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# Methodology for multi-criteria assessment of working conditions as an object of qualimetry

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ABSTRACT
The article considers several modern scientific papers substantiating the need for assessing workplace safety and focusing on methods applied for the quantitative assessment of working conditions. The analysis found unsolved problems in qualimetry, which could lead to the development of new practical and generally applicable methods to effectively assess working conditions. The analysis proved the relevance of the topic and helped to determine the aim of the article, i.e., the development of a methodology for the quantitative assessment of working conditions in industries, considering harmful production factors. An exponential distribution, which belongs to the theory of extreme statistics, was proposed for the transition of heterogeneous single indicators of harmful factors into a dimensionless scale. Affine transformations were used to combine dissimilar scales, making it possible to divide segments on dissimilar scales into equal proportions. The article proposes a step-by-step method for determining a complex indicator of working conditions in industries. The proposed methodology allows management decisions that minimise the deviation in actual values of harmful factors from the optimal ones. The developed technique was tested at one specific metallurgical production site.

KEY WORDS
**methodology for assessment, multi-criteria assessment, workplace safety, qualimetry object, complex indicator quality, management system**

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## Introduction

The successful development of a manufacturing enterprise, ensuring the competitiveness of products and achieving the set strategic goals requires not only improving technologies but also safe working conditions. Workplace safety management systems encompass the processes of identification, control, assessment and management, thus ensuring integrated support. An effective control system requires a scientifically grounded methodology for the quantitative assess-

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ment of harmful factors to control and minimise their impact on the human body, considering the characteristics of technological processes.

Technological processes are characterised by the weight and intensity of the work performed; type of working conditions; ergonomics of the workplace; technology safety; the level of technological discipline; the general organisation of the working process; and harmful and dangerous factors. A complex assessment of the state of workplace safety at an enterprise necessitates the quantitative indicators of harmful production factors that reflect applicable technological particularities.

Qualimetry methods are used to obtain quantitative indicators for various objects. Qualimetry is a subject of science that studies the methodology for quantitative assessment of the quality of objects and processes. Under the object of qualimetry, this article considers the system of harmful production factors for the health and life of people.

The system of harmful production factors, as an object of qualimetry, has several particularities: the possibility of performing measurements; various units and range of measurements; a different degree of influence on the human body; a different severity of the consequences of the disease; and the possibility of using special protective equipment. Such particularities determine the complexity of problem-solving in quantitative assessment of workplace safety in industries. To solve the problem, different-sized indicators of various factors must be put into a dimensionless scale, making a quantitative assessment of the generalised indicator of the state of workplace safety in industries.

Thus, the article aims to develop a methodology for the quantitative assessment of working conditions in production, considering the particularities of the system of harmful production factors.

The theoretical value of the article is the study of the possibility to use qualimetric methods for assessing working conditions in production. The practical value is the development of assessment methods that can be applied in different industries.

The article presents the literature review results related to the grounding of the need to assess workplace safety and focusing on methods used for assessing working conditions. Besides, it describes the research methodology and presents and discusses the research results. Furthermore, the article summarises the obtained results, explains the study limitations, and indicates the directions for further research. The last chapter also offers conclusions.

## 1. Literature review

The existing level of mechanisation and automation at industrial enterprises determines the impact inflicted on workers by a complex of harmful factors of the production environment and the labour process, i.e., vibration, noise, industrial aerosols, chemicals, psychological stress, moving and lifting loads manually, and fixed and forced working postures (Kukhar et al., 2018). Harmful production factors can cause occupational and general diseases (Schulte, 2005; Schulte et al., 2019). Thus, the mechanism for ensuring workplace safety at industrial enterprises should include processes for identifying and quantitative assessment of obvious and potential hazards to predict and prevent them.

In the article, Levanchuk et al. (2020) determined the safe duration of the exposure to a combination of unfavourable factors present in the working environment based on the application of the methodology for assessing the health risk of workers. The authors used regression formulas to predict the loss of health of locomotive crew drivers and determine age groups with a high degree of probability of a work-related and occupational pathology.

Several publications are devoted to the complex assessment of occupational health in an enterprise and the methodology for assessing the effectiveness of technical measures (Chebotarev & Sementsova, 2021; Shkrabak et al., 2020). The analysis of scientific papers demonstrated the absence of a substantiated mathematical apparatus in the publications. Regression models used as a mathematical analysis are ineffective, and scientific approaches are organisational.

Zavadskas & Turskis (2010) used the ARAS multi-criteria method for assessing the microclimate in an office building. This method uses an auxiliary function that determines the relative effectiveness of different options for assessment. This auxiliary function has a linear relationship between the relative results of the measured values and the weight factor of the criterion under consideration.

The decision matrix risk-assessment method (DMRA) was used by Gul & Guneri (2016) in the developed methodology for assessing risks in the field of safety and health protection. The authors proposed a fuzzy approach that allowed experts to use linguistic variables to assess two factors as parameters of the matrix method, eliminate the disadvantages of accurate risk assessment and reduce inconsistency in decision making.

Cherniak et al. (2020) proposed to use mathematical dependencies to assess the indicators of harmful factors, considering the maximum, minimum and optimal values of the factors and the shape variable. When changing the shape variable, different estimates are obtained on a dimensionless scale. To determine the shape variable, a hierarchy analysis method was applied, which allowed obtaining reliable values with a small number of experts. Similar mathematical relationships have been used to evaluate various other objects (Trisch et al., 2016; Ginevičius et al., 2015).

To prioritise occupational safety and health indices in the construction industry, Yarahmadi et al. (2016) used the TOPSIS method (Technique for Order Preference by Similarity to an Ideal Solution) (Beinoraitė, & Drejeris, 2014; Vavrek et al., 2017). This method is one of the most popular, most commonly used, theoretically based multi-criteria methods. The principle of the method is that from the variants being compared, the object that has the smallest difference from the best variant (by the total amount of all criteria) and the largest difference from the worst variant will be approved as the best.

Gul (2018) performed a critical review of the current state of research on risk assessment in the field of workplace safety using MCDM-based approaches.

The analysis of scientific materials showed that different multi-criteria methods for assessing harmful production factors are used in various production environments. However, each production is unique, and each workplace differs by hazardous and harmful factors. Therefore, this study aimed to develop a universal methodology for the quantitative assessment of working conditions in industries using qualimetric methods, considering their characteristics as an object of qualimetry.

## 2. Research methods

In the process of labour, a human is affected by harmful and dangerous factors, which can cause health deterioration and the loss of productivity. Different units and measurement ranges of harmful and hazardous factors lead to the difficulty in drawing a conclusion about a comprehensive quantitative assessment of the state of workplace safety.

For the transition of the dimensions of harmful and hazardous factors into a dimensionless scale, it is proposed to apply non-linear mathematical relationships between the measured indicators of harmful production factors and their estimates on a dimensionless scale. As mathematical dependencies, it is proposed to use the well-known dependencies derived by Gnedenko (1943) and previously applied for assessing the reliability of technical systems, which are related to the theory of extreme statistics. Using the theory of extreme statistics and the proposed mathematical relationships by Gnedenko, Harrington (1965) proposed a method for multi-criteria assessment of residential premises. Later, Azgaldov (1973) used it to evaluate various objects in the field of qualimetry. The methodology developed by Harrington is based on the application of a single mathematical relationship to the assessment of different, sometimes inconsistent assessment criteria. This dependence is expressed by the equation:

$$d_i = \exp[-\exp(-Y_i')] \tag{1}$$

where $Y_i'$ — some dimensionless quantity, in some way related to any of the parameters of the factors $Y_i$.

In qualimetry, functional dependencies are used to assess the quality of various objects. Among the mathematical dependencies, linear and non-linear are used. In each specific case, it is necessary to justify the choice of a dependence. In the article, to assess working conditions in production, it is proposed to use a non-linear form of dependence (1). This is justified by the fact that the rate of change of estimates at the edges of the mathematical dependence has a lower rate than at the middle. That is, the values of harmful factors that are close to the limits of permissible values change slower than in the middle of the permissible values.

The scales on the axes are linked by a mathematical relationship (1). If a single indicator has a quantitative expression, the dependence (1) is used, and the quantitative assessment scale is converted into a logarithmic:

$$f(Y_i') = \ln(-\ln(-d_i)) \tag{2}$$

The correspondence of the two assessment scales is shown in Table 1 and Fig. 1.

To obtain a complex indicator of working conditions, it is proposed to determine the geometric mean of single quality indicators di, that is, it is proposed to make the transition from di to D according to the formula:

$$D=\sqrt[n]{\prod_{i=1}^{n} d_i} \tag{3}$$

where D — complex indicator of working conditions, and n is the number of hazardous and harmful factors.

Such presentation of a complex indicator of workplace safety conditions (2) is justified if at least

Tab. 1. Correspondence of two assessment scales

| **Dimensionless scale** | **0** | **0.2** | **0.37** | **0.63** | **0.8** | **1** |
|---|---|---|---|---|---|---|
| Qualitative scale | Very bad | Bad | Satisfactory | Good | Excellent | |
| Logarithmic scale | -3 | -0.476 | 0 | 0.772 | 1.5 | 3 |

Source: elaborated by the authors based on Harrington (1965).

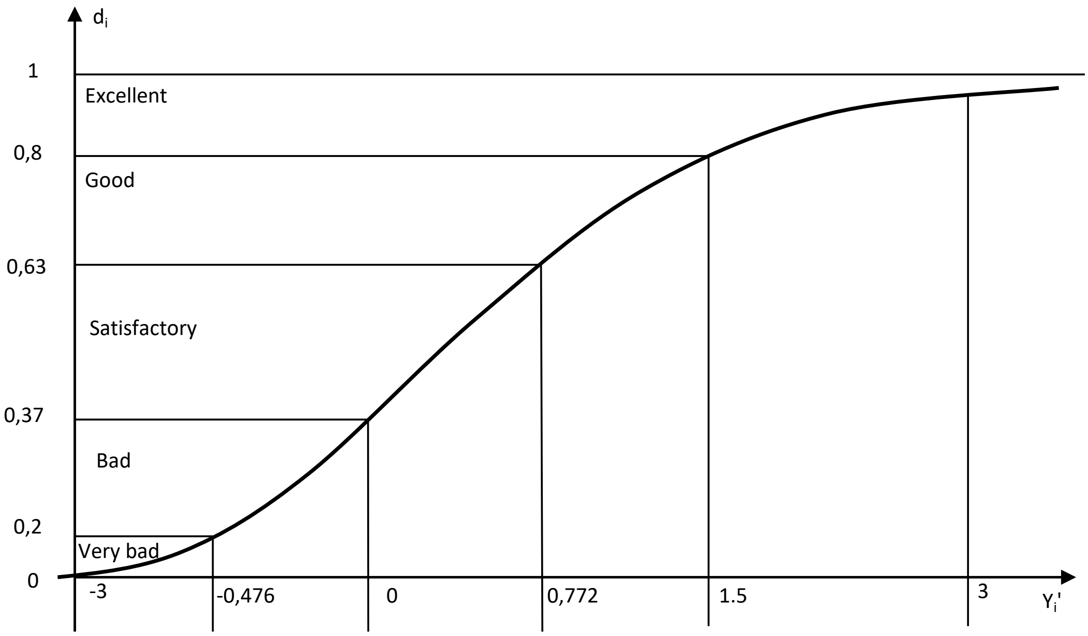


Fig. 1. General view of the mathematical dependence of two scales

Source: Harrington, 1965.

one of the single indicators $d_i = 0$, then D = 0. On the other hand, D = 1, then, and only then, if all $d_i = 1$ (i = 1, 2, ...,n). Therefore, a comprehensive assessment of the indicator of working conditions D, which is extremely sensitive to small values of single indicators di.

To determine the complex indicator of working conditions D, it is necessary to determine the transition from a separate dimensional factor $Y_i$ to dimensionless Y'. To convert single measurable quality indicators into a dimensionless scale using function (1), it is necessary to have formulas for the transition from one scale to another. It is proposed to use an affine transformation for the transition to the dimensionless scale Y' for the measured indicators ($Y_i$), which keep the same distribution ratios of the segment. Consequently, if there are upper $Y_{bi}$ and lower $Y_{ni}$ boundaries of the $Y_i$ indicator and the upper value $Y'_b$ and lower $Y'_n$ of the $Y_i$ indicator correspond to

$$\lambda = \frac{Y_{bi} - Y_i}{Y_i - Y_{ni}} \quad (4)$$

$$Y' = \frac{Y_b' + \lambda Y_n'}{1+\lambda} \quad (5)$$

them, then the values of the distribution of the segment are equal to each other. Hence, it follows that if

If the upper $Y_{bi}$ and lower $Y_{ni}$ boundaries of different assessments of the quality factors $Y_i$ are determined on the scale, then formulas (4 and 5) make it simple to find the normalised dimensionless separate factor indicator. These boundaries are proposed to be found with the help of a group of experts who deal with occupational safety issues. The group should have at least seven experts (a smaller number means a greater likelihood of accepting a random assessment). The decision is taken only if 2/3 of the members of the expert group agreed with the adoption.

The boundary of the estimates of the factor $Y_i$ is determined as the arithmetic mean of the estimates given by each expert:

$$Y_{bi} = \frac{1}{n}\sum_{j=1}^{n} Yb_j \quad (6)$$

$$Y_{ni} = \frac{1}{n}\sum_{j=1}^{n} Yn_j \quad (7)$$

where $Y_{bi}$; $Y_{ni}$ — the value of the boundaries of the estimates of factors, put down by the j-th expert, n — the number of experts.

Note that the complex indicator of working conditions is a quantitative, unambiguous, unique and universal indicator and can be used for multidimensional statistical control of factors and a workplace safety management system in industries.

This article proposes a step-by-step method for determining a complex indicator of working conditions in production:

- determine the list of harmful and dangerous factors in production;
- determine the maximum and minimum allowable value of each factor;
- establish the optimal (best) value of each factor;
- determine the intermediate boundaries of assessments of each factor, with the help of a group of experts, using formulas (6) and (7). The value of these boundaries is applied to the graphical model of the desirability function;
- perform measurements of each factor;
- convert the value of the measured factors $Y_i$ into a dimensionless scale Y' using formulas (4) and (5).
- determine the single indicators of factors di using formula (1).
- using formula (3) to determine a complex indicator of working conditions, considering all single indicators.

## 3. Results and discussion

To confirm the efficiency of the developed methodology for assessing the safety of working conditions, research was carried out at a machine-building enterprise. The assessment considered harmful production factors in the foundry. The foundry was chosen as an example of a production site with harmful and dangerous factors for human health. The main harmful production factors in the foundry were microclimate (air temperature, relative air humidity, air velocity, and thermal radiation intensity), noise, and vibration.

The values of harmful production factors were measured and recorded at workplaces and in the working area within a month (31 days). A combined device FLIR EM54 was used to measure air temperature, relative air humidity and air velocity-. The intensity of the thermal radiation was measured with a thermal radiation radiometer "IR-meter". The measurement of noise level and general vibration was carried out with a digital sound level meter GM1351 and a vibrometer AR63A (GM63A). The permissible norms of harmful factors are determined at the enterprise following the current regulatory documents.

The obtained experimental values of the above-mentioned indicators of harmful factors and the results of mathematical transformations are shown in Table 2.

Tab. 2. Results of the implementation of the methodology for assessing the safety of working conditions in industries

| No. | Indicators of harmful factors | $q_{min}$ | $q_{max}$ | $q_{опт}$ | $q_i$ | λ | Ý | $d_i$ |
|---|---|---|---|---|---|---|---|---|
| 1 | air temperature, °C | 13 | 19 | 16 | 17 | 0.5 | 1.272 | 0.76 |
| 2 | relative humidity, % | 25 | 75 | 50 | 70 | 1 | 3 | 0.95 |
| 3 | air velocity, m/s | 0 | 0.5 | 0 | 0.1 | - | -0.476 | 0.2 |
| 4 | intensity of thermal radiation, W/m$^2$ | 0 | 140 | 0 | 94 | 1.8 | -0.476 | 0.2 |
| 5 | noise, dBA | 60 | 80 | 0 | 65 | 3 | 1.897 | 0.86 |
| 6 | local vibration, m/s$^2$ | 0 | 0.2 | 0 | 0.09 | 3 | 0.579 | 0.57 |

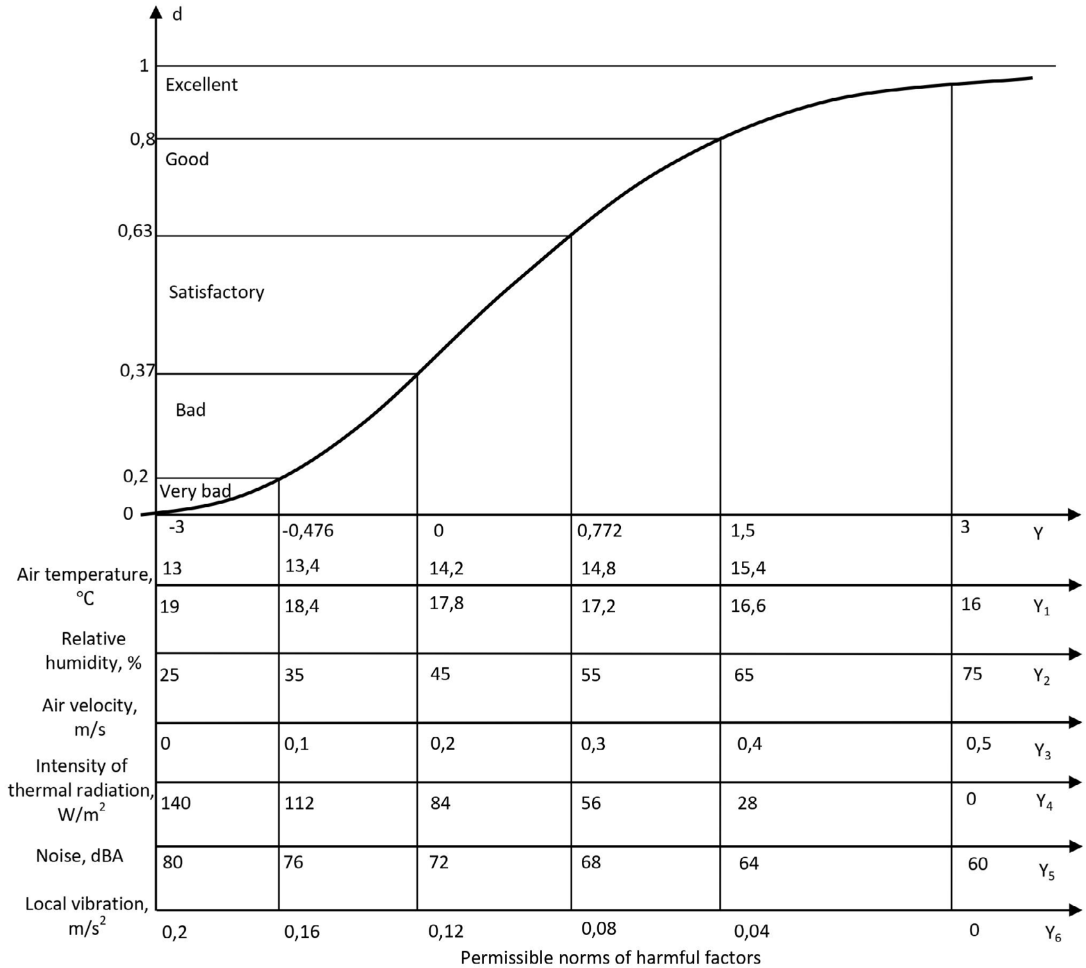


Fig. 2. Graphical model for assessing indicators of harmful factors

To adjust the scales for each indicator of a harmful production factor, it is necessary to divide the difference between its minimum and maximum value by the number of intervals that is on the corresponding intermediate scale. The graphical model for assessing the indicators of harmful factors is illustrated in Fig. 2.

Since the estimates of single indicators of harmful factors have the same measurement scale (0 – 1), it is possible to find a generalised indicator by applying one of the average values. In this case, the geometric mean is used.

$$D = \sqrt[n]{\prod_{i=1}^{n} d_i} = \sqrt[6]{0{,}76 \cdot 0{,}95 \cdot 0{,}2 \cdot 0{,}2 \cdot 0{,}86 \cdot 0{,}57} = 0{,}49 \qquad (9)$$

Thus, the use of the developed system of relationships between single indicators of harmful production factors and their values on a dimensionless scale provides a quantitative assessment of working conditions in industries. Using the proposed methodology, it is possible to take management decisions that lead to the minimisation of the deviation of the actual values of harmful factors from the optimal ones.

The proposed methodology is universal since it can be applied to assess working conditions in various industries. In individual cases, if necessary, the mathematical dependence (1) can be modified by multiplying it by dimensionless coefficients from 0 to 1. This way, it is possible to change the steepness of the relationship and obtain other estimates on a dimensionless scale. This will make it possible to manage the assessment process depending on the degree of influence of the harmful factor on human health.

It is not enough for the enterprise to ensure the permissible norms of harmful factors, but it is necessary to minimise their influence. This methodology allows making management decisions in increasing and decreasing the requirements for harmful factors in the workplace. Different values of estimates on a dimensionless scale can be obtained by choosing a dimensionless coefficient. Future studies plan to use dependence (1) on the example of various industries using dimensionless coefficients.

# Conclusions

Multi-criteria assessment of working conditions uses qualimetry instruments since they allow obtaining a quantitative assessment of production factors deemed harmful and dangerous to humans. The system of harmful production factors, as an object of qualimetry, has a number of particularities that should be considered when solving the problem of a quantitative assessment of workplace safety in production.

An exponential distribution, which belongs to the theory of extreme statistics, is proposed for transforming heterogeneous unit indicators of harmful factors into a dimensionless scale. To combine dissimilar scales, it is proposed to apply affine transformations that allow dividing segments on dissimilar scales in equal proportions.

The developed methodology was tested at one specific metallurgical production site. The applied methodology resulted in a generalised indicator of working conditions at the site.

The scientific value of the proposed methodology lies in its universality. It can be used to assess working conditions in various industries, using a different number of harmful factors and a different range of their measurement. In addition, factors can have different measurement scales. They may be defined by legal requirements or corporate requirements of the company. They can also be revised and changed to effectively manage the labour safety system. The limitations of this methodology are related to its application to quantifiable factors. The development of a methodology using verbal scales and qualitative assessments will be the aim of the following studies.

For the further development of the task, it is possible to consider the use of other mathematical relationships between the measured indicator of working conditions and the assessment on a dimensionless scale, which would consider various particularities of the qualimetry object. It is also desirable to study the assessments of the system of working conditions in a dynamic state, which means the process of changing assessments with time, allowing the application of control actions. It is advisable to develop a computer program based on the proposed methodology that would automate the assessment process.

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