EDUMALSYS
Journal of Research in Education Management

e-ISSN : 2988-1188
p-ISSN : 2988-1196

Index : Dimensions, Scilit, Crossref, Garuda, Semantic, Google Scholar, Base, etc

https://doi.org/10.58578/edumalsys.v4i1.8457

Risk Assessment Based on Factor-Parametric Modeling

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Article Info:

Submitted:	Revised:	Accepted:	Published:
Dec 20, 2025	Jan 17, 2026	Feb 5, 2026	Feb 22, 2026

Abstract

This article presents a scientific analysis of a factor-parametric modeling method that enables systematic risk assessment within labor protection management systems. It develops a logical basis for risk by constructing a factor-parametric framework for the "factors–object–protection–employee" system, conceptualized as a complex of fuzzy sets representing different configurations of factor and parameter types. At the core of this framework is the "v–f–r" model ("impact–mitigation–sensitivity"), which formalizes the interconnection between risk-inducing impacts (v), mitigating protection systems (f), and the sensitive object, i.e., the human (r). The condition for risk occurrence is evaluated by examining the balance and interaction among these components, thereby allowing the quantification and qualification of risk levels under varying combinations of impacts, protective measures, and human sensitivity. The proposed model contributes to the refinement of risk assessment methodologies by integrating factor-parametric modeling with fuzzy set representations, supporting more nuanced evaluation of occupational hazards and informing the design of more effective protection systems in labor protection management.

Keywords: Risk Assessment; Factor-Parametric Modeling; Fuzzy Sets; Occupational Safety; Protection Systems

Introduction

Currently, the effective development of systematic labor protection management at industrial enterprises places significant emphasis on issues of systematization, modeling, and the assessment of the complex of risks arising in production processes. This necessitates the analysis of the "factors–object–protection–employee" technical system and its internal and external factors, as well as the substantiation of interconnections between system components. Consequently, the possibility arises to create a universal model of the relationships and interactions among all factors within the system.

Methodology

The research employed methods of bibliographic comparative analysis, semantic analysis, generalization, risk theory, as well as probability theory, technical diagnostics and computer modeling, planning of practical research, and mathematical-statistical processing of results.

Results and Discussion

Based on the assessment of hazards arising during production processes, an enterprise gains the following capabilities [1]:

• obtaining maximally objective information about existing risks and hazards, as well as working conditions affecting employees;

• developing a nomenclature of hazards, classifying them according to their level of risk, identifying the most vulnerable points in occupational safety, and developing measures aimed at managing hazards and reliably ensuring employee safety;

- developing preventive and regulatory measures to protect workers from risks, in accordance with the priority order established by relevant safety standards.

- obtaining detailed information for making decisions regarding the management of potential hazards.

It is deemed appropriate to utilize a factor-parametric-based methodological approach for the reliable assessment of the set of risk factors, their parameters, and safety indicators to achieve the aforementioned results. For a precisely defined workplace, developing a factor-parametric basis is required to describe risks and potential hazards within the "factor-object-protection-worker" technical system. This basis consists of theoretical foundations and production-related physical quantities (energy, concentration, heat flux density, electromagnetic radiation, noise, vibration, etc.).

The primary goal of the research is to develop and practically apply accident models and to substantiate their connection with the main components that lead to adverse consequences.

Currently, while logical and parametric models of accidents and adverse consequences have been created, the method for their quantitative assessment is not fully developed as a complete logical system, and methodologies for ranking (classifying) working conditions have not been thoroughly studied. Consequently, there is a probability of errors arising in the results of comparative analysis of workplaces. Regarding these issues, scientists such as K.V. Frolov, N.I. Makhutov, I.A. Ryabinin, V.P. Gaenko, G.Z. Faynburg, V.A. Bolotin, B.Ch. Meshki, V.V. Novikov, A.A. Korotkiy, S.V. Belov, A.G. Fedorets, N.P. Barsukov, A.S. Batugin, F.Ya. Yakubov, Yu.I. Bulygin, and E.M. Lyumanov have conducted extensive research and achieved practical results. However, the fact that workplaces possess varying levels of potential hazards, the unexpected occurrence of these hazards, and the need to improve methods for their prediction and assessment underscore the importance and urgency of advancing scientific research in this field.

The research employs the factor-parametric modeling method, which enables risk assessment.

This method is fundamentally based on the following:

1. A logical framework of risks structured in accordance with the labor protection management system;

2. The factor-parametric basis of the "Factors – Object – Protection – Employee" system, which is a complex of fuzzy set signatures with various collections of factor and parameter types.

The logical basis of risks and hazards consists of a set J = {j} of HSE indicators (factors) and a set I = {i} of conditions (outcomes) of their impact on an employee or HTO (hazardous technogenic object):

$$YB = \{aji\}, \quad (1)$$

where:

a = 0; if a = 1, then condition *i* is applied to factor *j*, and the sum of the indicators becomes equal to:

$$\sum_1^{29} \sum_1^{v} = 154 \quad (2)$$

where:

— According to the Regulations of the Labor Protection Management System, the number of factors is accepted as 28 and the number of parameters is accepted as 154.

We develop the factor-parametric basis on the following sets:

- a set of influencing and susceptibility parameters;

- a set of criteria for parameters where influence exceeds susceptibility;

- a group of processes based on a fuzzy set signature.

This basis was introduced for the following purposes:

- to fully and uniformly describe all factors (to the extent possible) of accidents occurring within the defined system;

- to calculate numerical measures of the probability of accidents occurring;

- to conduct a comparative analysis of occupational safety conditions for employees at different enterprises;

- to systematize all identified risks and hazards and to numerically assess the influencing hazards.

Modeling the occurrence of accidents or adverse events in the system can be described using cause-and-effect analysis via factor-parametric models in the form of "load – bearing capacity" and "impact – sensitivity level". In this context, the occurrence of an adverse event is often assessed based on the condition that the impact parameter (magnitude) "s" exceeds the sensitivity level parameter "r", i.e., (s > r). Based on this criterion, we introduce the following Boolean set (a mathematical set whose elements can take only one of two conventional values: "yes" (True, 1) or "no" (False, 0). Its main characteristic is operation based on binary logic):

$$YX=\{x_{ji}\} \qquad (3)$$

Here, each Boolean variable x_{ji} (yes=1 or no=0) indicates whether or not its corresponding criterion b_{ji} (i.e., the condition s > r) is satisfied. The set of all x_{ji} variables constitutes the complete set of potential causes (indicators) leading to an adverse outcome. Therefore, b_{ji} → x_{ji}.

x_{ji} — Boolean variable indicating the exceedance of the criterion;

The variable x_{ji} takes only two values:

1 (yes), if the condition s > r (criterion b_{ji}) is true (impact is strong);

0 (no), if s ≤ r (impact is weak).

Thus, it is a signal of whether this logical condition is met or not.

x_{ji} = 1, if (s > r)_{ji}

In the "Protection – Object – Environment" system, depending on the accuracy, completeness, and reliability of practically applicable data for the parameters *s* and *r*, the maximum possible value of the outcome or its exceedance can be expressed as a necessity measure n = Nec(t), a probability measure p = Pro(t), or a possibility measure π = Pos(t) for ensuring the safety of working conditions [2, 3].

Normalized on the real number interval [0,1], these measures for a single, separately considered criterion are in the following relationship [4,5,6]:

$$Nec\ (S > r) \leq Pro\ (s > r) \leq Pos\ (S > r), \qquad (4)$$

Here, *s* and *r* are expressed respectively as follows:

for the Nec operator – as deterministic (precise) quantities;

for the Pro operator – as random variables;

for the Pos operator – as fuzzy quantities (parameters), which constitute the parametric model for realizing the outcome at the highest level.

For any accident, the fundamental relationship between the numerical measures of safety assurance—"necessity measure," "probability measure," and "possibility measure"—is defined and described.

In such cases:

- if the "factors – object – protection – worker" system is deterministic, then the measure takes one of two values: 0 or 1.

- if the "factors – object – protection – worker" system is random, and the probability distribution densities φ(s) and φ(r) of the random variables *s* and *r* are known, then the probability of the condition (s ≥ r) occurring is found based on constructing the parametric model of "impact s – sensitivity r".

This system allows for the selection of the following parametric model as "universal" for determining the numerical measure of accident occurrence:

V = {v} (impact) - F = {f} (mitigation) - R = {r} (sensitivity) (5)

In a single-parameter expression, model (5) takes the following form:

"v – f – r", (6)

here:

v – the parameter of the influencing factor;

f – the mitigation function of the influencing factor, defined on the real number interval [0,1].

Also:

the condition f = 0 represents the complete mitigation of the hazardous factor's impact.

the condition f = 1 describes the absence of protection against the hazardous factor.

mitigation conditions for an "external" impact *v* at three levels of protection:

f_1 = 0.001 – practically complete mitigation of the hazardous factor's impact;

f_2 = 0.01 – mitigation of the hazardous factor's impact up to the level of 1% (satisfactory protection);

f_3 = 0.1 – mitigation of the hazardous factor's impact up to the level of 10% (poor protection).

r – is the sensitivity parameter of an object, element, or subject (human) to the impact of a hazardous factor. It describes the change in state, the emergence of conditions necessary for an accident to occur, or the possibility of an accident happening. Similar to impact parameters, sensitivity parameters are often expressed through fundamental or derived quantities of the International System of Units (SI) [4,5].

Furthermore, the Pos(•) operator is the possibility operator.

The sets in expressions (3) and (4) – the set of risk impacts V, the set of risk mitigation F, and the set of risk sensitivity R – together with the fuzzy sets (5), constitute the system's factor-parametric basis (FPB).

Conclusion

In conclusion, it can be emphasized that factor-parametric risk modeling is a scientific-methodological approach for analyzing and assessing risks and hazards. In this method, a risk (e.g., industrial accidents) is modeled through various factors and their numerical parameters. The model considers the interconnections between risk-inducing impacts (v), mitigating protection systems (f), and the sensitive object (human) (r) [4,5].

Its main components are taken as follows:

V = {v} – the impact set: the numerical parameter of a risk/hazard factor (e.g., voltage, temperature, substance concentration).

F = {f} – the mitigation set: a function indicating the extent to which a protection system reduces the impact (from 0 to 1, or 0% to 100%).

F=0 – complete protection, f=1 – no protection.

R = {r} – the sensitivity set: a parameter indicating the resistance limit of an object, device, or person to a specific impact (e.g., rated maximum voltage, heat resistance level).

Accordingly, in our research, the "v – f – r" model (i.e., "impact – mitigation – sensitivity") has been adopted as the primary model, and the condition for risk realization is assessed as follows [6,7]:

- if the impact (v) exceeds the object's sensitivity threshold (r), an accident occurs. However, in this relationship, mitigation (f) affects the impact value: the actual impact is expressed by the value v * f.

- the final condition for a hazardous outcome takes the form $v * f \geq r$. That is, if the mitigated impact exceeds the sensitivity threshold, an accident occurs.

This model enables the following:

- quantitative risk assessment: expressing the probability of risk occurrence in numerical terms;

- analysis of the effectiveness of protection systems (parameter f);

- development of safety-enhancing scenarios ("What if the impact doubles, but we improve protection (reduce f from 0.1 to 0.01)?");

- determining which risk management measures (reducing impact, strengthening protection, raising the sensitivity threshold) are more effective [8].

Factor-parametric risk modeling involves reducing the complex nature of potential hazards into a simple and analyzable parametric model. It holds significant importance for engineers, occupational safety specialists, and researchers in scientifically assessing risks, predicting them in advance, and developing effective mitigation strategies.

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