# TECHNOSPHERE SAFETY
# ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

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Original Empirical Research

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

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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

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*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

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**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.

[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.



[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].



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

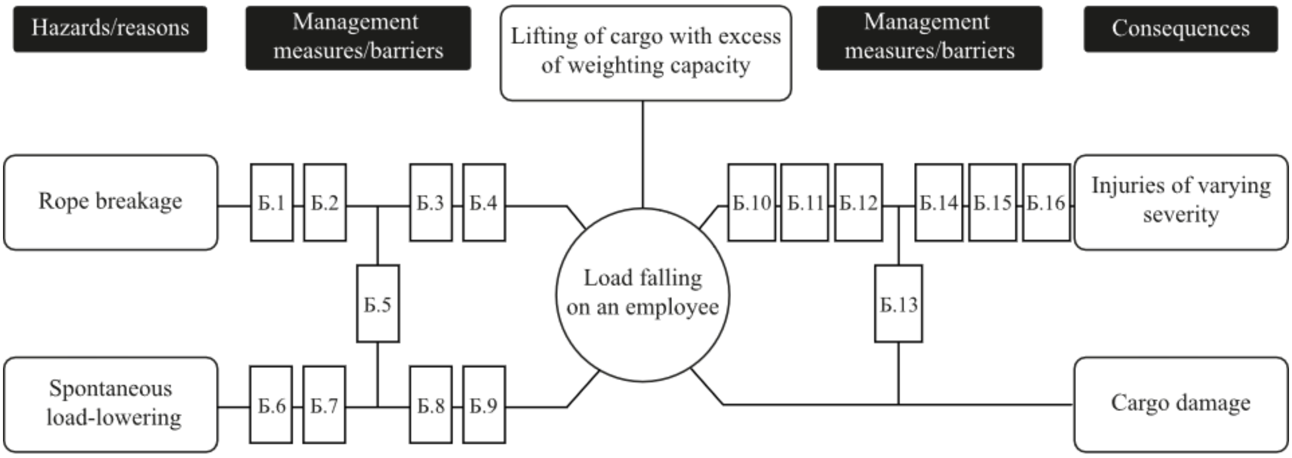


Fig. 1. Bow Tie risk analysis: Б1 — assessment of the rope condition by the crane operator before starting work; Б2 — instrumental control of rope wear; Б3 — load limiter; Б4 — overwinding switch; Б5 — absence of people in the danger zone; Б6 — assessment of wear on the brake pads of the main hoist; 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, … $n$) 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.

[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:

$$P_{\text{ПС}} = (1-0.9\cdot1\cdot1)\cdot(1-0.8\cdot0.7\cdot0.51)\cdot(1-0.8\cdot1\cdot0.71)\cdot(1-0.7\cdot1\cdot0.36)\cdot$$
$$\cdot(1-0.6\cdot0.3\cdot0.71)\cdot(1-0.6\cdot1\cdot1)\cdot(1-0.5\cdot0\cdot0.51)\cdot(1-0.5\cdot1\cdot1)\cdot(1-0.2\cdot0\cdot0.51)\cdot$$
$$\cdot(1-0.2\cdot1\cdot1)\cdot(1-0.1\cdot0.3\cdot0.71) = 0.025.$$

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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