed approach forms the basis for improving fire and industrial safety management practices in the oil and gas industry, ensuring more informed decision-making to reduce risks.

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Conflict of Interest Statement: **the authors declare no conflict of interest.**

All authors have read and approved the final version of manuscript.

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Конфликт интересов: **авторы заявляют об отсутствии конфликта интересов.**

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 20.11.2025
Reviewed / Поступила после рецензирования 15.12.2025
Accepted / Принята к публикации 12.01.2026

Safety of Technogenic and Natural Systems. 2026;10(1):32–46. eISSN 2541–9129

MACHINE BUILDING
МАШИНОСТРОЕНИЕ

UDC 629
https://doi.org/10.23947/2541-9129-2026-10-1-32-46

Original Theoretical Research

Predicting the Reliability of Steel Ropes at the Design Stage

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Abstract

Introduction. Ensuring the safety of lifting equipment is closely linked to the reliability of steel ropes operating under variable loads and in aggressive environments. Increased design complexity, higher operational intensity, and larger machine lifting capacities lead to increased human-made risks and economic losses. Traditional methods, such as static safety factors and visual inspections, are ineffective in the face of digitalization and increased operational intensity. According to regulatory authorities, 20% of accidents involving lifting equipment are caused by rope defects, with more than 5,000 injury incidents recorded annually. The literature describes statistical defect analysis, tribological models of wire wear that take into account friction and lubricant degradation, and hierarchical modeling of rope as a system. However, there are still some serious systemic problems: models are not fully integrated into practice, theoretical knowledge is not always applied in engineering methods, and predictive models do not allow for a comprehensive analysis of operational factors. To address these issues, the aim of this work is to develop a predictive model for assessing the reliability of steel ropes at the design stage. This model takes into account regulatory requirements in order to prevent sudden failures and optimize operations.

Materials and Methods. The study was based on the proposed hierarchical decomposition of rope reliability by degradation levels, which allowed for the algorithmic implementation of the “weakest link” principle for sequential systems. The modeling object was a 6×36 WS FC (two lay rope type) steel rope according to GOST 7668–80 used in gantry crane mechanisms. RD ROSEK 012–97 standards were adapted to the design tasks using a polynomial approximation method of discrete criteria into continuous limit state functions. To assess reliability at various hierarchical levels, a combination of Kelvin-Voigt, Archard, and Weller models, as well as the Weibull, Poisson, and normal distributions, was applied. Mathematical data processing and probability calculations were implemented in MS Excel and Mathcad. The model was verified by comparing predicted curves with the estimated service life according to the ISO 16625 methodology for M5 and M6 modes.

Results. Based on the RD ROSEK 012–97 rejection standards, generalized limit states for 6×36 WS FC rope (GOST 7668) were determined. Analytical functions were derived for the relationship between the permissible number of breaks, wear, and corrosion, as well as the dependence of cross-sectional area loss on accumulated defects for M1–M8 modes. A comprehensive predictive reliability model was developed that integrates probabilistic processes of wire breakage accumulation, wear kinetics, and rheological degradation of the core into a single calculation model.

Discussion. The proposed approach aims to bridge the gap between theoretical knowledge and operational practice, by considering the synergy of degradation mechanisms. It resolves the contradiction between the parallel development of defects and the sequential approach (“weakest link model”), using the principle of criticality in any limit state. Unlike additive methods, this approach incorporates the concept of dynamically dependent parameters. The rheology of the material alters the contact conditions between wires, accelerating fatigue damage accumulation. Using this approach as an analytical tool during design ensures high accuracy in predictions. However, due to the heterogeneity of models, it is necessary to develop a specific criterion for assessing overall error.

Conclusion. The model is designed to be used during the design phase of lifting equipment to predictively assess reliability and minimize the risk of sudden rope failure in accordance with GOST 7668–80. It takes into account regulatory requirements and provides a 37% more conservative forecast compared to ISO 16625. Future development plans include extending the model to other rope design groups and integrating it into engineering practice.

Keywords: steel rope, reliability, failure-free operation, predictive model, hierarchical decomposition, wear and corrosion, rheological degradation of the core

Acknowledgements. The author would like to express their gratitude to the reviewers for their critical assessment of the submitted materials and their constructive suggestions for improvement. These comments have significantly contributed to the enhancement of the quality of the research presentation.

For Citation. Kotesov AA. Predicting the Reliability of Steel Ropes at the Design Stage. *Safety of Technogenic and Natural Systems*. 2026;10(1):32–46. https://doi.org/10.23947/2541-9129-2026-10-1-32-46

Оригинальное теоретическое исследование

Прогнозирование надежности стальных канатов на этапе проектирования

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Аннотация

Введение. Обеспечение безопасности грузоподъемных машин тесно связано с надежностью стальных канатов, работающих под переменными нагрузками и в агрессивных средах. Рост сложности конструкций, высокая интенсивность эксплуатации и увеличение грузоподъемности машин приводят к росту техногенных рисков и экономическим потерям. Традиционные методы — статические коэффициенты запаса и визуальный контроль — неэффективны при цифровизации и росте интенсивности эксплуатации. По данным надзорных органов, 20 % аварий на подъемных сооружениях вызваны дефектами канатов, а ежегодно фиксируется свыше 5000 инцидентов с травматизмом. В литературе описаны статистический анализ дефектов, трибологические модели износа проволок с учетом трения и деградации смазки, иерархическое моделирование каната как системы. Однако сохраняются серьёзные системные проблемы: модели слабо интегрированы в практику, теория отделена от инженерных методов и предиктивные модели не предусматривают комплексного анализа динамики эксплуатационных факторов. Поэтому целью данной работы явилась разработка предиктивной модели оценки надежности стального каната на этапе проектирования с учетом нормативных требований для исключения внезапных отказов и оптимизации эксплуатации.

Материалы и методы. В основе исследования — предложенная иерархическая декомпозиция надежности каната по уровням деградации, позволившая алгоритмизировать принцип «слабого звена» для последовательных систем. Объект моделирования — стальной канат 6×36 ЛК-РО по ГОСТ 7668-80 в составе механизмов портального крана. Адаптация норм РД РОСЭК 012-97 к задачам проектирования выполнена методом полиномиальной аппроксимации дискретных критериев в непрерывные функции предельных состояний. Для оценки безотказности на различных уровнях иерархии использован комплекс моделей Кельвина–Фойгта, Арчарда, Веллера, а также распределения Вейбулла, Пуассона и нормальный закон. Математическая обработка данных и расчеты вероятностных показателей реализованы в средах MS Excel и Mathcad. Верификация модели проведена сопоставлением прогнозных кривых с расчетным ресурсом по методике ISO 16625 для режимов M5 и M6.

Результаты исследования. На основе норм браковки РД РОСЭК 012–97 определены обобщённые предельные состояния каната 6×36 ЛК-РО (ГОСТ 7668). Получены аналитические зависимости допустимого числа обрывов от износа и коррозии, а также функции связи потери площади сечения с накопленными дефектами для режимов M1–M8. Разработана комплексная предиктивная модель надежности, объединяющая вероятностные процессы накопления обрывов проволок, кинетику износа и реологическую деградацию сердечника в единую вычислительную схему.

Обсуждение. Предложенный подход сокращает разрыв между теорией и практикой эксплуатации за счёт учета синергии механизмов деградации. Противоречие между параллельным развитием дефектов и последовательной «моделью слабого звена» разрешено через принцип критичности каждого предельного состояния. В отличие от аддитивных методов реализована концепция динамически зависимых параметров — реологические изменения сердечника трансформируют условия контакта проволок и тем самым ускоряют накопление усталостных повреждений. Применение разработанного аппарата в проектировании повышает точность прогноза. В то же время гетерогенность используемых моделей диктует необходимость создания специфического критерия достоверности для оценки суммарной погрешности.

Заключение. Модель предназначена для применения на этапе проектирования грузоподъёмных машин с целью предиктивной оценки безотказности и минимизации рисков внезапных отказов канатов по ГОСТ 7668–80. Модель позволяет учесть нормативные требования и обеспечивает на 37 % более консервативный прогноз по сравнению с ISO 16625. Дальнейшее развитие предполагает распространение модели на другие конструктивные группы канатов и внедрение в инженерную практику.

Ключевые слова: стальной канат, надежность, безотказность, предиктивная модель, иерархическая декомпозиция, износ и коррозия, реологическая деградация сердечника

Благодарности. Автор выражает благодарность рецензентам, чья критическая оценка представленных материалов и конструктивные предложения по их совершенствованию способствовали существенному повышению качества изложения результатов исследования.

Для цитирования. Котесов А.А. Прогнозирование надежности стальных канатов на этапе проектирования. *Безопасность техногенных и природных систем.* 2026;10(1):32–46. https://doi.org/10.23947/2541-9129-2026-10-1-32-46

Introduction. Steel ropes are critically important load-bearing elements of lifting machines that determine their safety and operational efficiency. According to Rostechnadzor and global industry research, up to 20% of lifting accidents are related to critical rope defects. Rope failure can lead to economic losses due to downtime and disruptions of logistics cycles, as well as man-made consequences. Statistics show that over 5,000 incidents occur annually due to broken traction and load-bearing elements, with approximately 30% having consequences for human life and health [1].

A steel rope is a complex mechanical and technical system that distributes the load between interconnected elements that operate in different conditions and are subject to aging, corrosion, wear, and fatigue damage. This makes it difficult to assess the reliability of the entire system. Existing design methods compensate for uncertainty through significant safety factors. However, practice shows that this approach does not provide the required reliability for modern high-power lifting machines with high work intensity —it does not exclude sudden failures and is economically inefficient. In these conditions, in order to reduce man-made risks and improve operational efficiency, it is necessary to move from the use of stock coefficients and visual control to predictive design and analytics that provide an estimated level of reliability based on predictive failure models.

Research on steel ropes reliability has been conducted for decades and covers the stages of design, production and operation. In 1963, with the support of OITAF and RILEM organizations, the international organization for the study of rope fatigue, OIPEEC, was established.

Modern development of artificial intelligence and digital vision has significantly advanced the issues of predictive analytics of steel ropes. The developed methods and automated digital control systems described in the works of M.N. Khalfin [2, 3], A.A. Korotkov [4, 5], A.V. Panfilov [6, 7] and A.A. Kulchitskiy [8] are being actively implemented in operational practice.

An important stage for the development of predictive design is the updating of ISO 16625, which involves determining the margin coefficient and evaluating fatigue life, taking into account a variety of factors, which marks the transition from simplified calculations to deep modeling of real-world operating conditions.

The complexity of distribution of mechanical properties and loads between the elements is a determining factor in the reliability of a steel rope. The multilayer structure of the rope is hierarchical in nature: the internal elements serve as a support for the external ones. The violation of these supporting links leads to degradation of the rope structure and changes in the working conditions of its elements. Wahid A. [9, 10] designates this phenomenon as the effect of “systemic wear” that occurs when core stability is lost.

The basis for the implementation of predictive design is the consideration of the rope as a system. Mouradi H. [11] proposed a method for predicting durability using majority logic, where the key aspect is the mathematical relationship between the probability of trouble-free operation and the degree of accumulated damage. Bassir Y. [12] notes that the analysis of the hierarchical structure makes it possible to transform the failure statistics of the basic elements into an accurate forecast of the reliability of the entire rope. Xia Y. [13] suggests conducting finite element analysis at three hierarchical levels: at the micro level — wire contact, at the meso level — the interaction of strands, and at the macro level — the behavior of the entire rope. This approach takes into account local friction and intermittent sliding during bending, described in the Han Y. model [14], as well as the loss of cross-sectional area from wear over time, considered by Salleh S. [15]. Studies by Peng Y. [16] and Xu C. [17] focus on the processes of internal friction and inter-wire wear, confirming that the degradation rate directly depends on lay parameters and lubrication rate. V.P. Golovin [18] demonstrates the effectiveness of synthetic thickeners of rope lubricants, and Peng H. [19] emphasizes the need to take into account the degradation of lubricant properties as a key factor in rope durability. V.Yu. Volokhovsky [20] examines the effect of thermal cycles on the ropes of metallurgical cranes and suggests a transition from deterministic calculations to risk assessment as the probability of a random event in which the diagnostic indicator of the rope exceeds the established rejection level.

The analysis of modern research shows that, despite the in-depth study of certain aspects of rope operation, the issue of assessing their reliability as machine elements remains insufficiently studied. The gap between theoretical degradation models and practical design methods prevents the full realization of the potential of the predictive approach. As a result, reliability rationing becomes an urgent task, requiring the establishment of quantitative normative values and the selection of adequate evaluation criteria. There is an objective need to create comprehensive reliability forecasting models that take into account the design features of the rope, the expected operating conditions and the requirements of regulatory and technical documentation.

The aim of this research is to develop a model for predicting the reliability of a steel rope, taking into account the multicomponent structure, operating conditions and requirements of regulatory and technical documentation (using the example of a two lay rope GOST 7668 as part of gantry crane mechanisms).

Research objectives:

– perform the analysis of the requirements of regulatory and technical documentation and determine the limits of the steel rope's operability;

– determine boundary values of indicators corresponding to the transition of the system to the limiting state, taking into account the dominant mechanisms of destruction;

– integrate regulatory criteria into the reliability forecasting model;

– develop a comprehensive mathematical model for reliability assessment.

Materials and Methods. The research was based on the proposed hierarchical decomposition of steel rope reliability by degradation levels and algorithmization of the “weak link” principle for sequential systems according to the principles of calculating the probability of trouble-free operation of elements of lifting cranes RTM 24.090.25–76. The object of the simulation was a two lay steel rope with a diameter of 27 mm. 6×36(1+7+7/7+14)+1 WS FC according to GOST 7668–80 as part of lifting mechanism of Kirovets gantry crane 16/20 (Fig. 1, Table 1).

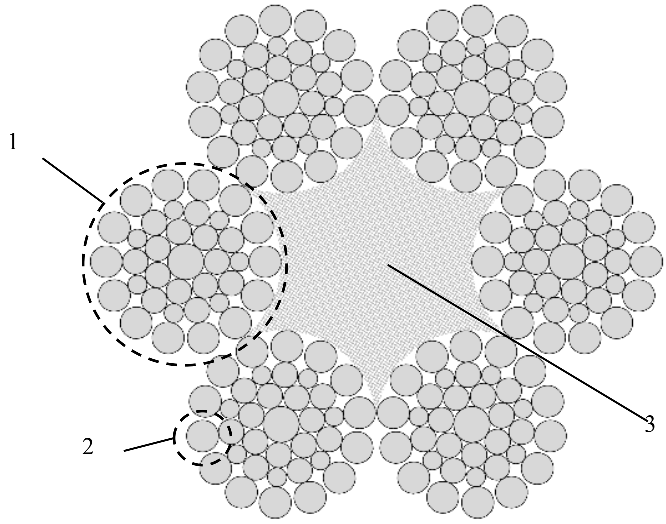
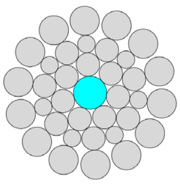
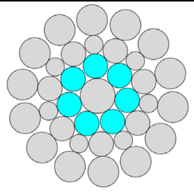
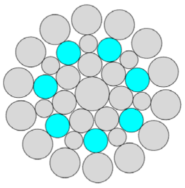
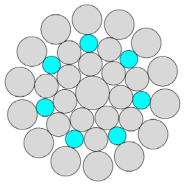
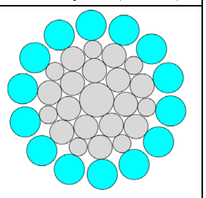


Fig. 1. Cross section of a steel rope 6×36(1+7+7/7+14) +1 WS FC according to GOST 7668–80:
1 — strand; 2 — wire; 3 — fiber core

Table 1

Scheme of a strand of steel rope 27 mm 6×36 WS FC according to GOST 7668–80

	Central	1-st layer	2nd layer A	2-nd layer B	3-d layer (outer)
Group of wire strands					
Number, pcs.	1	7	7	7	14
Wire diameter, mm	1.70	1.20	1.20	0.90	1.50

Reliability was accepted as an indicator of the failure-free operation of a steel rope in accordance with GOST R 27.102–2021[1]. The choice of the indicator was due to the unmaintainability of the rope as a separate element of the lifting machine and the continuous nature of the processes of corrosion of wires and aging (decomposition) of the core, which could occur regardless of the intensity of operation.

To establish the limits of the working capacity of a steel rope, an analysis of RD ROSEC 012–97[2] rejection standards was performed, which took into account defects caused by natural wear and aging of the rope material (Table 2) and the acceptable number of wire breaks, taking into account the wear rate and the classification group (operating mode) of the mechanism (Table 3). The analyzed defects were systematized by the nature of degradation: A — wire breaks, B — wire wear, C — fiber core degradation. Taking into account the discrete nature of the damage accumulation process, the calculated values of the number of breaks were rounded upward. Critical defects that occurred instantly, such as creases, kinks, electric arc damage, lightning, fire, etc., were excluded from consideration.

Table 2

Rejection standards of steel rope 6×36(1+7+7/7+14) +1 WS FC GOST 7668 when operating on lifting cranes according to RD ROSEK 012–97

Defect designation	Defect description	Rejection standards	Mechanism (cause) of the defect
A1	External wire breaks in 6d section	Acceptable number of breaks is shown in Table 3	Fatigue wear, mechanical wear, corrosion (oxygen, electrochemical, chemical)
A2	External wire breaks in 30d section	Acceptable number of breaks is shown in Table 3	
A3	Local wire breaks concentrated on a single rope strand	Three or more broken wires	
Б1	Surface wear of the rope	Outer wires diameter reduction by 40% or more	Mechanical wear and corrosion (oxygen, electrochemical, chemical)
Б2	Loss of the metal part of the rope cross-section (loss of the inner section)	Loss of the metal part of the rope cross-section by 17.5% or more	Breakages, mechanical wear and corrosion (oxygen, electrochemical, chemical) of the wires of inner layers
Б3	Surface wear and corrosion	Rope diameter reduction by 7% or more	Mechanical wear, corrosion (oxygen, electrochemical, chemical)
B1	Reduction of rope diameter as a result of core damage	Rope diameter reduction by 10%	Wear, crumpling, tearing, aging of fibers or complete destruction (breakage) of the core
B2	Local increase in rope diameter	Rope diameter increase by 7 %	Exposure to moisture and low temperatures leads to expansion (swelling) of the core. Uneven redistribution of core fibers along the length (rolling area)

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[1] GOST R 27.102-2021. *Dependability in Technics. Dependabiity of Item. Terms and Definitions.* (In Russ.) URL: https://rosgosts.ru/file/gost/21/020/gost_r_27.102-2021.pdf (accessed: 20.10.2025)

[2] RD ROSEC 012-97. Regulatory Document. *Steel Ropes. Control and Rejection Standards.* (In Russ.) URL: https://files.stroyinf.ru/Data2/1/4293850/4293850134.pdf (accessed: 20.10.2025)

Table 3

Number of wire breaks in the presence of which steel ropes of lifting cranes working with steel and cast-iron blocks of 6×36(1+7+7/7+14) +1 WS FC design are rejected according to GOST 7668 in accordance with RD ROSEC 012–97

Reduction of wire diameter as a result of surface wear or corrosion, %	Percentage of acceptable wire breaks depending on wear and tear, %	Mechanism classification (mode) group	Number of wire breaks N^*			
			Cross lay		Long lay	
			In a section of length			
			6d	30d	6d	30d
0	100	M1 – M4	7	14	4	7
		M5 – M8	14	29	7	14
10	85	M1 – M4	5	11	3	5
		M5 – M8	11	24	5	11
15	75	M1 – M4	5	10	3	5
		M5 – M8	10	21	5	10
20	70	M1 – M4	4	9	2	4
		M5 – M8	9	20	4	9
25	60	M1 – M4	4	8	2	4
		M5 – M8	8	17	4	8
30 и более	50	M1 – M4	3	7	2	3
		M5 – M8	7	14	3	7

Note: $^*N$ — number of wire breaks in the 3rd (outer) layer; d — rope diameter, mm

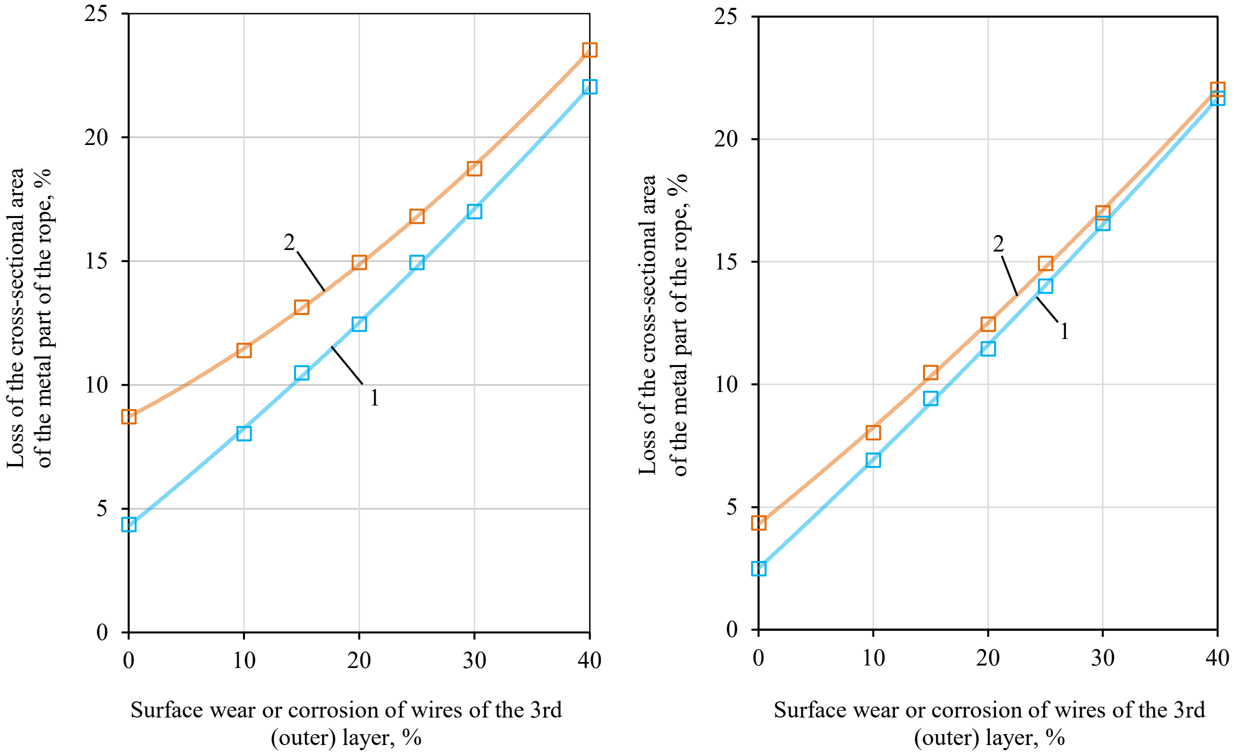
To synthesize the forecasting model, we decomposed the steel rope's reliability by degradation levels and determined generalized limiting states for groups A, B, and C (Table 4). We implemented a hierarchical relationship between degradation levels through a system of dynamically dependent parameters. In this system, the predicted values of wear and deformation at the current time step acted as variable boundary conditions for evaluating the subsequent states of the system. The method of calculating losses of metal cross-section was based on a combined consideration of mechanical wear of wires and atmospheric corrosion. We introduced the parameters of medium aggressiveness into the model as an additive degradation factor that determined the rate of decrease in wire diameter in the outer layer of the rope.

The methodology for substantiating the generalized limit state for group B was implemented through the calculation of the total loss of metal section area as a function of surface wear of wires, taking into account the dynamic breakage threshold N_{lim}, which determined the point of joint achievement of the limit state according to criteria B1 (wear) and B2 (loss of cross-sectional area) (Fig. 2, 3).

The dynamically changing threshold for the acceptable number of N_{lim} breaks was determined based on the approximation of discrete dependencies presented in Table 3 (Fig. 4, 5).

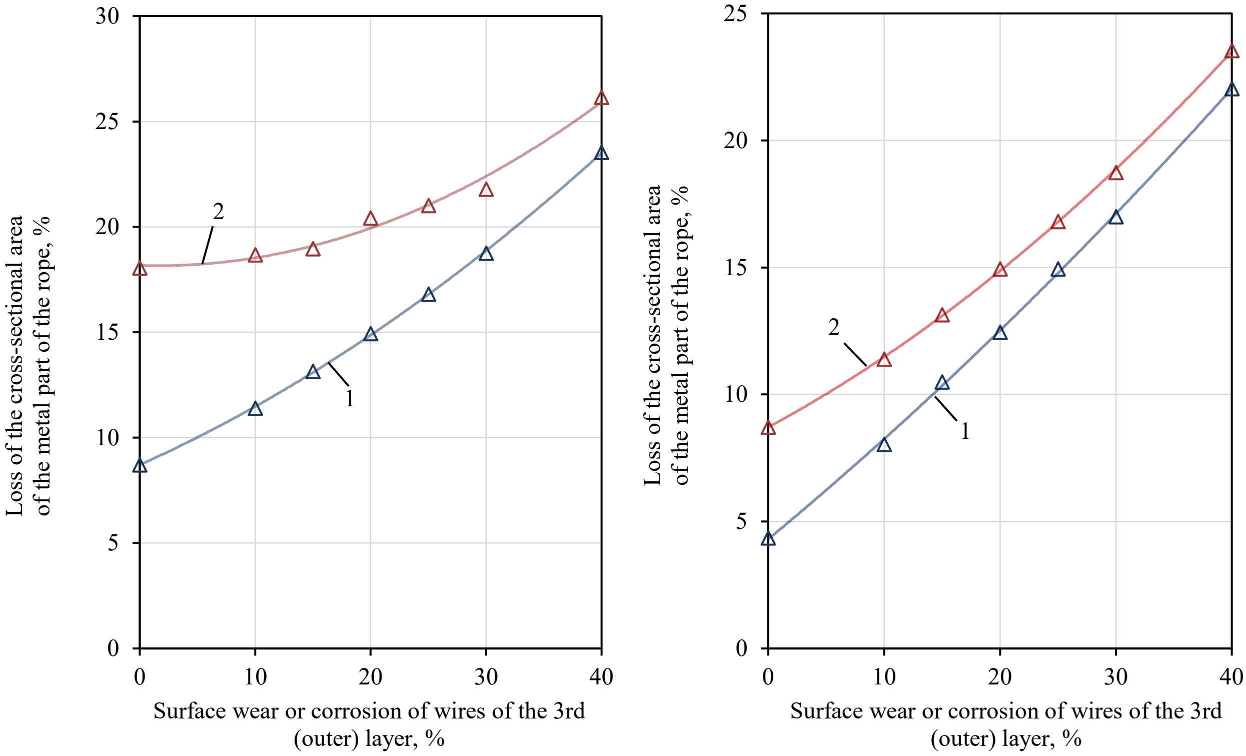
To verify the results, a comparative analysis of the predicted reliability curves with the calculated value of the median service life for M6 operating mode according to ISO 16625 was applied. Mathematical data processing was performed using MS Excel 14.0.4760.1000 and Mathcad 14.0.0.163. The dependencies were approximated by a polynomial function of 3–4 orders of magnitude; the coefficient of determination was in the range 0.9425–0.9998.

Results. During the study, we obtained the dependencies of the total loss of cross-sectional area of the rope metal part on the amount of surface wear of wires in the outer layer (Fig. 2, 3). Based on the curves obtained, we found that, considering the contribution of the dynamic number of wire breaks N_{lim} and formal compliance with regulatory requirements for wear (Table 2), a critical threshold of 17.5% (defect B2) was achieved with surface wear values less than 40% (defect B1).



a) *b)*

Fig. 2. Dependence of the loss of cross-sectional area of the metal part of the rope on the number of breaks, surface wear or corrosion of the wires of the 3rd (outer) layer for the classification group (mode) of M1–M4 mechanism: *a* — cross lay; *b* — long lay; 1 — in a section with a length of *6d*; 2 — in a section with a length of *30d*; d — rope diameter



a) *b)*

Fig. 3. Dependence of the loss of cross-sectional area of the metal part of the rope on the number of breaks, surface wear or corrosion of the wires of the 3rd (outer) layer for the classification group (mode) of M5–M8 mechanism: *a* — cross lay; *b* — long lay;

As a result of hierarchical decomposition of rope reliability by degradation levels, a generalization of regulatory defects was performed (Tables 2, 3) and a selection of mathematical models for predicting reliability was made. The formulated generalized criteria for limit states and the corresponding calculation apparatus were systematized and described in Table 4.

Table 4

Generalized limiting conditions and models for predicting the reliability of 6×36(1+7+7/7+14)+1 WS FC steel rope by groups of defects according to GOST 7668

Group of defects	Combined private defects	Generalized limit state of the group	Reliability assessment model
A	A1, A2 (distributed breaks), A3 (local breaks on strands)	Reaching the threshold number of N_{lim} breaks, dynamically dependent on current wear or the presence of ≥ 3 breaks in one strand	Inhomogeneous Poisson process combined with a "weak link" model (estimates the probability that a discrete number of breaks will not exceed the safety threshold)
B	B1 (wire wear), B2 (internal cross section), B3 (nominal diameter)	Reduction of the metal cross-sectional area below the acceptable one (17.5%) as a result of cumulative wear of external and internal wires	Kinetic model of Archard degradation with a corrosion additive (determines the probability of maintaining the bearing capacity above a critical level)
C	C1 (shrinkage or destruction of the core), C2 (core swelling)	Nominal diameter of the rope goes beyond the range [–10%; +7%], leading to the loss of radial support of the strands	Rheological model of Kelvin-Voigt structure stability (estimates the probability of non-destruction of the core and maintenance of the geometric shape of the rope)

Based on the data in Table 3, analytical dependencies of the acceptable number of N_{lim} wire breaks on the degree of surface wear and corrosion of the outer layer of wires (expressed as a percentage of the nominal diameter of wires) were obtained, determining the dynamically changing limits of rope operability in the reliability model (Fig. 4, 5).

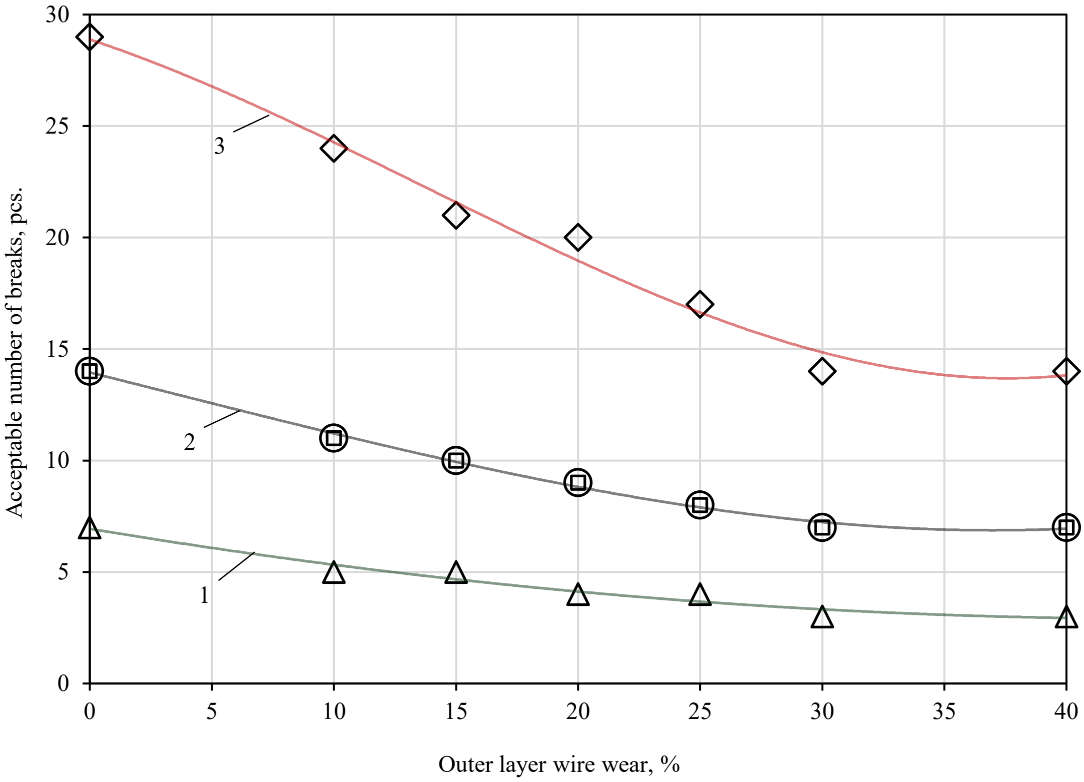


Fig. 4. Dependence of the acceptable number of breaks on wear and corrosion of wires of the outer layer for the classification group (mode) of M1-M4 mechanism for 6×36(1+7+7/7+14) +1 WS FC GOST 7668 rope structure:
1 — long lay at section *6d* ($R^2 = 0.9617$); 2 — cross lay in section *6d* and long lay in section *30d* ($R^2 = 0.9959$);
3 — cross lay in section *30d* ($R^2 = 0.9866$); *d* — rope diameter

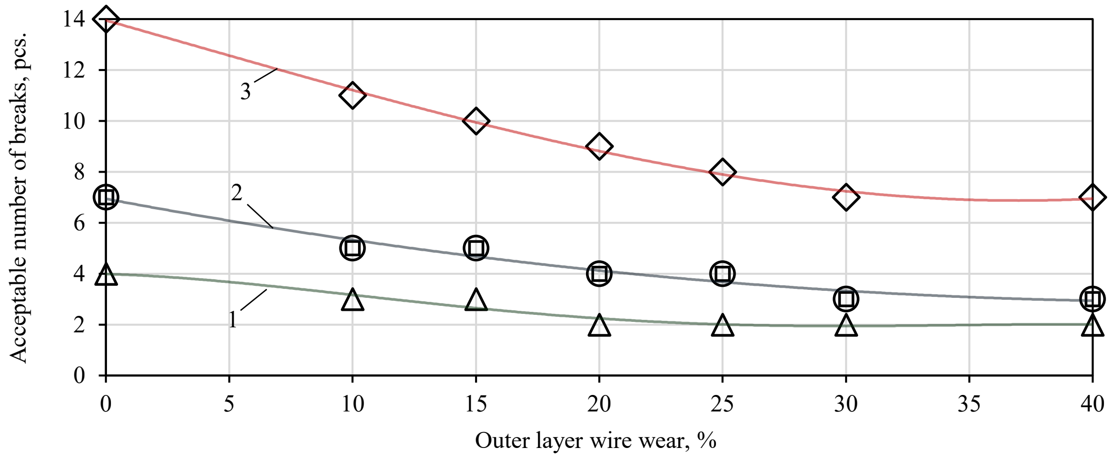


Fig. 5. Dependence of the acceptable number of breaks on wear and corrosion of wires of the outer layer for the classification group of the mechanism M5-M8 for 6×36(1+7+7/7+14) +1 WS FC GOST 7668 rope structure: 1 — long lay in *6d* section (R^2 = 0,9959); 2 — cross lay in section 6d and long lay in section *30d* (R^2 = 0,9617); 3 — cross lay in section *30d* (R^2 = 0,9425); *d* — rope diameter

To determine the acceptable number of wire breaks $N_{lim}(x)$, we obtained the following expressions for ropes:

– long lay in sections *6d* in M1-M4 mode and *30d* in M5-M8 mode, as well as cross lay in section *6d* in M5–M8 mode:

$$N_{lim}(x)=\left(-3.0\cdot10^{-18}\right)x^3+\left(2.0\cdot10^{-3}\right)x^2-0.18x+6.94; \qquad (1)$$

– cross lay in sections *6d* in M1-M4 mode and *30d* in M5-M8 mode, as well as long lay in in section 3*0d* in M1-M4 mod:

$$N_{lim}(x)=\left(8.0\cdot10^{-5}\right)x^3-\left(6.0\cdot10^{-4}\right)x^2-0.28x+13.95; \qquad (2)$$

– cross lay in section 30d in M1–M4 mode:

$$N_{lim}(x)=\left(3.0\cdot10^{-4}\right)x^3-\left(1.28\cdot10^{-2}\right)x^2-0.37x+28.88; \qquad (3)$$

– long lay in section 6d in M5–M8 mode:

$$N_{lim}(x)=\left(-4.0\cdot10^{-6}\right)x^4+\left(4.0\cdot10^{-4}\right)x^3-\left(8.7\cdot10^{-3}\right)x^2-\left(2.81\cdot10^{-2}\right)x+3.99. \qquad (4)$$

Based on reasonable criteria for limiting conditions (Table 4), an algorithm for predictive reliability modeling has been developed, presented as a flowchart in Figure 6.

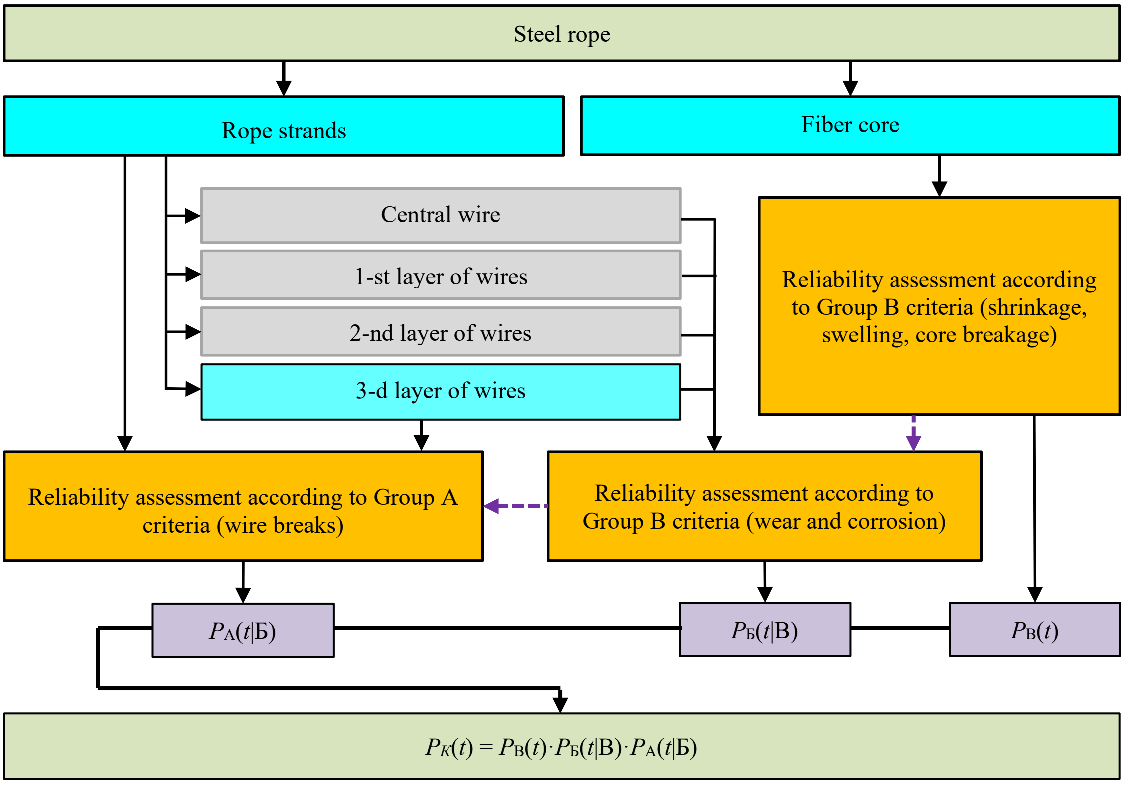


Fig. 6. Flowchart of a model for predicting the reliability of a steel rope structure 6×36(1+7+7/7+14) + 1 WS FC according to GOST 7668

Description of the model. The following is an analytical description of the reliability assessment models according to criteria groups C, B, and A according to Table 4 and the flowchart in Figure 6.

I. Reliability assessment in accordance with the limiting condition of group C:

$$P_{\text{В}}(t)=exp\left(-\left(\frac{t}{T_{\text{В}}}\right)^{\beta_{\text{В}}}\right), \tag{5}$$

where $T_{\text{В}}$ — fiber core characteristic resource, h; $\beta_{\text{В}}$ — parameter that determines the intensity of core aging;

$$T_{\text{В}}=\frac{1}{k_{\text{дег.}}}\cdot ln\left(1-\frac{\varepsilon_{lim}\cdot E_{B}}{q}\right),$$

where $k_{\text{дег.}}$ — constant of the core degradation process, h–1; $E_{\text{В}}$ — core elasticity modulus, MPa; q — radial pressure of the strands, MPa.

Deformation of the core under load at time t according to the Kelvin-Voigt model:

$$\varepsilon(t)=\frac{q}{E_{\text{В}}}\left(1-e^{-\frac{E_{\text{В}}}{\eta_{\text{В}}}\cdot t}\right),$$

where $\eta_{\text{В}}$ — dynamic viscosity of the rope lubricant, MPa·h; t — estimated time, h.

To account for changes in the structural stability of the core when assessing reliability according to the limiting state of group B, it is proposed to determine the coefficient of wear intensification in case of structural instability of the core:

$$K_{\text{стр.}}=1+\frac{\varepsilon(t)}{\varepsilon_{lim}},$$

where ε_{lim} — maximum acceptable deformation.

II. Reliability assessment in accordance with the limiting condition of group B:

$$P_{Б}(t)=\Phi\left(\frac{k_{A}\cdot A_{0}-E\left[\Delta A_{\Sigma}(t)\right]}{\sqrt{D\left[\Delta A_{\Sigma}(t)\right]}}\right), \tag{6}$$

where k_A — coefficient of acceptable loss of metal section of the rope; A_0 — nominal cross-sectional area of the metal part of the rope, mm^2; ΔA_{Σ} — cumulative loss of the cross-sectional area of wires of outer and inner layers, mm^2; $E[\Delta A_{\Sigma}]$ and $D[\Delta A_{\Sigma}]$ — mathematical expectation and variance of a random value of cumulative loss of cross-sectional area of the metal part of the rope.

The mathematical expectation of the cumulative loss of cross-sectional area of the metal part of the rope is determined by the expression:

$$E\left[A_{\Sigma}(t)\right]=E\left[A_{внеш}(t)\right]+E\left[A_{внут}(t)\right],$$

where $\Delta A_{\text{внеш.}}(t)$ and $\Delta A_{\text{внут.}}(t)$ — cumulative loss of cross-sectional area of outer and inner wires at time t.

$$\Delta A_{\text{внеш.}}(t)=Z_{\text{внеш.}}\cdot f_{\Delta A}\left(E\left[h_{\text{внеш.}}(t)\right]\right) \text{ and } \Delta A_{\text{внут.}}(t)=Z_{\text{внут.}}\cdot f_{\Delta A}\left(E\left[h_{\text{внут.}}(t)\right]\right),$$

where $Z_{\text{внеш.}}$ and $Z_{\text{внут.}}$ — number of wires in outer and inner layers; $f_{\Delta \text{A}}(h(t))$ — function that determines the area loss depending on the amount of wear $h(t)$.

Mathematical expectations of the amount of wear on outer and inner wires are determined by the Archard model of wear kinetics with a corrosion additive:

$$E\left(h_{\text{внеш.}}(t)\right)=\left(\frac{K_{\omega}\cdot p\cdot \upsilon}{H}\cdot K_{\text{стр.}}+\upsilon_{\text{кор.}}\right)\cdot t \text{ and } E\left(h_{\text{внут.}}(t)\right)=\left(K_{f}\cdot K_{\text{стр.}}\cdot \sigma_{\text{кон.}}\cdot \delta+\upsilon_{\text{кор.}}\right)\cdot t,$$

where K_{ω} — coefficient of wear rate (depends on the conditions of friction and lubrication); p — average contact pressure in the “wire — block groove” pair, MPa; υ — average relative sliding speed of the rope in the groove, mm/h; $\upsilon_{\text{кор.}}$ — average corrosion rate for a specific category of medium, mm/h; H — hardness of the wire material, MPa; K_f — coefficient of fretting wear of wires (determined from reference data); $K_{\text{стр.}}$ — coefficient of wear intensification with structural instability of the core; $\sigma_{\text{кон.}}$ — contact stress between the wires inside the strand, MPa; δ — amplitude of wire slippage during bending, mm; $h_{\text{внеш.}}(t)$ — amount of wear on the outer wires, mm; $h_{\text{внут.}}(t)$ — amount of wear on the inner wires, mm; t — estimated time, h.

The average corrosion rate for a specific category of medium is proposed to be determined according to GOST ISO 9226[3].

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[3] GOST ISO 9226 – 2022. *Corrosion of Metals and Alloys. Corrosivity of Atmospheres. Determinationof Corrosion Rate of Standard Specimens for the Evaluation of Corrosivity, IDT).* (In Russ.)

The dispersion of the cumulative cross-sectional area losses of the metal part of the rope is determined by the expression:

$$D\left[\Delta A_{\Sigma}\left(t\right)\right]=D\left[A_{\text{внеш.}}\left(t\right)\right]+D\left[A_{\text{внут.}}\left(t\right)\right]+2\,cov\left[A_{\text{внеш.}}\left(t\right),A_{\text{внут.}}\left(t\right)\right].$$

Accordingly, the expression includes variances of the random value of the loss of the cross-sectional area of the outer and inner wires:

$$D\left[\Delta A_{\text{внеш.}}\left(t\right)\right]=\left(E\left[\Delta A_{\text{внеш.}}\left(t\right)\right]\cdot \nu_{\text{внеш.}}\right)^{2} \text{ and } D\left[\Delta A_{\text{внут.}}\left(t\right)\right]=\left(E\left[\Delta A_{\text{внут.}}\left(t\right)\right]\cdot \nu_{\text{внут.}}\right)^{2},$$

where $\nu_{\text{внеш.}}$ — coefficient of variation of loss of the cross-sectional area of outer wires; $\nu_{\text{внут.}}$ — coefficient of variation of loss of the cross-sectional area of inner wires.

As well as the covariance matrix:

$$cov\left[A_{\text{внеш.}}\left(t\right),A_{\text{внут.}}\left(t\right)\right]=\rho\sqrt{D\left[\Delta A_{\text{внеш.}}\left(t\right)\right]\cdot D\left[\Delta A_{\text{внут.}}\left(t\right)\right]},$$

where ρ — correlation coefficient.

III. Reliability assessment in accordance with the limiting condition of group A. The model assumes the use of Poisson distribution, where the intensity of defects is modeled by Weibull's law and increases with wear:

$$P_A\left(t\right)=\left[\sum_{k=0}^{N_{lim}-1}\frac{\left(\Lambda\left(t\right)\right)^{k}e^{-\Lambda\left(t\right)}}{k!}\right]\cdot\left[e^{-\Lambda\left(t\right)}\left(1+\frac{\Lambda\left(t\right)}{n_{\text{пр}}}+\frac{\Lambda\left(t\right)^{2}}{2{n_{\text{пр}}}^{2}}\right)\right]^{n_{пр}}, \tag{7}$$

where N_{lim} — safety threshold for the number of breaks (decreasing with wear); k — accumulated number of breaks over time; Λ(t) — mathematical expectation of the number of breaks at time t; $n_{\text{пр}}$ — number of strands; t — estimated time, h.

To take into account the predicted wear when estimating the probability of trouble-free operation under limiting conditions of group B, you should determine $A(t)$ using function $f_{\Delta A}(h(t))$ (see part II), and the maximum number of breaks N_{lim} using dependencies 1 – 4, assuming $x = 100\ (A_0 - A(t))\ /\ A_0$.

The frequency of breaks, considering the accumulation of fatigue damage:

$$\Lambda\left(t\right)=\left(\frac{t}{\eta\left(A\left(t\right)\right)}\right)^{\beta_A},$$

where β_A — shape parameter that determines the wear rate; η(A(t)) — scale parameter that determines the resource, h.

The scale parameter defines the following dependency:

$$\eta\left(A\left(t\right)\right)=\eta_0\left(\frac{A\left(t\right)}{A_0}\right)^{m},$$

where m — indicator of sensitivity of the characteristic resource to overstress (indicator of the angle of inclination of the fatigue curve); η_0 — characteristic resource of the new rope with nominal cross-section A_0, h; A_0 — nominal cross-sectional area of the steel rope wire without wear, mm^2; $A(t)$ — cross-sectional area of the steel rope wire at time t, mm^2.

The scale parameter assumes that the equivalent stress in the wire section increases as the wire cross-sectional area decreases:

$$\sigma\left(t\right)=\frac{S}{A\left(t\right)},$$

where S — equivalent load on the wire, N.

It should be noted that this model uses the dependence of the resource on the cross-sectional area, which corresponds to the Weller model:

$$\sigma^{m}\cdot N_{\text{циклов}}=const\,.$$

Since stresses σ(t) are inversely proportional to cross-sectional area of wire A(t), the following expression can be derived:

$$\left(\frac{1}{A}\right)^{m}\cdot N_{\text{циклов}}=const.$$

In this case, indicator of the inclination angle of fatigue curve m in this model is equivalent to the indicator of the slope of the fatigue curve of the wire material.

$$\eta_0=\frac{N_{\text{циклов}}}{\omega\cdot n_{\text{б}}\cdot k_p},$$

where $N_{\text{циклов}}$ — number of cycles before cracks appear, ω — frequency of operation — the number of work cycles per hour, h^{-1}; $n_{\text{б}}$ — number of blocks; $k_{\text{п}}$ — multiplicity of work per cycle.

To predict the number of cycles before the appearance of cracks $N_{\text{циклов}}$, it is proposed to use the empirical formula of Professor K. Feirer:

$$LgN_{\text{циклов}} = b_0 + \left(b_1 + b_3 \cdot lg\frac{D}{d}\right)\cdot\left(lg\frac{S}{d^2} - 0.41\cdot lg\frac{R_0}{1770}\right) + b_2\cdot lg\frac{D}{d},$$

where D/d — ratio of the diameter of the carriage rollers to the diameter of the rope. S — rope tension, N; R_0 — marking group of wire strength, N/mm²; b_0, b_1, b_2, b_3 — empirical constants that take into account lay density and the shape of wires ($b_0 = 2.634$; $b_1 = 4.375$; $b_2 = -1.72$; $b_3 = -0.4$).

According to the proposed model, the predicted rope failure is a consequence of the parallel development of several degradation mechanisms. Despite the fact that the processes of wear, corrosion and fatigue occur simultaneously in the rope, the principle of sequential connection of the system elements is embedded in the structure of the model. The model assumes that the system's performance stops when any of the three established failure criteria is reached — the “weak link model”. The mutual influence of degradation processes in the proposed model is realized through dependent parameters and coefficients. Therefore, the overall reliability of a steel rope is determined by the probability of trouble-free operation of a sequential system with dynamically dependent parameters:

$$R_{\text{К}}(t) = P_{\text{В}}(t)\cdot P_{\text{Б}}(t|\text{В})\cdot P_{\text{А}}(t|\text{Б}), \tag{8}$$

where $P_{\text{В}}(t)$ — probability of failure free operation within a given time interval t according to the criteria of group C; $P_{\text{Б}}(t|\text{В})$ — probability of failure free operation within a given time interval t according to the criteria of group B, taking into account the coefficient obtained based on the forecast of the model of group C; $P_{\text{А}}(t|\text{Б})$ — probability of failure free operation within a specified time interval t according to the criteria of group A, taking into account the forecast of the dependent parameters of models of Group B.

Example of calculation and verification of the model. As an example, the calculation of the probability of trouble-free operation of a steel rope was performed during operation as part of the lifting mechanism of the Kirovets gantry crane 16/20 (operating mode group M6). The calculated parameters of the rope and operating modes are presented in Table 5. Based on the calculation results, a graph of the dependence of the probability of trouble-free operation on time is shown in Figure 7.

For verification, the graph shows the calculated value of the median service life of a steel rope according to ISO 16625 — $T_{\text{M6}} = 3200$ hours for a given operating mode M6.

Table 5

Initial data for assessing the reliability of a steel rope

Probability of failure free operation	Parameter designation	Value	Unit of measurement
$P_{\text{В}}$(t)	$\beta_{\text{В}}$	3	–
	q	68	MPa
	$\eta_{\text{В}}$	0.36	MPa·h
	$k_{\text{дег.}}$	0.0004	h^{-1}
	$E_{\text{В}}$	110	MPa
	ε_{lim}	0.25	
$P_{\text{Б}}$ (t|В)	δ	0.05	–
	H	5100	MPa
	$\sigma_{\text{кон.}}$	850	MPa
	k_f	$5.0\cdot10^{-7}$	–
	k_ω	$4.1\cdot10^{-8}$	–
	$k_{\text{А}}$	0.175	–
	p	7.0	MPa
	$\nu_{\text{вар.}}$	0.15	–
$P_{\text{А}}$ (t|Б)	β_A	4	–
	η_0	3200	h
	A_0	283.79	mm^2
	m	6	–

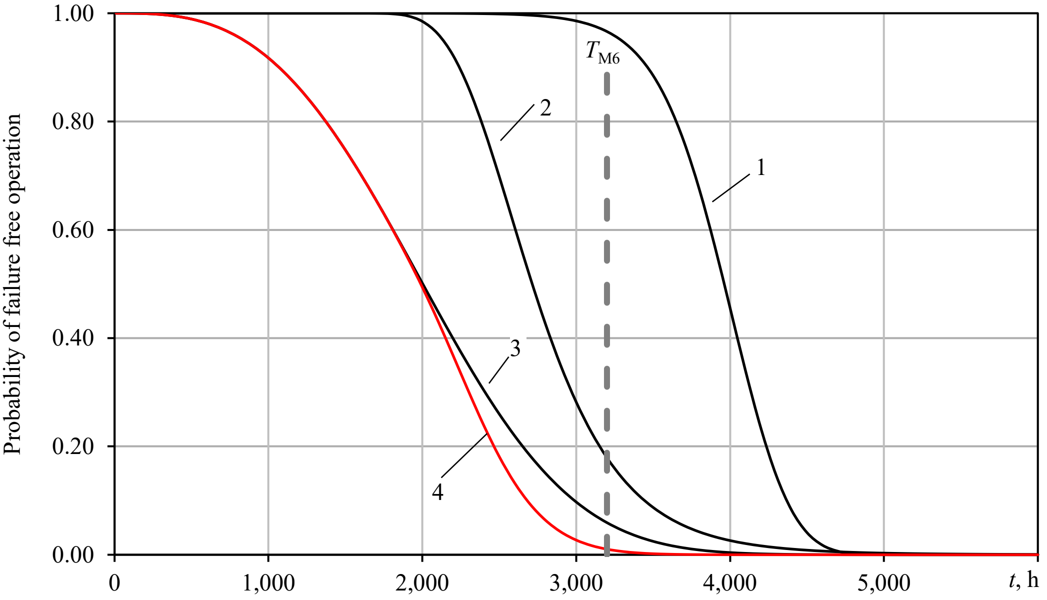

Fig. 7. Comparison of the predictive reliability assessment of a steel rope of 6x36 WS FC GOST 7668-80 construction with the calculated values of the median resource according to ISO 16625: 1 — assessment of reliability according to the criteria of group A — dependence $P_{\text{А}}(t|\text{Б})$; 2 — assessment of reliability according to the criteria of group B — dependence $P_{\text{Б}}(t|\text{В})$; 3 — assessment of reliability according to the criteria of group C — dependence $P_{\text{В}}(t)$; 4 — probability of failure of the rope $R_{\text{К}}(t)$; $T_{\text{М6}}$ — life of the steel rope in the M6 mode, h

Discussion. The analysis of the results shows that the proposed set of models consistently bridges the gap between the theoretical assessment of reliability and operational documentation regulations. A key feature of the proposed interpretation of failures is the consideration of the synergetic interaction of several degradation mechanisms that form an integral picture of wear and damage. When modeling rope survivability, the central methodological issue is the contradiction between the physical nature of the processes and the mathematical scheme used. Within the framework of the proposed concept, the predicted rope failure is interpreted as the result of the parallel development of several degradation mechanisms — wear, corrosion and fatigue — despite the fact that the mathematical model purposefully includes the principle of sequential connection of elements (“weak link model”). Such a statement is justified by the fact that achieving any of the limiting criteria leads to a loss of performance of the system as a whole.

An essential feature of the model is the realization of the mutual influence of degradation processes through a system of dependent parameters and coefficients. Rheological degradation of the core and wear kinetics change the stress-strain state of wires, thereby modifying the rate of accumulation of fatigue damage and the redistribution of local loads. As a result, the overall reliability of the rope is determined by the probability of failure-free operation of a sequential system with dynamically dependent parameters, which provides higher forecast accuracy compared to additive approaches that ignore interprocess communications.

Unlike common studies, where degradation factors are treated as independent variables, this paper implements the concept of dynamic parameter dependence, reflecting the actual connectivity of mechanisms. The applicability of the developed apparatus as an analytical tool for design calculations of rope reliability in order to prevent critical defects and optimize design solutions is shown. At the same time, the heterogeneity of the apparatus used complicates the assessment of the total error by standard methods, which necessitates the development of a special reliability criterion that takes into account the particular errors of each component of the model and their possible correlation.

Conclusion. In the course of the research, we developed a comprehensive predictive mathematical model for steel rope reliability, which describes the combined effects of wire breaks, wear, atmospheric corrosion, and core rheological degradation. The hierarchical decomposition of rope reliability allows us to justify the calculation scheme with interdependent parameters and take into account synergistic effects of degradation, reducing the risk of sudden failure. The proposed calculation apparatus incorporates regulatory requirements into the forecasting process. Verification confirmed the consistency of predicted reliability curves with calculated values of median resource according to ISO 16625. At the same time, estimated median resource turned out to be 37% more conservative compared to traditional methods. The scope of applicability is limited to the assessment of the reliability of double lay ropes with an organic core according to GOST 7668–80 at the design stage and assumes the availability of statistical parameters of degradation models, as well as data on the strength and load of rope elements. Further research will focus on the development and experimental verification of models for ropes of different design groups, taking into account the specifics of operation, and their application in engineering practice for the reasonable selection of parameters and optimization of maintenance regulations.

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Conflict of Interest Statement: **the author declares no conflict of interest.**

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Конфликт интересов: **автор заявляет об отсутствии конфликта интересов.**

Автор прочитал и одобрил окончательный вариант рукописи.

Received / Поступила в редакцию 17.11.2025
Reviewed / Поступила после рецензирования 18.12.2025
Accepted / Принята к публикации 30.12.2025

CHEMICAL TECHNOLOGIES, MATERIALS SCIENCES, METALLURGY
ХИМИЧЕСКИЕ ТЕХНОЛОГИИ, НАУКИ О МАТЕРИАЛАХ, МЕТАЛЛУРГИЯ

UDC 620.1:620.179.16
https://doi.org/10.23947/2541-9129-2026-10-1-47-60

Original Empirical Research

Local Gradient Indicator of Magnetic Variability under Cyclic Loading of Steels

EDN: BZBQLB

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Abstract

Introduction. Fatigue failure is one of the main causes of failure of metal structures subjected to variable loads. Initially, this damage is not visible as cracks, but it leads to the accumulation of microdefects and the redistribution of internal stresses. Currently, it is not possible to monitor the progression of these defects in large structures with a significant surface area. To detect such processes in a timely manner, highly sensitive inspection methods are required that can identify potential areas of failure with a high degree of accuracy during the early stages of structural operation. Such methods do not currently exist, and our research aims to solve this problem to a certain extent. One promising approach is the monitoring of changes in the strength of a permanent magnetic field, which reflects the evolution of material state. The current study aims to investigate the potential of spatial analysis of magnetic response to identify instability zones during fatigue loading, where the likelihood of failure is high, as well as to analyze changes in steel structure.

Materials and Methods. The study focused on samples made of 09G2S steel, subjected to loading to fracture on a servohydraulic testing machine INSTRON-8801. Magnetic measurements were taken at 12 points along the sample using an IKN-2M-8 instrument. Changes in the resulting strength of the permanent magnetic field were recorded at different stages of fatigue loading. All measurements were repeated at least three times to ensure the reliability of the results.

Results. It has been found, that at the stage of relative operating time Ni/Np = 0.4–0.5, anomalous changes in the magnetic field strength corresponding to the fracture nucleus were recorded at certain points. Additionally, a characteristic area of signal stabilization was observed in the range Ni/Np = 0.8–0.9. This could be explained by the temporary relaxation of stresses prior to destruction. The obtained data demonstrate the local variability of the magnetic response and confirm the sensitivity of this method to the early stages of material degradation.

Discussion. The conducted research has shown that spatial analysis of changes in the strength of a permanent magnetic field can be used to locate fracture nuclei in ferromagnetic steels. This dataset can be used as a basis for training samples for intelligent monitoring systems, including neural network algorithms that focus on predicting the remaining life and automatically assessing the technical condition of structures. This is particularly important for welded structures with a high number of welds.

Conclusion. The introduction of energy into a system inevitably leads to a reorganization of the structure of the material in order to adapt to external forces. This reorganization is accompanied by a change in the material's magnetic field. By recording these changes, it is possible to interpret the measurement results in terms of possible destruction, as the most efficient way for the system to utilize the supplied energy is through the formation of new surfaces, or cracks.

Keywords: magnetic test, fatigue damage, localization of fracture nucleus, ferromagnetic materials, distribution of magnetic tension, near-surface layer, residual stresses, domain structure, degradation of the material, multifractals

Acknowledgements. The authors would like to thank the Editorial board of the journal for their prompt review of the article and valuable comments that helped the authors to improve its quality.

Funding Information. The research was done with the financial support of a grant from the Russian Science Foundation project under Agreement No. 25–29–00200 dated December 28, 2024, titled “Forecasting the degradation level of properties of welded joints using artificial intelligence to identify and prevent emergencies”.

For Citation. Shermatov DN, Borisov AO, Gafarova VA, Kuzeev IR. Local Gradient Indicator of Magnetic Variability under Cyclic Loading of Steels. *Safety of Technogenic and Natural Systems*. 2026;10(1):47–60. https://doi.org/10.23947/2541-9129-2026-10-1-47-60

Оригинальное эмпирическое исследование

Локальный градиентный индикатор магнитной изменчивости при циклическом нагружении сталей

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Аннотация

Введение. Усталостное разрушение является одной из основных причин выхода из строя металлоконструкций, работающих под воздействием переменных нагрузок. На ранних стадиях такие повреждения не сопровождаются видимыми трещинами, однако приводят к накоплению микродефектов и перераспределению внутренних напряжений. Проследить за развитием таких дефектов в конструкциях с большой протяженностью и необходимостью контроля большой площади поверхности в настоящее время не представляется возможным. Для своевременного выявления этих процессов необходимы высокочувствительные методы контроля, которые способны на ранних стадиях функционирования конструкции определить с высокой долей вероятности возможное место разрушения. Такие методы не развиты, и представленные исследования в определенной степени могут решить эту проблему. Одним из перспективных направлений является регистрация изменений напряжённости постоянного магнитного поля, отражающих эволюцию состояния материала. Цель настоящей работы — исследовать возможности пространственного анализа магнитного отклика для локализации зон нестабильности в процессе усталостного нагружения, в которых высока вероятность разрушения, и одновременно проанализировать изменения структуры стали.

Материалы и методы. Объектом исследования являлись образцы из стали 09Г2С, подвергнутые нагружению до разрушения на сервогидравлической испытательной машине INSTRON-8801. Магнитные измерения проводились в 12 точках вдоль образца с использованием прибора ИКН-2М-8. Фиксировались изменения результирующей напряжённости постоянного магнитного поля на различных стадиях усталостного нагружения. Все измерения повторялись не менее трёх раз для повышения достоверности результатов.

Результаты исследования. Установлено, что на стадии относительной наработки Ni/Np = 0,4–0,5 в отдельных точках регистрировались аномальные изменения напряжённости магнитного поля, соответствующие зоне зарождения очага разрушения. Кроме того, зафиксирован характерный участок стабилизации сигнала в диапазоне Ni/Np = 0,8–0,9, что может быть связано с временной релаксацией напряжений перед разрушением. Полученные данные демонстрируют локальную вариативность магнитного отклика и подтверждают чувствительность метода к ранним стадиям деградации материала.

Обсуждение. Проведённое исследование показало, что пространственный анализ изменения напряжённости постоянного магнитного поля может быть использован для локализации очагов разрушения в ферромагнитных сталях. Представляется возможным полученный массив данных положить в основу обучающих выборок для интеллектуальных систем мониторинга, включая нейросетевые алгоритмы, ориентированные на прогнозирование остаточного ресурса и автоматическую оценку технического состояния конструкций. Особенно это важно для сварных конструкций с большой протяженностью сварных швов.

Заключение. Введение в систему энергии неизбежно приводит к реорганизации структуры конструкционного материала с целью приспособления к внешнему воздействию. Реорганизация сопровождается изменением собственного магнитного поля материала. Фиксация таких изменений позволяет интерпретировать результаты измерений с позиции возможного разрушения, поскольку наиболее эффективным способом реализации поступившей в систему энергии является образование новой поверхности, то есть образование трещины.

Ключевые слова: магнитный контроль, усталостные повреждения, локализация очага разрушения, ферромагнитные материалы, распределение магнитной напряжённости, приповерхностный слой, остаточные напряжения, доменная структура, деградация материала, мультифракталы

Благодарности. Авторы благодарят редакцию журнала за оперативную подготовку статьи к публикации и за ценные замечания, устранение которых позволило улучшить её содержание.

Финансирование. Работа выполнена при финансовой поддержке гранта проекта Российского научного фонда по соглашению № 25–29–00200 от 28.12.2024 «Прогнозирование уровня деградации свойств сварных соединений с помощью искусственного интеллекта для выявления и предотвращения аварийных ситуаций».

Для цитирования. Шерматов Д.Н., Борисов А.О., Гафарова В.А., Кузеев И.Р. Локальный градиентный индикатор магнитной изменчивости при циклическом нагружении сталей. *Безопасность техногенных и природных систем.* 2026;10(1):47–60. https://doi.org/10.23947/2541-9129-2026-10-1-47-60

Introduction. The importance of accurately assessing the remaining lifespan of metal structures stems from the need to balance industrial safety with operational costs. This issue is particularly relevant for extended welded shells, tanks, and pipelines, which require monitoring a large surface area and substantial amounts of metal under conditions of limited access and challenging loading conditions.

Traditional methods of non-destructive testing, such as ultrasound, radiography, and acoustic emission, are effective at detecting formed defects like macrocracks and discontinuities. However, these methods have limitations when it comes to an early detection of fatigue damage. They usually require careful surface preparation, significant labor costs, and are not well-suited for rapid mapping of extended welds. Additionally, they often provide an integrated assessment of the condition, without the ability to locate the initial areas of degradation or residual stress gradients. As a result, a significant portion of the design effort is spent blindly, potentially leaving dangerous areas undetected until the stage when macrocracks have developed.

In this context, here has been a growing interest in methods that rely on recording the material's own physical fields. These methods are sensitive to changes in the internal state of the material without directly injecting energy into the controlled volume. One of the most promising methods is the analysis of the intensity distribution of the permanent (residual) magnetic field that forms in ferromagnetic steels as damage accumulates and residual stresses redistribute. Magnetic methods have a number of important advantages: the possibility of remote measurements, high speed of examination of large areas, and sensitivity to the early stages of stress and defect redistribution, when macrocracks have not yet formed [1].

Reliable diagnosis of the remaining life of metal structures relies on a thorough analysis of microscopic changes that occur in the material's structure as fatigue damage accumulates. One of the most sensitive and informative indicators of these changes is the material's magnetic field, which forms as a result of changes in its domain structure. Changes in the domain configuration integrally reflect a combination of microstructural transformations and the evolution of residual stresses, making them a valuable basis for developing highly accurate diagnostic criteria.

In ferromagnetic materials, there are significant differences in the magnetic domain structure near the surface compared to the interior. Experimental studies have shown that domain walls near the surface can be significantly wider than inside the material. This leads to a decrease in magnetic energy density in the wall and, as a result, affects the mobility of domain boundaries and their response to local mechanical stresses and defects [2]. Therefore, it is important to take into account the special magnetic properties of surface layers when analyzing the overall magnetic texture of a material.

Direct visualization of internal domain structures within the volume of solid materials is still a challenging task due to the limited spatial resolution of most magnetic imaging techniques. Techniques such as magneto-optical imaging and magnetic force microscopy can only effectively record magnetic morphology on the surface of a sample. Instead, indirect approaches are used to study the three-dimensional magnetic structure. Classical micromagnetic models and multiscale numerical simulations allow us to predict domain configurations and their dynamics by taking into account both the local magnetic fields and the crystallographic properties of the material. For example, the introduction of dislocation stresses into micromagnetic simulation demonstrates how dislocations can serve as anchor points for domain boundaries and influence the Barkhausen effect [2].

It is worth mentioning the latest methods for reconstructing magnetic structures based on machine learning. In [3], a model based on a convolutional neural network (MagNet) is presented, which increases the accuracy of reconstructing the three-dimensional configuration of magnetization from tomography data. This approach overcomes the limitations of classical vector tomography algorithms, eliminating the artifacts of incomplete data and significantly improving the quality of the reconstructed magnetic field.

A similar principle was applied in the study [4], where a neural network model is trained to transform images of an external magnetic field (for example, leakage field maps) into the distribution of the magnetization vector inside the material. This makes it possible to reconstruct complex domain textures with a variable direction of magnetization, which are inaccessible to traditional inversion methods [4]. Such neural network approaches expand the possibilities of interpreting experimental data and bring researchers closer to the direct reconstruction of the internal magnetic texture by indirect measurements.

The microstructure of the material, including the distribution of magnetization, changes as a result of plastic deformation under cyclic loading conditions. Modern measurement methods do not directly track the movement of individual magnetic domains within a material, but the cumulative magnetic response, such as a hysteresis loop, is sensitive to these microstructural changes. The restructuring and reorganization of domain boundaries on a microscopic level is manifested in measurable changes in magnetic permeability, coercive force, and other material parameters. Thus, the analysis of the dynamics of magnetic characteristics under load makes it possible to judge changes in the internal structure. By taking these effects into account, we can move from an overall assessment of the material's condition to a more localized analysis aimed at detecting areas that are prone to damage.

The internal (volumetric) behavior of the material during fatigue deformation differs significantly from the processes occurring near the surface. In the thickness of the material, plastic deformation is distributed more evenly and the gradients of residual stresses are significantly lower than at the surface [5]. In a polycrystalline volume, dislocations are generated and accumulate in groups, causing significant local stresses, which are difficult to remove due to the lack of a free surface. Grain boundaries act as an internal "surface", however, for dislocations to escape through these boundaries, an energy barrier must be overcome [6]. Only after reaching a critical level of accumulated stresses and defect energy [7], it is possible for microcracks to form inside the material. These features are consistent with the Mura concept of relaxation of internal stress fields [8], as well as with experimental data on the uneven distribution of residual stresses (stress anisotropy) in steels [9].

Unlike the volume, the free surface of the material acts as an effective source for dislocations, requiring significantly less energy for defects to form. This explains why fatigue cracks often initiate on the surface. As a result, changes occurring in the subsurface layer during loading can serve as informative diagnostic indicators of developing degradation.

One of these signs is the formation of self-similar (fractal) structures on the surface as defects develop. These structures have the property of self-similarity at different scales, as noted by B. Mandelbrot [10]. The morphology of the damaged metal surface often exhibits fractal characteristics, which can be quantified [11]. The analysis of relief elements at various scales helps to establish a connection between surface fatigue and volume destruction processes [12].

The heterogeneity and roughness of the surface can also affect the magnetic properties of the subsurface layer. Research has shown that changes in the fractal structure of a deformed material correlate with its magnetic parameters, such as saturated magnetization and magnetic permeability [11]. In other words, as damage increases, the distribution of physical properties may exhibit multifractal features. Tracking the evolution of several such multifractal parameters expands the possibilities of diagnostic interpretation, allowing for more reliable identification of the early stages of material degradation.

Thus, the analysis of the literature confirms the need for an integrated approach to the diagnosis of damage in ferromagnetic structural materials. Magnetic domain structures near the surface and in the volume react differently to the presence of defects and mechanical stresses. Combining classic micromagnetic models with modern neural network reconstruction methods [3, 4] allows for a deeper analysis of internal changes in the magnetic texture that cannot be directly observed. At the same time, taking into account the features of damage accumulation (dislocation structures and residual stresses) in the volume [5–9] and related fractal features on the surface [10–12] provides a more complete control of the state of the material. The synthesis of magnetic and fractal degradation criteria, confirmed by literature data, opens the way to the creation of highly sensitive methods of non-destructive testing for early detection of defects.

Magnetic diagnostic methods based on the distribution of strength of a permanent magnetic field are used to identify stress concentration zones and local degradation sites in ferromagnetic steels. Their basis is the sensitivity of the magnetic response to the redistribution of residual stresses and to defects that form local field inhomogeneities. At the same time, known approaches often use integral indicators or one-dimensional profiles along a selected line and do not strictly relate spatial field anomalies to (*i*) stage of fatigue loading and (*i*) parameters of the microstructure in terms of material thickness.

However, to date, it has not been sufficiently investigated how local anomalies in the distribution of the resulting constant magnetic field strength on the surface of structural steels are quantitatively consistent with changes in the microstructure and its multifractal parameters in the subsurface layer and in the volume under cyclic loading. The absence of such a connection limits the formation of a stable diagnostic feature space for early localization of fracture nucleus.

In this study, we aim to experimentally validate a diagnostic approach that compares spatially localized measurements of the residual magnetic field during cyclic bending of 09G2S steel with multifractal microstructural parameters calculated from micrographs taken in specific thickness zones.

Materials and Methods. For the research, samples of 09G2S low-alloy structural steel were taken and subjected to cyclic loading in order to simulate the operating conditions of elements under variable mechanical stresses (for example, reservoirs, pipelines, and bearing elements of metal structures) (Fig. 1). To measure the strength of a permanent magnetic field, an IKN-2M-8 device (stress concentration meter) was used.).

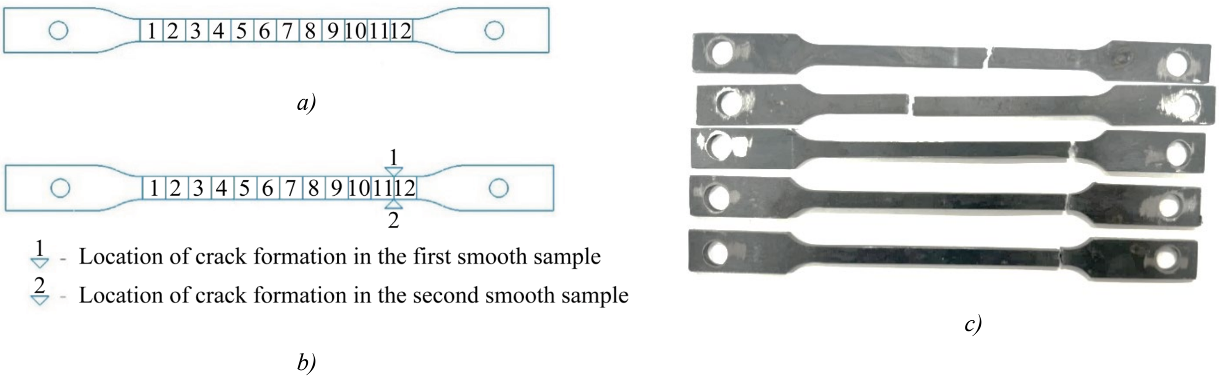


Fig. 1. Test samples: *a* — in the initial state; *b* — places of destruction of the samples; *c* — tested samples

Magnetic measurements were taken at 12 different points, spaced 10 millimeters apart. At each level of loading, the testing machine paused and the measurements were taken according to a consistent process at predetermined control points, ensuring accurate data comparison between cycles. In order to assess reproducibility and statistical significance, measurement results were collected from five identical samples that underwent the same cyclic loading regimen. This allowed us to confirm the consistency of the magnetic response and minimize the influence of random factors related to local microstructural variations. To further enhance the reliability of our analysis, all measurements were replicated at least three times at each point.

After the cyclic tests were completed and the fracture was fixed, sections were cut out of the studied samples to analyze microstructural changes.

Fractal microstructure analysis was used to establish the relationship between the structural heterogeneity of the metal and local magnetic anomalies observed when measuring the resulting strength of permanent magnetic field *Hr*. The microstructure was studied using micrographs obtained in the cross-section of the destroyed sample in three characteristic zones:

- in the zone adjacent to the outer surface;
- in the central (volumetric) part;
- in the area adjacent to the fracture nucleus.

Additionally, microstructures of the initial state of the metal obtained before cyclic loading were used for comparative analysis.

Micrographs of each studied zone were obtained at magnifications of ×200, ×500 and ×1000, which provided an analysis of the structure at various scale levels. Image processing was performed in the *MFRDrom Fast* program developed by Professor G.V. Vstovsky [13, 14], in the Normalized By D_1 mode, with the Pseudo analysis type.

Parameters characterizing fractal dimension, latent periodicity, and degree of uniformity of the microstructure were calculated for each zone [13]. Their comparison between the zones along the thickness of the sample and at different scales allowed us to estimate spatial and scale variability of structural organization of the material. This approach made it possible to compare the gradient of microstructural complexity with the distribution of magnetic response *Hr* recorded on the corresponding sections of the sample surface.

Results. The results of measurements of the resultant strength of permanent magnetic field *Hr* on the surface of the samples under cyclic loading, as well as the results of calculating the index of local change in magnetic characteristic *Gi*, were obtained. The level of accumulated damage was determined by relative operating time *Ni/Np*, where *Ni* — current number of cycles, *Np* — number of cycles before destruction. Measurements were performed on five samples ($n = 5$), three repetitions were performed at each measuring point at each *Ni/Np* level ($m = 3$). For each point — level *Ni/Np* combination, the average value and the standard deviation were calculated, and Figures 2 and 3 show the average values with error bars. The standard error of the measuring device did not exceed 10%.

Figure 2 provides dependencies of *Hr* on *Ni/Np* for points 1, 11, and 12. In the entire *Ni/Np* range, *Hr* values at point 1 remained at a significantly lower level compared to points 11 and 12. In the range *Ni/Np* = 0.4–0.5, a discrepancy in *Hr* behavior was recorded at points 11 and 12: at point 11, there was a decrease in *Hr* relative to neighboring levels, while at point 12, there was an increase in *Hr* with the formation of a local maximum. The differences between points 11 and 12 in the specified range exceeded the spread (±SD) and were reproduced from a series of measurements (*n* = 5).

To quantify the variability of the magnetic response, indicator of local change *G_i* was calculated, and its dependencies on *Ni/Np* for points 1, 11, and 12 are shown in Figure 3. In the range *Ni/Np* = 0.2–0.6, *Gi* values at points 11 and 12 significantly exceeded the values obtained at point 1. The maximum values of *G_i* at points 11 and 12 were observed at *Ni/Np* of the order of 0.35–0.5, with a further increase in *Ni/Np*, a decrease in *Gi* was recorded. At point 1, *Gi* values remained at a lower level, with no pronounced peaks comparable to points 11 and 12. Thus, the results of magnetic measurements confirmed the spatial heterogeneity of *Hr* distribution and the localization of the largest changes in the magnetic characteristic in the area of points 11, 12 in *Ni/Np* range of the order of 0.35–0.5 (Fig. 2–3).

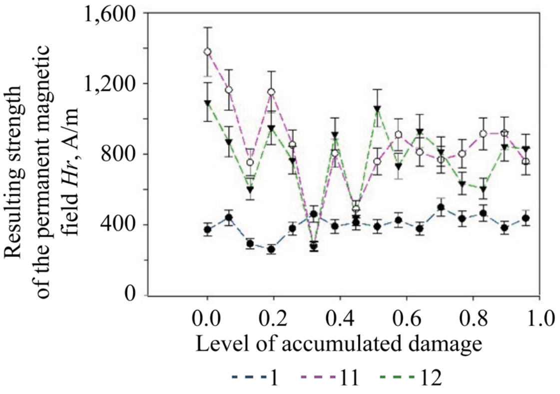


Fig. 2. Dependence of the change in the resulting strength of the permanent magnetic field on the level of accumulated damage

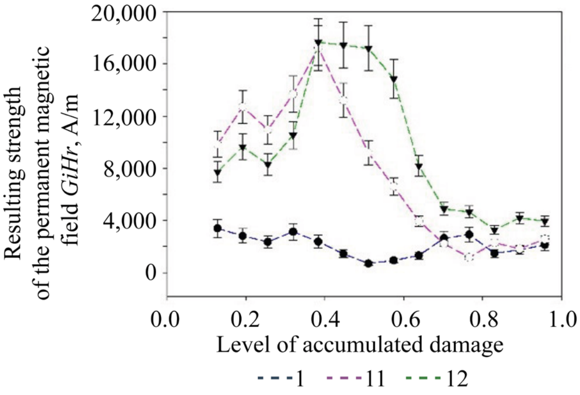


Fig. 3. Dependence of the local change in the resulting strength of the permanent magnetic field on the level of accumulated damage

The maximum *Gi* values at points 11 and 12 were observed at *Ni/Np* of the order of 0.35–0.5, with a further increase in *Ni/Np*, *Gi* values decreased, and at *Ni/Np* = 0.75, a distinct decrease in the indicator was recorded (Fig. 3). At point 1, *Gi* values remained at a lower level, without pronounced peaks, comparable to points 11 and 12.

Discussion. The results obtained confirm the diagnostic potential of spatially localized measurements of the resulting permanent magnetic field strength *Hr* under cyclic loading. The most pronounced magnetic variability was observed in the range *Ni/Np* = 0.4–0.5, and the maximum local changes in parameters were recorded in the area where the fracture occurred, which was consistent with the previously demonstrated sensitivity of magnetic characteristics to damage accumulation in model elements of metal structures [1].

In the range *Ni/Np* = 0.8–0.9, a phase of relative stabilization of the magnetic response (a decrease in the variability of *Hr* and/or derived indicators) was revealed, followed by a transition to a more unstable regime. A similar “lull → abrupt change” type of dynamics was described for acoustic signals as a diagnostic sign of pre-collapse [15]. Comparable approaches to monitoring degradation by physical parameters under operating conditions were also demonstrated by ultrasound monitoring [16].

The interpretation of the observed magnetic effects should consider the relationship between the magnetic response and the defective structure, as well as the local stress state of the material. Micromagnetic modeling has shown that the interaction of domain walls with dislocations and defects can lead to local changes in magnetic parameters [2]. Additionally, the informative value of magnetic methods sensitive to microstructural inhomogeneities at the grain and boundary levels was confirmed by studies of Barkhausen magnetic noise with high spatial resolution [17].

The practical applicability of the technique for real metal structures was determined by the requirements for the accuracy and reproducibility of measurements and the stability of the result to external factors. Critical conditions included reproducible sensor positioning (sensor-surface orientation and clearance), repeatable scanning trajectory, and magnetic background monitoring. The results could be influenced by the geometry of the object (curvature, thickness variation, proximity of welds and cutouts), magnetic history (residual magnetization), and extraneous magnetic field sources. Residual stresses were an essential factor in interpretation, as they were a component of the current state of the material. This was emphasized in review papers on the topic [5].

Figure 4 demonstrates the results of studying the changes in multifractal parameters in accordance with [13, 14].

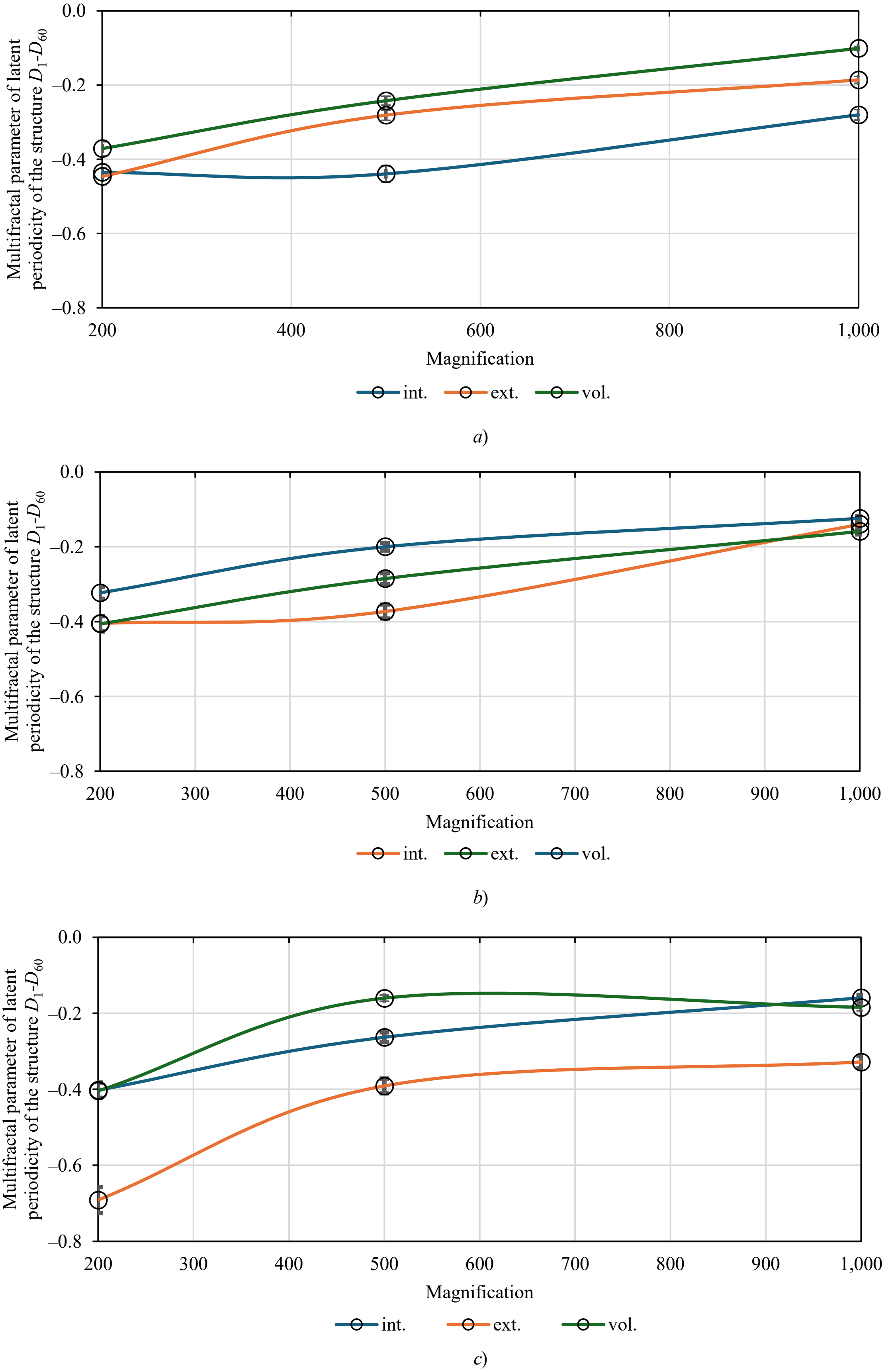


Fig. 4. Change in the multifractal parameter of latent periodicity of D_1–D_0 structure depending on the scale of observation (magnification of the microscope) for different zones of the 09G2S steel sample: *a* — initial state; *b* — area far from the fracture zone; *c* — destruction zone

In the initial state (Fig. 4*a*), the dependencies of parameter D_1–D_0 on the magnification were smooth and did not show sharp differences between the zones in the thickness of the sample, indicating the absence of signs of local degradation.

In the area away from the fracture zone (Fig. 4*b*), the dependencies of parameter D_1–D_0 continued to increase, but the difference between the zones in terms of thickness became more pronounced. At a magnification of ×500, the maximum difference in the curves was observed, which was linked to the transition from grain to sub-grain structure organization, which was most sensitive to internal stresses. The inner region was characterized by a lower value of parameter D_1–D_0, indicating a partial loss of structural order.

The volume part, however, retained a high level of latent periodicity, which indicated its relative stability. Therefore, at this stage of damage development, a gradient of microstructural organization was formed from a stable region (volume) to an unstable region, which corresponded with the distribution of internal stresses in the cyclically loaded sample.

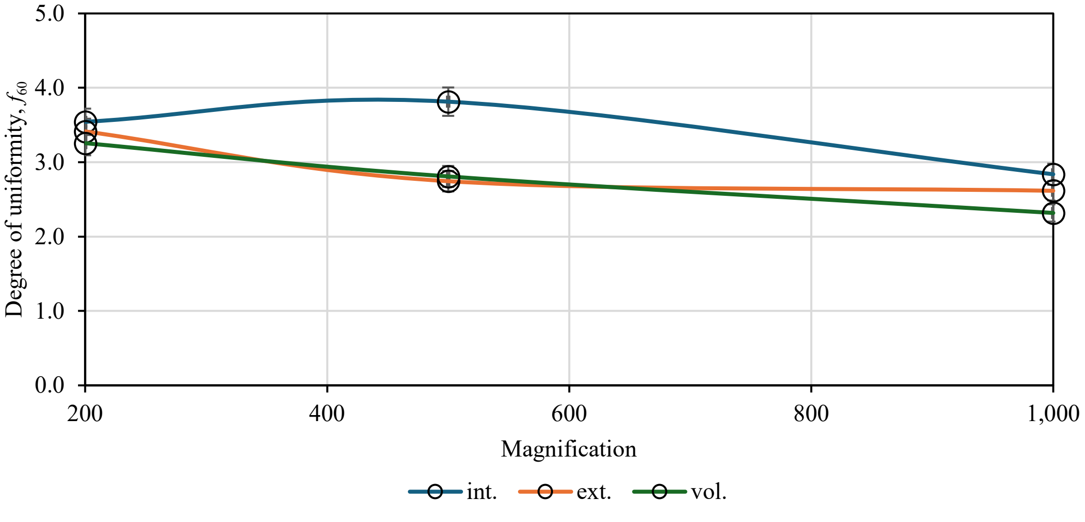
In the destruction zone (Fig. 4*c*), the most dramatic change in the nature of D_1–$D_0 = f$ (increase) dependence was observed. For the inner surface adjacent to the fracture site, the parameter values became minimal (up to –0.6... –0.7), which indicated a loss of latent periodicity and an increase in the random distribution of structural elements.

A comparison of the obtained dependencies demonstrated that as the transition from the initial state to the fracture zone proceeded, there was a steady downward trend in the parameter D_1–D_0, especially in the area adjacent to the fracture site.

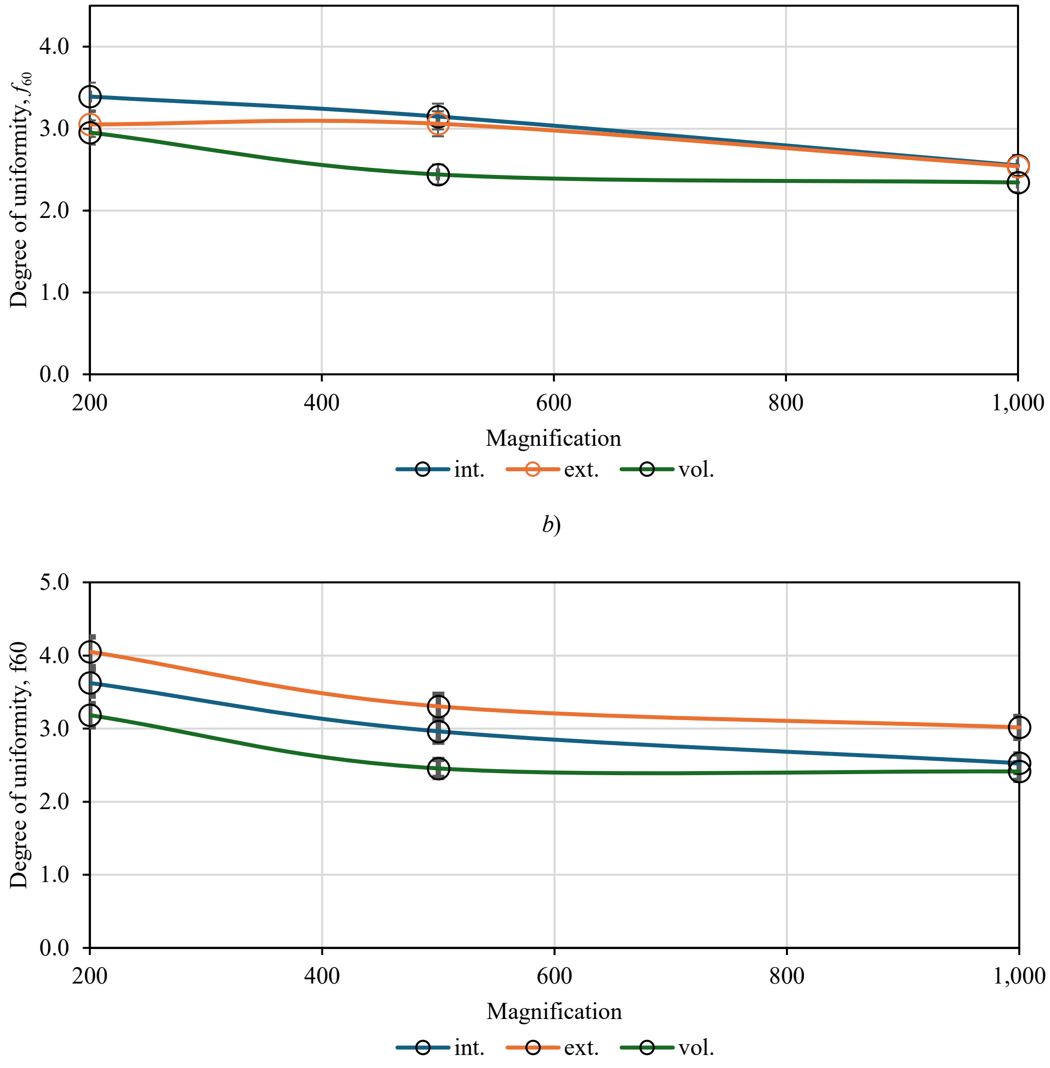
Thus, multifractal parameter D_1–D_0, characterizing the latent periodicity, could be considered as a sensitive indicator of the transition of the structure from a stable state to an unstable one. Its spatial distribution correlated with the zone of magnetic anomalies identified by changes in the resulting magnetic field strength *Hr*, which indicated the general nature of microstructural and magnetic signs of degradation in the studied material.

A comparison of the dependencies of multifractal parameter of latent periodicity of D_1–D_0 structure for different stages of the material's state (Fig. 4) showed that as the transition from the initial state to the fracture zone progressed, there was a steady tendency for the parameter to decrease and the structural periodicity to disappear. In its initial state, the structure of 09G2S steel exhibited a pronounced scale order and a weak technological gradient in thickness. Far from the fracture site, there was a formation of a gradient in microstructural stability, with inner regions showing a decrease in D_1–D_0 due to local deformation, while the outer regions maintained the substructure regularity. However, in the destruction zone, the correlation between structural elements was completely lost, the hidden periodicity disappeared, and the microstructure became statistically chaotic. Thus, the change in D_1–D_0 parameter reflected the transition of the material from the state of structural equilibrium to the degradation phase and could be used as a sensitive quantitative indicator of the degree of damage in ferromagnetic steels.

A comparison of the dependence of the degree of uniformity f_{60} for different zones on the thickness of the sample (Fig. 5) showed that during the transition from the initial state to the fracture zone, there was a steady tendency to decrease the parameter and a disruption of uniform distribution of structural elements. In the initial state, the structure of 09G2S steel was characterized by high uniformity and a weak technological gradient. In the zone away from the fracture nucleus, there was an alignment of f_{60} values, which indicated the beginning of destabilization of the structure and a partial redistribution of internal stresses. In the destruction zone, there was a further decrease in the degree of uniformity and a shift in the ratio between the zones: the outer surface retained a residual order, while the volume part lost its structural consistency. Thus, the decrease in f_{60} was a quantitative indicator of the increase in the uneven distribution of the microstructure and corresponded to the fractal sign of material degradation, previously established by D_1–D_0 parameter.



a)

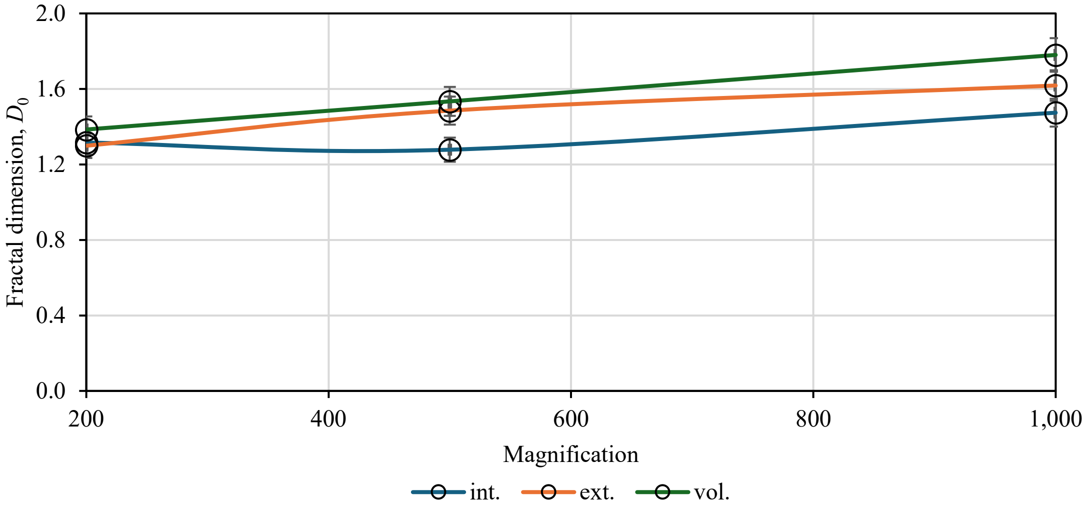


b)

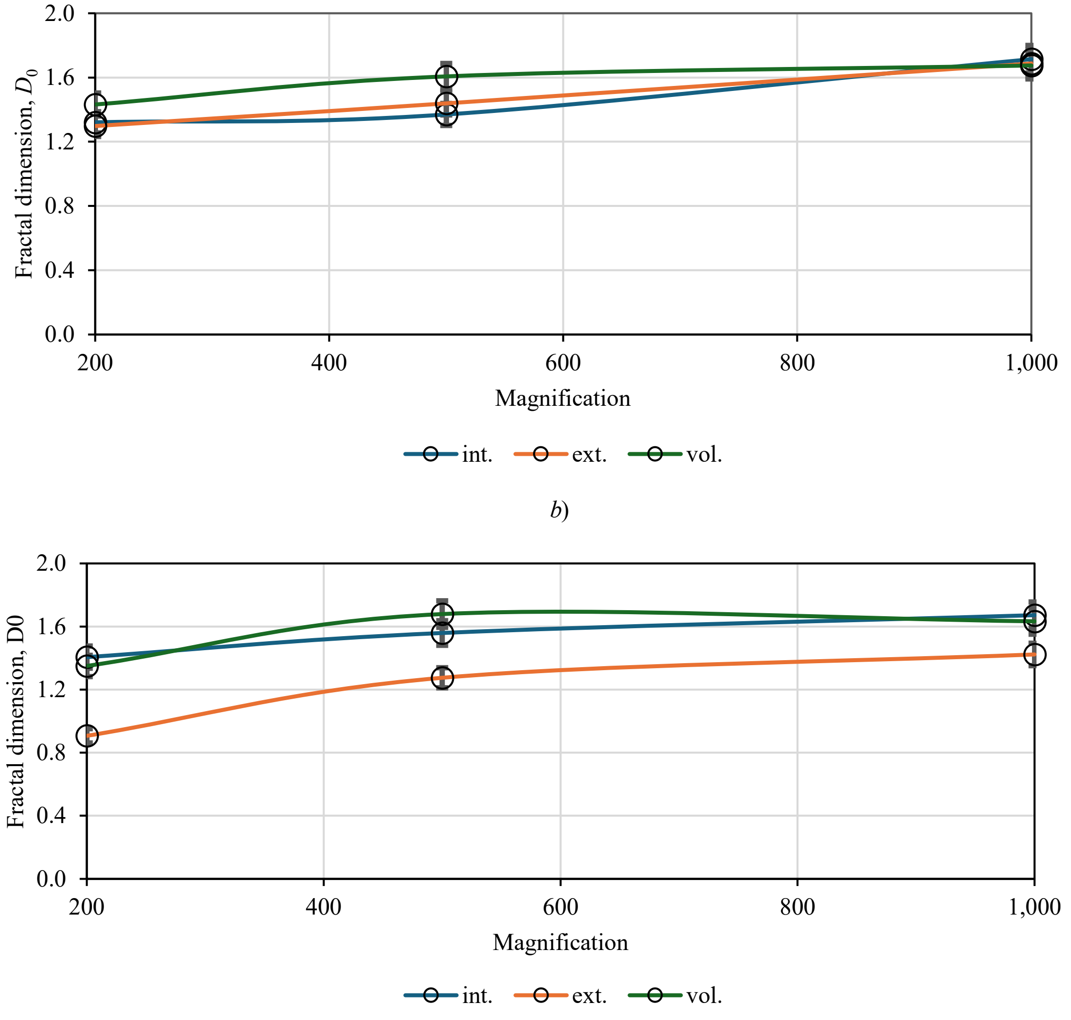
c)

Fig. 5. Change in the multifractal parameter of the degree of uniformity f_{60}
depending on the scale of observation (magnification of the microscope) for different zones of the 09G2S steel sample:
a — initial state; *b* — area far from the fracture zone; *c* — fracture zone

Analysis of changes in fractal dimension D_0 for different zones of the sample showed a regular evolution of the geometric complexity of the microstructure as it transitioned from the initial state to the fracture zone (Fig. 6).



a)



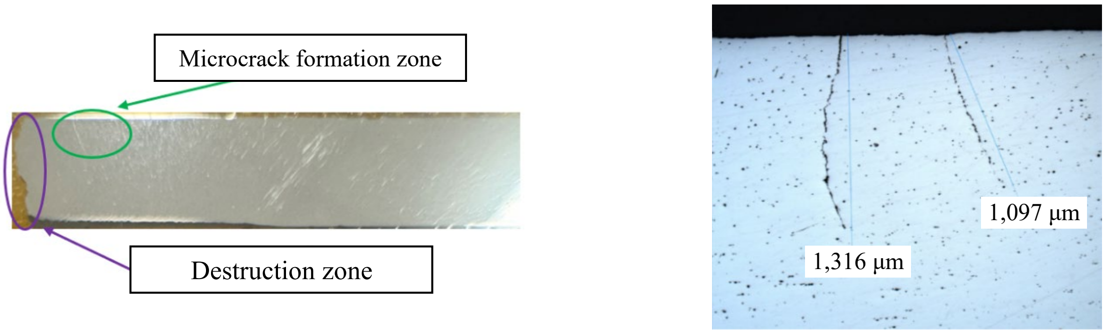
b)

c)

Fig. 6. Change in the fractal dimension D_0 depending on the scale of observation (magnification of the microscope) for different zones of the 09G2S steel sample: *a* — initial state; *b* — area far from the fracture zone; *c* — fracture zone

The most significant changes were observed in the destruction zone (Fig. 6*c*). For the outer surface, the largest decrease in fractal dimension D_0 (up to 1.3) was recorded, while for the inner and volumetric parts the values remained higher (1.6–1.7). This reflected the loss of structural complexity and the destruction of the self-similar organization of the microstructure in the surface layers.

Thus, a decrease in fractal dimension D_0 serves as an indicator of the loss of structural complexity and self-organization of the material, reflecting the transition from a stable configuration of a granular and subgrain structure to a fragmented and chaotic one. The minimum values of D_0 on the outer surface corresponded to the zones of microcrack origin shown in Figure 7.



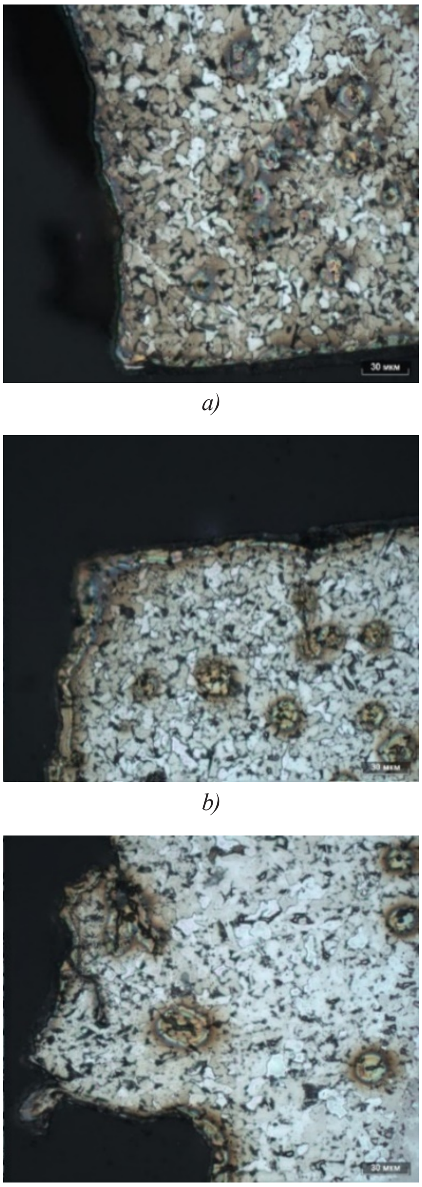
a) *b)*

Fig. 7. Macrostructure and microcracks in the cross-section of 09G2S steel sample near the fracture zone after cyclic bending:
a — general view of the cross-section with the identification of the fracture area and the area of microcrack formation;
b — micrography of microcracks in cross-section indicating the characteristic lengths of 1097 and 1316 μm (×100)

It should be noted that a decrease in fractal dimension D_0 on the outer surface was accompanied by similar changes in other multifractal parameters.

The local drop in all three parameters (D_0, D_1–D_0 and f_{60}) was consistent with H_r anomalies detected by magnetic measurements, which confirmed the general nature of damage accumulation and microcrack origin.

To visually confirm the patterns identified by the multifractal and magnetic parameters, the microstructure of the samples in the characteristic zones was analyzed. The images shown in Figure 8 demonstrate a gradual disruption of the structure's order — from the inner part to the outer surface, where microcracks formed.



a)

b)

c)

Fig. 8. Microstructure of parts of the cross-section of the sample wall in the fracture zone:
a — external; *b* — central; *c* — internal

On the microstructure of the outer surface adjacent to the fracture zone, there was a high degree of fragmentation of ferrite and perlite grains, as well as local areas with uneven contrast, indicating the development of plastic deformation. Initial microcracks and submicroscopic fractures along the grain boundaries were visible, accompanied by a loss of clarity of their outlines and local misorientation of substructural elements (Fig. 8).

The comparison of microstructures of the outer, central and inner parts of the sample in the fracture zone (Fig. 8) showed a pronounced gradient in the degree of degradation of the structure in thickness. The inner part maintained ordered ferrite-pearlite morphology, clear grain boundaries, and a uniform phase distribution, corresponding to high values of fractal dimension D_0 and uniformity parameter f_{60}. The initial restructuring of the grain-subgrain structure was observed in the central zone: small-angle sub-boundaries and local contrasts appeared, indicating an increase in internal instability and a decrease in D_1–D_0. parameter. Finally, maximum fragmentation and local microcracking occurred on the outer surface, which was accompanied by a decrease in all three fractal indicators: D_0, D_1–D_0 and f_{60}.

This distribution of microstructural features was fully consistent with the results of multifractal analysis and magnetic measurements: the outer part, where the greatest loss of structural complexity occurred, coincided with the area of magnetic anomalies H_r and reflected the zone of maximum damage accumulation. Thus, a comparison of microstructural, fractal and magnetic data confirmed that the degradation of the material had a pronounced gradient character — from a stable internal structure to a destroyed surface, where a focus of fatigue failure was formed.

The resulting set of magnetic and multifractal features was considered as the basis for the subsequent construction of models for assessing the technical condition and predicting the remaining resource. The generated array of parameters can be used in the future as a training base for intelligent technical condition assessment systems, which opens up opportunities for building more stable and adaptive methods of predictive monitoring.

Conclusion. A comprehensive study of 09G2S steel during cyclic bending has shown a uniform pattern of evolution of magnetic, fractal and microstructural parameters reflecting the processes of damage accumulation and destruction. Magnetic measurements of the distribution of the resulting field strength H_r revealed local anomalies coinciding with areas of increased residual stresses and localization of deformation near the outer surface.

The results of the multifractal analysis of micrographs performed in the *MFRDrom Fast* program confirmed the connection of magnetic anomalies with microstructure degradation. There was a consistent decrease in fractal dimension D_0, latent periodicity parameter $D_1–D_0$, and degree of uniformity f_{60}, indicating the destruction of the self-similar organization and an increase in the randomness of the substructure.

Metallographic analysis revealed a clear degradation gradient in thickness: the inner part maintained a stable ferrite-pearlite structure, the central part was characterized by partial fragmentation, and the outer part was most destroyed and contained microcracks. A comparison of these three levels showed consistent behavior of the parameters H_r, D_0, $D_1–D_0$ and f_{60}, which confirmed their interrelated nature.

Thus, the degradation of 09G2S steel during cyclic bending has a multilevel character: magnetic changes reflect the accumulation of defects, fractal parameters reflect the destruction of a large-scale structure, and microstructural analysis is the final stage of microcracking. The combination of these features can be used as a single diagnostic criterion for the condition of the material and the basis for assessing the residual life of elements operating under variable loads.

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VA Gafarova: investigation, writing – original draft, administration.
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Conflict of Interest Statement: **the authors declare no conflict of interest.**

All authors have read and approved the final version of manuscript.

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Заявленный вклад авторов:

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А.О. Борисов: проведение исследований, формальный анализ.

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Конфликт интересов: **авторы заявляют об отсутствии конфликта интересов.**

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 08.12.2025
Reviewed / Поступила после рецензирования 15.01.2026
Accepted / Принята к публикации 27.01.2026

Safety of Technogenic and Natural Systems. 2026;10(1):61‒72. eISSN 2541‒9129

TECHNOSPHERE SAFETY
ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

UDC 331.452

https://doi.org/10.23947/2541-9129-2026-10-1-61-72

Original Empirical Research

Methodology for Implementing a Barrier-Oriented Approach to Risk Assessment of Personnel Injuries Based on the Haddon Model

EDN: XUJVSZ

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Abstract

Introduction. Modernization of production facilities, with increased automation and complexity of technological processes, leads to a greater psychophysiological burden on workers and a higher likelihood of errors. This, in turn, increases the risk of occupational injuries. The increasing number of workplace accidents underscores the economic and social importance of accident prevention, as injuries reduce productivity and increase compensation costs. Modern approaches to occupational risk management require a systematic assessment of not only the likelihood of an incident and the severity of its consequences, but also the state of protective mechanisms — safety barriers that limit the impact of hazardous factors. Haddon's methodology, originally developed for transportation safety, can be used to identify weak links and analyze the sequence of incidents. Its barrier-oriented principles are theoretically applicable to industrial environments. However, existing research on barrier models in industry is fragmented and does not provide a unified tool for quantifying the effectiveness of barriers and their contribution to reducing injury risks. Therefore, the aim of this study is to develop a method for applying a barrier-oriented approach based on the Haddon model for a comprehensive quantitative assessment of personnel injury risks.

Materials and Methods. A barrier safety model was used to solve the problem of reducing occupational injuries. The study consisted of three parts. The first was a comprehensive analysis of the requirements of Russian legislation in the field of occupational risk assessment, as well as scientific publications on the use of a barrier-oriented approach. The second was the description of the methodology for determining the likelihood of a hazard based on the results of an assessment of the reliability of safety barriers. The assessment of safety barriers was conducted according to checklists using the adapted Haddon model. Finally, an illustration of practical application of barrier approach using model example was provided.

Results. A methodology for using a barrier-oriented approach to assess injury risks has been developed. A method for quantifying the impact of current hazards has been defined, taking into account the reliability of safety barriers. Risk levels for the hazard realization have been determined. Both the methodological principles proposed in this study and those already applied have been considered, indicating their advantages and limitations. An example of calculating the probability of hazards occurring when lifting and moving goods using hoisting devices has been given.

Discussion. The presented methodology for applying the barrier-oriented approach allows us to take into account the influence of organizational factors and human factor on the safety of production processes and to obtain quantitative estimates of the possibility of hazard occurrence. Additionally, this approach provides a comprehensive assessment of safety barriers, considering not only their presence and effectiveness, but also reliability indicators — efficiency and sustainability of operation. This creates a basis for simplifying the process of prioritizing injury prevention measures and optimizing occupational risk management systems.

Conclusion. The main results of the research include a practical way to calculate the probability of hazardous production factors, as well as recommendations for the gradual implementation of the developed methodology into the practice of occupational safety and health management. The practical significance of this work lies in its potential for integration of the proposed approach with operational monitoring tools in the field of occupational safety and health and in its applicability to solving problems related to worker injury risk management in various production conditions.

Keywords: hazardous production factor, risk of injury, safety barrier, risk assessment, industrial injuries

Acknowledgements. The author would like to thank the Head of the research project, E.P. Pototskii, the reviewer, and the Editorial team of the journal for their competent expertise and valuable recommendations for improving the article.

For Citation. Gart VA. Methodology for Implementing a Barrier-Oriented Approach to Risk Assessment of Personnel Injuries Based on the Haddon Model. *Safety of Technogenic and Natural Systems*. 2026;10(1):61–72. https://doi.org/10.23947/2541-9129-2026-10-1-61-72

Оригинальное эмпирическое исследование

Методология применения барьерно-ориентированного подхода для оценки рисков травмирования персонала на основе модели Хаддона

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Аннотация

Введение. Модернизация производств с ростом автоматизации и усложнением технологических процессов повышает психофизиологическую нагрузку на работников и вероятность ошибок, что усиливает риск производственного травматизма. Наблюдаемый рост числа пострадавших на рабочих местах подчеркивает экономическую и социальную значимость предотвращения несчастных случаев: травматизм снижает производительность и увеличивает расходы на компенсации. Современные подходы управления профессиональными рисками требуют системной оценки не только вероятности инцидента и тяжести последствий, но и состояния защитных механизмов — барьеров безопасности, ограничивающих воздействие опасных факторов. Методология Хаддона, изначально разработанная для транспортной безопасности, показала свою способность выявлять слабые звенья и анализировать последовательность развития инцидентов; её барьерно-ориентированные принципы теоретически применимы в промышленной среде. Однако существующие исследования барьерных моделей в промышленности фрагментарны и не дают универсального инструмента для количественной оценки эффективности барьеров и их вклада в снижение рисков травмирования. В связи с этим цель настоящего иссле-дования — разработать методику применения барьерно-ориентированного подхода на основе модели Хаддона для комплексной количественной оценки рисков травмирования персонала.

Материалы и методы. Для решения задачи снижения производственного травматизма была использована барьерная модель обеспечения безопасности. Исследование включало три части. Первая — комплексный анализ требований российского законодательства в сфере оценки профессиональных рисков, а также научных публикаций, посвящённых применению барьерно-ориентированного подхода. Вторая — описание методологии определения вероятности реализации опасности на основе результатов оценки показателей надежности барьеров безопасности. Оценка барьеров безопасности выполнялась по чек-листам с использованием адаптированной модели Хаддона. Третья — иллюстрация практического применения барьерного подхода на модельном примере.

Результаты исследования. Разработана методология применения барьерно-ориентированного подхода для оценки рисков травмирования. Определён способ количественной оценки влияния актуальных опасностей с учётом показателей надежности барьеров безопасности. Сформированы уровни риска реализации опасности. Отражены как предлагаемые в рамках данного исследования, так и уже применяемые методологические принципы с указанием их преимуществ и ограничений. Приведён пример расчёта вероятности реализации опасностей, возникающих при подъёме и перемещении грузов с использованием подъемных сооружений.

Обсуждение. Представленная методология применения барьерно-ориентированного подхода позволяет учитывать влияние организационных факторов и человеческого фактора на безопасность производственных процессов и получать количественные оценки возможности реализации опасности. Кроме того, подход обеспечивает комплексную оценку барьеров безопасности, учитывающую не только их наличие и результативность, но и показатели надежности — эффективность и устойчивость функционирования. Это создаёт основу для упрощения процедуры определения приоритетности реализации мероприятий по профилактике травматизма и оптимизации системы управления профессиональными рисками.

Заключение. Основными результатами проведённого исследования являются: обоснованный способ расчёта вероятности реализации опасных производственных факторов и рекомендации по поэтапному внедрению разработанной методологии в практику управления охраной труда. Практическая значимость работы заключается в возможности интеграции предложенного подхода с инструментами оперативного мониторинга в области охраны труда и в его применимости для решения задач, связанных с управлением риском травмирования работников в различных производственных условиях.

Ключевые слова: опасный производственный фактор, риск травмирования, барьер безопасности, оценка рисков, производственный травматизм

Благодарности. Автор благодарит руководителя научного проекта Е.П. Потоцкого, рецензента и редакционную команду журнала за компетентную экспертизу и ценные рекомендации по улучшению статьи.

Для цитирования. Гарт В.А. Методология применения барьерно-ориентированного подхода для оценки рисков травмирования персонала на основе модели Хаддона. *Безопасность техногенных и природных систем.* 2026;10(1):61–72. https://doi.org/10.23947/2541-9129-2026-10-1-61-72

Introduction. Currently, one of the main priorities of the industry is to modernize production facilities by introducing modern equipment and cutting-edge technologies. However, the increasing level of automation and complexity of technological processes have a negative impact on the safety of workers, leading to an increase in employee errors and stress on psychophysiological functions.

These negative trends are supported by statistical data. According to [1] and the International Labor Organization (ILO), approximately 340 million industrial accidents are registered worldwide every year, with about 2.3 million workers dying as a result of work injuries. Based on [1], 2.8 million industrial accidents were recorded in the United States in 2022, and there were 5.19 thousand deaths in 2021. According to [1], in the UK in 2022–2023, 561 thousand workers were injured in the workplace. The analytical review “Occupational Injury Analysis”[1] of the Federal State Budgetary Institution “All-Russian Research Institute of Labor” of the Ministry of Labor of the Russian Federation, found that 21.4 thousand workers were injured and 1.04 thousand died in Russia in 2024. At the same time, since 2021, the number of victims in the workplace has increased by 1.1 thousand people.

The analysis of statistical data reveals a consistent trend towards high levels of occupational injuries in various countries. This circumstance determines the increasing importance of labor protection issues in industrial enterprises in the context of accelerated technological development. Current global trends in reducing occupational injuries cover the following areas: digitalization of safety procedures; use of artificial intelligence for monitoring working conditions and employee health; the introduction of “smart” personal protective equipment; the use of virtual reality (VR) and augmented reality (AR) to train employees in safe working methods; the formation of a sustainable safety culture; the transition from a traditional, predominantly reactive approach based on post-incident analysis to proactive occupational risk management.

The need to implement proactive risk management has been confirmed by Letter of the Ministry of Labor and Social Protection of the Russian Federation dated July 14, 2025 No. 15-3/10/V-11850 “On the Increase in Occupational Injuries”[2]. The document states that the main causes of industrial accidents are: poor organization of work, violations of traffic regulations, deviations from the established technological processes, as well as non-compliance with labor regulations and labor discipline by employees. It is also noted, that among the accidents with serious consequences that occurred in the Russian Federation in 2024 due to unsatisfactory organization of work, events caused by poor work organization were more prevalent due to a lack of control by managers and departmental specialists over the progress of work and adherence to labor discipline. The combination of organizational factors and human behavior patterns in the context of injuries highlights systemic deficiencies in occupational safety. These issues can be addressed by implementing effective occupational risk management, such as identifying potential hazards, assessing the level of risk associated with them, and implementing measures to minimize the risk of injury to employees.

Considering the above, assessing and reducing the risk of injury to employees is a crucial area of scientific research.

One of the key documents regulating approaches to risk assessment is the international standard GOST R ISO/IEC 31010 “National Standard of the Russian Federation. Risk Management. Risk Assessment Methods”[3]. This standard describes a wide range of risk assessment methods, each of which has its own scope and specifics of practical implementation. Table 1 presents some of these methods.

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[1] *Analysis of Occupational Injuries in Russia:* Federal State Budgetary Institution “All-Russian Scientific Research Institute of Labor” of the Ministry of Labor and Social Protection of the Russian Federation. 2025 Report. (In Russ.)

[2] *On the Increase in Occupational Injuries:* Letter No. 15-3/10/V-11850 of the Ministry of Labor and Social Protection of the Russian Federation dated July 14, 2025. (In Russ.)

[3] *National Standard of the Russian Federation. Risk Management. Risk Assessment Methods:* GOST R ISO/IEC 31010. Order of the Federal Agency for Technical Regulation and Metrology dated September 24, 2021 No. 1011-st. (In Russ.)

Table 1

Review of occupational risk assessment methods

No.	Method name	Description	Advantages	Disadvantages
1	Delphi method	A method of summarizing expert opinions based on an anonymous survey and a multiple iterative process of agreeing opinions	It is suitable for solving complex issues where there are no unambiguous scientific approaches or insufficient statistics. High probability of getting an objective assessment	Time length of the procedure: conducting multiple survey cycles takes a significant amount of time. High dependence of the results on experts' competence
2	Checklists	A form of identification and analysis of potential occupational risks by compiling a list of questions and verification criteria	Simplicity of implementation and accessibility of understanding by employees of different skill levels. Ease of use as a primary control tool	Complexity of developing high-quality and complete checklists, especially for large enterprises with a variety of workflows
3	Event tree analysis	Assessment of the occurrence of undesirable consequences by step-by-step consideration of the sequence of possible outcomes of each event	Visibility, the possibility to take into account a variety of factors and conditions that affect the development of the situation	Dependence on data quality, limited probability estimates (presupposes the availability of a statistical base for calculating probabilities)
4	Failure modes and effects analysis (FMEA)	It is used to identify potential system malfunctions and analyze possible causes of defects	Improvement of the reliability of equipment and machinery by identifying critical units and components	It requires significant time and efforts of qualified specialists for a detailed analysis
5	Hazard and Operability Study (HAZOP)	An in-depth study of the technological process by a group of experts. The analysis is conducted sequentially for each element of the system, assessing possible deviations from the normal operating mode	A clear analysis procedure allows you to identify hidden threats, considers a wide range of possible deviations and consequences	Labor-intensive; the method is difficult to apply to large complex objects without simplifications
6	Bayesian method	It is used to estimate the probability of occurrence of undesirable events based on available a priori information and new incoming data	Reduction of the degree of subjectivity of the assessment. The ability to quickly respond to new data and improve prediction accuracy	Dependence on the quality of a priori data. It is difficult to accurately determine the probability of rare events

The existing tools for occupational risks assessment are mainly limited by the traditional approach based on the analysis of the probability of an accident and the severity of its consequences. However, the level of production safety is determined by the degree to which the impact of hazardous production factors on workers is limited by consistently placing "barriers" between the source of potential hazard and the object at risk. Therefore, when assessing the risks of injury, it is important to consider the condition of these "barriers", which minimize the impact of hazardous production factors. An assessment of the risk of injury should be conducted at the source of its formation at a specific workplace, taking into account the interaction of the employee with a specific hazard and the state of protective mechanisms.

The Haddon methodology [2], developed in the field of transport safety, has been successfully used to identify weaknesses in the safety system. The application of a similar approach in the industrial environments holds promise for the development of injury risk assessment practices. However, available publications on barrier safety models are limited to individual implementation examples — they do not offer a universal method for quantifying the effectiveness of barriers in relation to industrial production. Therefore, the current practice of occupational risk assessment requires the development of a new tool for comprehensive assessment of the effectiveness of safety barriers and their management optimization. To address this gap, this research aims to develop a methodology for applying a barrier-oriented approach based on the Haddon model for assessing injury risks to personnel.

To achieve this goal, we have solved the following tasks:

− we analyzed modern methods of occupational risk assessment and determined their limitations;

− we proposed a method for calculating the probability of the realization of hazardous production factors, based on the assessment of safety barriers reliability, determined in accordance with the Haddon model;

− we conducted an assessment of the probability of hazards associated with lifting and moving goods using lifting facilities.

An overview of the existing barrier modeling methods. In Russian-language sources, one of the first mentions of safety barriers can be found in the materials of the Russian-Norwegian Barents 2020 project[4]. This project aimed to assess the impact of Arctic conditions on the effectiveness of protective barriers. The emergence and development of the barrier concept was driven by the need to evaluate the efficiency of technical and organizational protection measures used at the facility [3, 4].

Currently, Russian regulatory practice in the field of occupational risk assessment includes recommendations on the use of a barrier safety model. Thus, the “Recommendations on the Choice of Methods for Assessing Occupational Risk Levels and Reducing Such Risks”[5], approved by Order No. 926 of the Ministry of Labor and Social Protection of the Russian Federation dated December 28, 2021, contain the following approaches:

1. Bow Tie method, as described in [5, 6], allows for assessing the completeness of a protection system for an analyzed object. Its advantage is visual representation of the relationships between potential hazard sources and negative consequences through a central point (“undesirable event”). This method has become widespread due to its clear presentation and versatility. However, it does not always provide the quantitative estimates necessary for prioritizing preventive measures.

2. Layer of Protection Analysis, discussed in [7, 8], is a quantitative assessment of the reliability of protective barriers based on their probabilistic failure characteristics. This method is recommended for justifying the need for setting new barriers or upgrading the existing ones.

The described approaches form the methodological basis of the barrier protection concept aimed at reducing the risk of injury. However, they have a number of limitations that reduce their effectiveness in production practice:

− they are focused on local objects and individual hazardous situations, which leads to a fragmented analysis and does not allow identifying the interrelationships between the safety system elements;

− they rely on statistical data on the probability of negative events and the effectiveness of the existing barriers. However, these assumptions can be inaccurate if the operating conditions of the equipment change. This requires regular updates to the source data, adjustments to calculation models, and it complicates risk management;

− the influence of organizational and human factors on the safety of production can be not sufficiently considered.

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[4] *Assessment of International Standards for the Safe Exploration, Production and Transportation of Oil and Gas in the Barents Sea:* Barents 2020 Project Report. (In Russ.)

[5] *Recommendations on the Choice of Methods for Assessing Occupational Risk Levels and for Reducing Such Risks:* Order No. 926 of the Ministry of Labor and Social Protection of the Russian Federation dated December 28, 2021. (In Russ.)

The idea of considering the reliability of barriers when assessing injury risks, as developed in Russian studies [9, 10], partially addresses these limitations. However, there is still a need to consider additional criteria, such as:

− the dynamics of the condition of barriers due to natural wear and tear (technical barriers) and changes in regulations (procedural and behavioral barriers);

− human factor as an indicator of the correct interaction between personnel and equipment and protective equipment.

Thus, despite the advantages, the considered methods have disadvantages that prevent their full implementation in the practice of injury risk management. This requires the development of a comprehensive methodology that combines the advantages of quantitative analysis with adaptability to changing operating conditions and the ability to take into account both engineering, organizational and psychological aspects of the safety system. The development of such methods will create a solid foundation for effective risk management.

Materials and Methods. The proposed method was based on a single mechanism for the industrial accident occurrence: a person in a production facility came into contact with an object (equipment, tools, materials) with enough energy, making it hazardous for humans [11, 12]. In 80–90% of accidents, the triggering factor of hazardous situations was the active (intentional or erroneous) actions of the victims themselves [13, 14]. Considering Article 209 of the Labor Code of the Russian Federation[6], we propose to determine the personal risk of injury during an accident at the source of its occurrence (specific location), taking into account the hazards and the influence of the human factor as follows:

$$R = \sum P_j \cdot W \cdot F_j, \tag{1}$$

where P_j — probability of occurrence the j-th hazardous production factor; W — employee's tendency to risk injury; F_j — severity of negative consequences when exposed to the j-th hazardous production factor.

The assessment of the probability of implementation of the j-th hazardous production factor was conducted using the example of the operational personnel of the metallurgical industry enterprise according to the following algorithm. At the first stage, the identification of hazardous production factors affecting the employee during labor operations was carried out. The sources of identification information were:

− workplace examination;

− work supervision;

− staff survey;

− analysis of regulatory legal acts;

− analysis of local regulatory legal acts of the enterprise.

Identification was carried out for all objects of research — types of work, places of work, non-standard and emergency situations.

At the second stage, an electronic checklist was developed for each identified factor that could potentially lead to an accident (Table 4) using the MCForms online service. Column 2 of the checklist was formed in accordance with the Haddon model and had a universal character for all hazardous production factors, regardless of the specifics of production. Column 3 of the checklist contained the most important safety requirements stipulated by regulatory legal acts and local acts of the production facility (standards, regulations, labor protection instructions, and technological instructions) that could interfere with the transfer of energy from a source (equipment) to a person — failure to comply with these requirements could lead to an accident at work. To implement the risk-based approach, such critical requirements were selected and adapted to the specifics of a particular production facility, taking into account the design features of the equipment and operating conditions using the Bow Tie method (Fig. 1). Column 4 of the checklist contained the effectiveness of protective barriers determined in accordance with [15].

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[6] *Labor Code of the Russian Federation:* Federal Law No. 197-FZ dated December 30, 2001. (In Russ.)

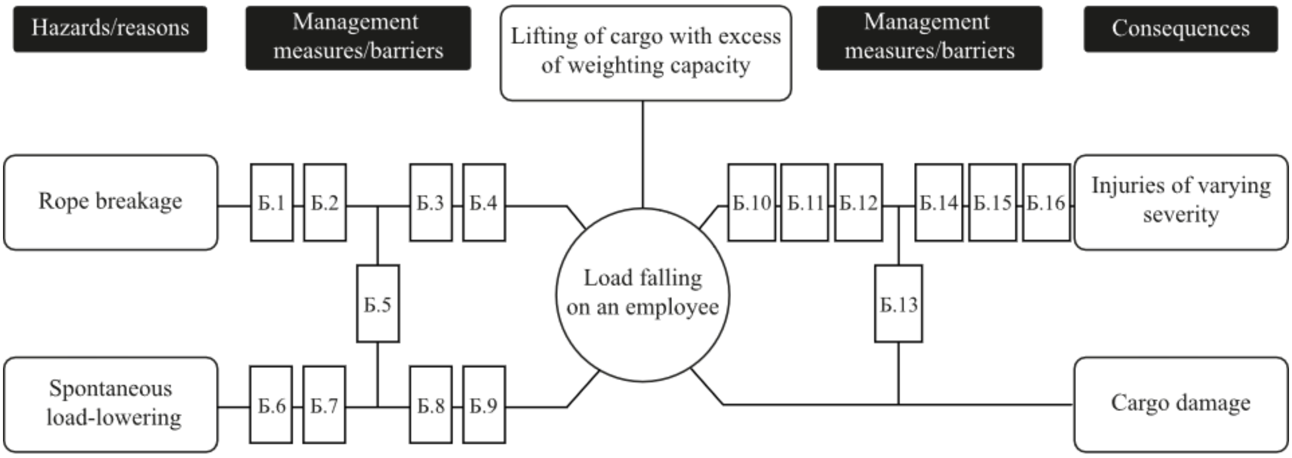

Fig. 1. Bow Tie risk analysis: Б1 — assessment of the rope condition by the crane operator before starting work; Б2 — instrumental control of rope wear; Б3 — load limiter; Б4 — overwinding switch; Б5 — absence of people in the danger zone; Б6 — assessment of wear on the brake pads of the main hoist; Б7 — zero blocking check; Б8 — lifting the load to a safe height; Б9 — routine maintenance; Б10 — protective fencing of hazardous areas; Б11 — warning signal; Б12 — use of PPE; Б13 — emergency response skills; Б14 — first aid training; Б15 — operational communication with the medical service; Б16 — first aid kit

At the third stage, the heads of production sites assessed the functioning of safety barriers according to a checklist as part of monitoring the state of occupational safety using QR codes placed at risk sites, in accordance with the scale presented in Table 2. The results of the production control of serviceability of the protective fences were entered into the MCForms electronic system (column 5 of the checklist). As a model example, we considered a situation in which the person responsible for maintaining a lifting structure evaluated safety devices together with the HD operator during periodic inspections within the time limits set by the schedule. Value "0" in terms of efficiency was set in the absence or malfunction of the device, value "1" — in the presence of technical comments without limiting performance (for example, the HD hook lift limiter was triggered when the distance between the hook and the winch was 100 mm at a speed of 200 mm or more). Value "3" was assigned with full technical serviceability in accordance with the technical data sheet of the device. At the same time, when calculating the probability of hazard occurrence according to formula (2), we did not use a specific expert assessment, but a generalized assessment based on the maximum possible number of points.

At the fourth stage, the mathematical processing of the results of the assessment of the probability of hazard realization was conducted and the values obtained were attributed to the levels of realization of hazardous production factors using Excel.

Results. Probability indicator of the identified hazardous production factors (P_j) from formula (1) was proposed to be evaluated taking into account the criteria of the dynamic state of safety barriers as follows:

$$P_j = \prod_{i=1}^{n} \left(1 - E_i \cdot N_i \cdot S_i\right), \tag{2}$$

where E_i, N_i, S_i — effectiveness, efficiency and stability of the i-th safety barrier, respectively ($i = 1, 2, \dots n$) during its operation.

Effectiveness (E_i), reflecting the importance of the barrier in the safety system of the production facility, was determined in accordance with GOST 12.0.011-2017 "Methods for Assessment and Calculation Risks of Railway Employees", approved by Order of the Federal Agency for Technical Regulation and Metrology dated December 22, 2017 No. 2065-st[7].

The assessment of safety barrier efficiency (N_i), which was a factor of serviceability, was evaluated according to the criteria in accordance with the scale and is presented in Table 2.

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[7] *Occupational Safety Standards System. Methods for Assessment and Calculation Risks of Railway Employees:* GOST 12.0.011-2017. Order of the Federal Agency for Technical Regulation and Metrology dated December 22, 2017 No. 2065-st. (In Russ.)

Table 2

Criteria for safety barriers effectiveness

Level	Description of the condition	Value
Satisfactory	Condition corresponds to the set level	3
Acceptable	Condition does not fully correspond to the set level	1
Critical	Safety barrier is not functioning	0

Stability (S_i), which characterized the frequency of detected inconsistencies in the functioning of safety barriers, was calculated using the formula:

$$S_i = e^{-\lambda t}, \tag{3}$$

where $\lambda = b/B$ — coefficient of the frequency of nonconformities; b — total number of nonconformities; B — number of performance checks (for a technical barrier)/the number of functional checks (for an organizational barrier); t — analyzed period ($t = 1$, if the analyzed period was 1 year).

The prioritization of the implementation of occupational safety measures was conducted depending on the estimated risk level of the hazard (Table 3).

Table 3

Realization level of hazardous production factors

Probability of hazard realization	Risk category of injury	Urgency of measures
0	No risk	No measures are required
<0.24	Moderate	Measures with deadlines for elimination are required
0.25–0.49	Significant	Urgent measures are required
0.5–1.0	High	It is required to stop work before the implementation of measures

As an example of application of the proposed methodological approach, an assessment was made of the probability of hazardous situations involving lifting and moving goods using hoisting devices. The assessment was conducted for the hoisting device operator of a metallurgical enterprise that performed slinging and strapping of goods before their subsequent movement by an overhead crane (hereinafter referred to as the HD operator). To analyze this hazardous production factor, a checklist was developed, a fragment of which is presented in Table 4.

Table 4

A fragment of the checklist for checking the functioning of safety barriers for hazards associated with lifting and moving goods using hoisting devices

No.	Safety barrier group function	Test object	Effectiveness (E_i)	Efficiency (N_i)	Sustainability (S_i)
1	2	3	4	5	6
1.	Prevention of energy release	1.1 Condition of metal structures and tooling	0.9	3	1

2.	Condition of metal structures and tooling	2.1 A device that restricts the lifting of the load-handling device above the maximum permissible level	0.8	2	0.51
		2.2 Emergency switch for HD de-energizing in emergency situations	0.8	3	0.71
3.	Installation of protective structures	3.1 Fences, other control systems that accidental sudden entry into the dangerous area	0.7	1	0.36
4.	Danger warning	4.1 Sound signal	0.6	1	0.71
		4.2 Device indicating excess of weighting capacity	0.6	3	1
5.	Description of procedures for handling hazards	5.1 Working methods for crane operators and slingers	0.5	0	0.51
		5.2 Meeting the schedule of maintenance and control procedures	0.5	3	1
6.	Readiness to perform official duties (training, medical examination)	6.1 Crane operators and slingers are trained, have successfully completed an internship and knowledge test	0.2	0	0.51
		6.2 No contraindications for health reasons	0.2	3	1
7.	Provision of PPE	Workwear suit	0.1	1	0.71

Column 6 of the checklist indicates the stability of safety barriers (S_i). This is generated automatically based on the results of ongoing assessments of safety barriers during the calendar year. For example, during the year, three health checks were carried out on barrier 3.1 of the model example shown in Table 4. During two inspections, comments were made about its serviceability. Thus, the stability coefficient (S_i), calculated by formula (3), will be equal to

$$S_i = e^{-0.67\cdot 1} = 0.51.$$

The probability of the realization of hazards associated with lifting and moving goods using hoisting devices, calculated by formula (2), in this example is:

$$P_{\text{ПС}} = (1-0.9\cdot 1\cdot 1)\cdot(1-0.8\cdot 0.7\cdot 0.51)\cdot(1-0.8\cdot 1\cdot 0.71)\cdot(1-0.7\cdot 1\cdot 0.36)\cdot$$
$$\cdot(1-0.6\cdot 0.3\cdot 0.71)\cdot(1-0.6\cdot 1\cdot 1)\cdot(1-0.5\cdot 0\cdot 0.51)\cdot(1-0.5\cdot 1\cdot 1)\cdot(1-0.2\cdot 0\cdot 0.51)\cdot$$
$$\cdot(1-0.2\cdot 1\cdot 1)\cdot(1-0.1\cdot 0.3\cdot 0.71) = 0.025.$$

According to Table 3, this corresponds to a moderate risk of injury, which requires the planned development of measures with a time frame for elimination.

Discussion. The proposed barrier-oriented approach to occupational risk assessment is fundamentally different from traditional methods that focus primarily on the frequency and severity of accidents. The main advantage of the new method is the assessment of the effectiveness, efficiency and sustainability of safety barriers in the workplace. The use of a barrier model based on the Haddon concept involves the creation of a multi-level protection system, each level of which is aimed at reducing the probability of exposure to a hazardous production factor. This concept integrates a comprehensive injury prevention system combining technical, organizational, and behavioral measures.

The literature review confirms the consistency of the presented conclusions with the results of studies [9, 10], emphasizing the importance of barrier safety systems in the prevention of occupational injuries. At the same time, the previously proposed methods focus on evaluating the effectiveness of individual barriers, while this study takes into account the dynamics of changes in their functions. The dynamic nature of the model makes it possible to reflect changing operating conditions that affect the reliability and stability of protective mechanisms, which increases the effectiveness of preventive measures. Thus, the application of the proposed approach provides occupational safety specialists and production managers with the opportunity:

− to obtain a more complete and accurate assessment of the level of workplace safety;

− to substantiate preventive measures aimed at preventing occupational injuries when addressing the expediency of their implementation;

− implement preventive measures in a timely manner;

− predict possible undesirable events.

The advantage of the approach is its compatibility with operational monitoring tools, for example, with any forms of production control operating at the facility in question. This improves the quality of production control, the lack of which, in turn, caused 61.5% of injuries in the Russian Federation in 2024 due to poor organization of work.

Despite these advantages, the barrier-oriented approach has limitations in versatility and scalability. Adaptation to the specifics of different industries and specific production conditions is required. The complexity of the implementation is associated with the need to collect, accumulate and process a large amount of information on the current state of barriers and the history of their failures. In order to obtain a reliable assessment of the probability of a hazard, strict requirements are placed on the accuracy and completeness of data on the criteria of efficiency (N_i) and sustainability (S_i) of safety barriers. At the same time, the human factor in the preparation of the initial data remains a potential source of errors.

Overcoming these limitations can be achieved through the expansion of the amount of statistics collected, the development of a software module that implements the proposed model, the introduction of modern technologies for monitoring the technical condition of facilities and the use of machine learning methods. These measures will allow for continuous monitoring of the state of safety barriers and increase the accuracy of hazard probability assessment.

Conclusion. As a result of the research, a barrier-oriented approach to assessing and managing the risk of injury to personnel has been developed, based on the effectiveness and sustainability of safety barriers. It is shown that the proposed model can be integrated with existing operational monitoring systems in the field of occupational safety, which contributes to improving the quality of risk management.

It has been established that the practical application of the approach is constrained by the need for reliable data on barrier conditions and failures, as well as human error in the collection of initial information. These constraints limit the flexibility and scalability of the model, necessitating its adaptation to the specifics of individual industries and production conditions.

The potential for future research is linked to expanding the statistical database, creating a software module based on the proposed model, and utilizing modern technologies for monitoring the technical condition of facilities, and machine learning methods to automate data collection and processing. This will ensure continuous monitoring of the state of safety barriers and increase the accuracy of hazard probability assessment.

Thus, the proposed approach is of practical significance for managing the risk of injury to personnel and can help reduce the level of occupational injuries.

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Conflict of Interest Statement: **the author declares no conflict of interest.**

The author has read and approved the final version of manuscript

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Конфликт интересов: **автор заявляет об отсутствии конфликта интересов.**

Автор прочитал и одобрил окончательный вариант рукописи.

Received / Поступила в редакцию 22.12.2025
Reviewed / Поступила после рецензирования 16.01.2026
Accepted / Принята к публикации 28.01.2026