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MULTI-CRITERIA DECISION ANALYSIS IN OCCUPATIONAL SAFETY MANAGEMENT SYSTEMS

Abstract: *Increasing the effectiveness of occupational safety increases the safety of an organization as its important performance. Safety performance indicators measure changes in the level of safety (related to accident prevention, preparedness and response) over time, which result from the actions taken to reduce appropriate risks. This paper presents the characteristics of basic types of safety indicators, the structure of safety factors, performances and indicators, as well as the multi-criteria decision analysis process and methods in safety management systems.*

Key words: occupational safety, performances, indicators, multi-criteria decision making.

INTRODUCTION

"The complexity of modern systems stems from the combination and use of various resources and the characteristics of the dynamic, turbulent environment in which they exist. Resources, internal and external environment interact to each other, and it defines system performances" [1]. The term includes a set of performance indicators to quantitatively or qualitatively describe the quality of a system.

Indicators of health and safety have been developed and explored along with the raising awareness of the need for continuous improvement of quality of life. This includes health and safety at work and the importance of indicators of social responsibility for improving the economic indicators of the organization. Two different types of safety indicators: activity indicators (indirect or lagging indicators) and outcome indicators (direct or leading indicators) have been analyzed in this paper. Furthermore, it describes safety analysis - accident investigation and predictive assessment – and the structure of safety factors, performances and indicators. Multi-criteria decision analysis (MCDA) methods that can be used in the occupational safety management systems, which are based on occupational safety indicators, have been presented at the end of the paper.

SAFETY MANAGEMENT SYSTEMS IN ORGANIZATIONS

Safety management systems are integrated mechanisms in organisations designed to control the risks that can affect workers' health and safety, and at the same time to ensure that the firm can easily comply with the relevant legislation [2]. They are parts of general organizational management systems that include organisational structure, responsibilities, practices, procedures, processes, and resources for determining and implementing an accident prevention policy; they also include data on organisation and personnel, identification and evaluation of hazards and risks, operational control, management of changes, planning for emergency situations, monitoring performance, audit and review [3].

A good safety management system is fully integrated into an organization, and it defines policies, strategies and procedures that provide internal consistency and management. Developing the effective safety management system means creation of awareness, understanding, motivation and commitment among all the employees in an organization [4].

Achieved safety performance are conditioned by the effects of internal and external factors that can be objective or subjective. Objective factors are: the social (and economic and market system), technical (type of production, technical progress, the characteristics of engineering and technology), natural (climate), dispositive (innovation, entrepreneurship, quality management). Subjective factors are the factors of organizational nature and everything that is reflected in the performance characteristics of employees and the organization as a whole [1].

As it is described in [5], there are some key aspects of a good occupational health and safety management system, which can reduce workplace accidents in a sustainable manner: Development of a Safety Policy; Participation; Training and development of employee competences; Communication and transfer of information about the workplace, possible risks and preventive measures; Planning; and Control and review of activities carried out within the organisation.

To achieve the best performance, safety must be integrated into all the organisation's decisions and actions. Integration on the level of organization is the coordination of processes that are defined in the context of the primary safety activities on the basis that removes organizational, procedural and informational

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barriers for efficient flow of materials and data exchange between different organizational units responsible for safety. It allows formulation of strategies, safety processes, information systems, technology and data within the boundaries of the organization in order to provide adequate safety level and as a consequence achievement of advantages over the competition [6].

Safety management system has a positive effect on competitiveness performance. It requires the formulation of working procedures, instructions, and planning and control of the work; the higher productivity, as a consequence of the improvement in quality and reduction in costs caused by the accidents; the higher customer satisfaction and better reputation of organization, since occupational safety is particularly important to society; higher organizational degree of innovation, due to the technological and organizational innovations derived from the improvements in safety [5].
The relationship between safety and competitiveness at the level of the organization is presented in Fig. 1 [7].

Figure 1. *The effects of safety at organizational level [7]*

Specialist knowledge and motivated employees are all assets that can provide organizations with a specific competitive advantage long periods of time. These assets are strongly affected by occupational accident rates and working conditions.

SAFETY PERFORMANCE AND INDICATORS

The concept of health and safety performance includes a set of indicators (indicators) that quantitatively or qualitatively describe the specific effects, contributions, and the results that are achieved in the safety system.

Safety indicators are approximate measures for items identified as important in the underlying models of safety [3]. Safety performance indicators measure the changes in the level of safety (related to accident prevention, preparedness and response) over time, as the result of actions taken to reduce appropriate risks [3].

Safety performance indicators system provides a global view of safety status in a plant or an organization. It can be used in conjunction with inspection and evaluation activities carried out for the regulatory control. Safety indicators evaluation results can be used as an input for inspections or audits planning [8]. Findings from others activities give information for safety indicators interpretation, and safety indicators system is useful to evaluate efficiency of regulatory strategies. A set of safety performance indicators is an assembly of direct and indirect measures of the organizational safety.

Process accidents are prevented by managing a safety performance indicator (SPI) program that consists of four different phases: identifying, measuring, analysing, and adjusting key process activities or indicators. Safety life cycle is an engineering process designed to achieve a risk-based level of safety with performance criteria that allow versatile technologies and optimal design solutions [9].

Organization for Economic Co-operation and Development (OECD) defines two classes of indicators: activities indicators and outcome indicators [3]. Activities indicators are means for measuring actions or conditions which, within the context accident prevention, preparedness and response, should maintain or lead to improvements in safety (e.g., reduction in risk, improvements in safety management and safety culture, mitigation of effects in event of an accident). Outcome indicators are used for measuring the results, effects or consequences of activities carried out in the context of a programme related to accident prevention, preparedness and response.

Safety indicator project [10] also defines two types of indicators: direct indicators and indirect indicators. Direct (or outcome) indicators utilize different types of experience data. Indicators that can give early warnings are known as indirect (or predictive) indicators that are measures of performance of the functional units within an organization, such as operation, maintenance, training, and engineering support [10]. These indicators can be used to evaluate safety by assessing the performance level and the performance trend.

Hopkins [11] discusses two dimensions of safety: personal safety versus process safety, and leading versus lagging indicators. Personal safety is about avoiding workplace incidents and workplace injuries of employees; it does not represent management of process hazards. According to that way of thinking, there are two different types of indicators: leading and lagging indicators.

Lagging or outcome indicators are a measure of the undesired outcomes, such as injuries, accidents, near misses, number of control deviations that exceed process limits, releases of chemicals, procedures not followed correctly, equipment failures, high level alarms, equipment deficiencies, etc. These indicators need to be monitored but they will not give adequate forewarning to prevent accidents.

Leading or activity indicators (also known as input indicators) are measures that determine the quality of activities that prevent outcomes. Leading indicators are selected to provide an early warning just in time to prevent process accidents. They include training, audits, and inspections, mechanical integrity checks, timely maintenance, use of check lists, emergency procedures that are tested on regular basis, risk assessments made and related to layers of protection analysis, and measurements of leadership and workforce attitudes.

According to [12], there are three indicator types, as presented in Tab. 1. The size of the set can be limited to get the required information using the smaller possible number of indicators. Indicators have to be predictive and sensitive. Considering the consequences produced by degradations at organizational level, indirect indicators can be included in order to evaluate those aspects.

Table 1. *Description of indicator types according to different systems of classification in the HSE guide [12]*

Indicator Type	Classification of indicators		
	Definition	**Examples**	**Input/ outcome**
Measures of safety activity		Lead	Lead
Failures revealed by safety activity	Lead	Lead	Lag
Failures in use	Lag	Lag	Lag

The dimensions in characterising safety indicators could relate to different final outcomes such as process safety or occupational safety. Indicators could also address: technical safety features being in place and their performance; nature and characteristics of the hazards; formal safety organization systems, which are in place and how they perform; informal safety issues; communication and co-operation issues as discussed in [3]; absolute values or trends (changes of performance over time); economic consequences and probability for different outcomes.

The first two areas can be the scope of technically oriented audits, and the third is concerned with organisational audits.

THE STRUCTURE OF SAFETY FACTORS, PERFORMANCES AND INDICATORS

Analysis of the problem of safety at work can be done on the basis of empirical data in terms of searching for the causes of accidents, or on the basis of speculation and retrospectives.

According to [13] the first perspective is related to the development of the search for causes of accidents, moving from technical, to human, and further to organizational causes, i.e. causal chain. The second perspective is based on a predictive and a retrospective view. It makes a big difference whether we try to predict the possibility of having a major accident "tomorrow", including all possible causes, or if we only try to establish the causes after-the-event. Based on these two presented perspectives, the technical-human-organizational, and the predictive-versus-retrospective, we establish a conceptual model in order to structure and illustrate the previous research. This simplified model is shown in Fig. 2.

The technical–human–organizational perspective is illustrated horizontally and the retrospective-versus-predictive perspective is illustrated vertically. For the prediction of risk, as for accident investigation, we can talk about a development from technical, to human, and even to organizational causes. This does not imply that all features of risk assessment can be classified according to technical–human–organizational scheme.

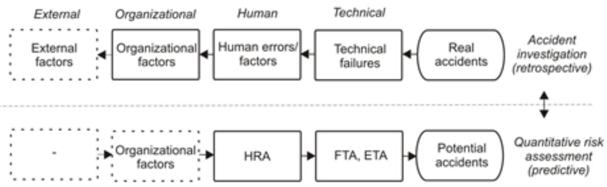

Figure 2. *Accident investigation versus predictive assessment [14]*

Depending on the application situation the demands on safety indicators will vary considerably. One approach is therefore to start with the purpose of the indicators and the way they will be used.

Fig. 3 illustrates each of the safety factors which are considered important by the key decision makers. The senior management team is hiring quality personnel, providing safety orientation, promoting safety through top management commitment, and developing a formal learning system. They were critical to improving an organizational safety performance.

The safety, health and environmental team can identify that individual empowerment, responsibility, and systems for anonymous reporting and feedback are essential to improve organizational and individual safety performance. The items elicited in the expert elicitation sessions thus represent the initial safety factor structure, as presented in Fig. 3.

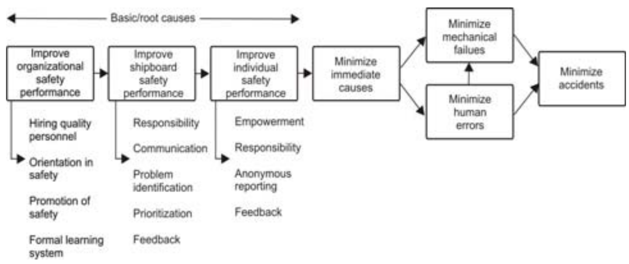

Figure 3. *Safety factors structure [11]*

Before defining the set of performance indicators, it was necessary to establish a framework to define the parameters and the associated indicators in order to assure that everything having influence on the organizational safety is included. After that, preliminary indicators were proposed in each area. In this stage all adequate indicators should be included. A screening process is necessary for all proposed indicators [8].

Based on the research presented in [3,13,15 and 16], we have defined the structure of safety factors, performances and indicators as shown in Tab. 2. Of course, this structure is neither complete nor final.

Performances and indicators for each group of factors are selected according to specific circumstances. The selection of indicators depends on the method of analysis of problems related to health and safety (the technical-human-organizational and the predictive-versus-retrospective).

Table 2. *Classification of safety factors and safety performance indicators (based on [3, 13, 15, 16])*

Factors	Performances	Indicators
Technical	Functionality Reliability Flexibility Maintenance Costs	Level of protection number Number of control deviations that exceed process limits Number of failures Number of accidents Failure and repair intensity Mean time between failures Mean time to repair Availability Maintenance and infrastructure cost
Human	Knowledge Competence Leadership ability Risk-taking and problem solving capabilities Education Experience	Creating results by using knowledge Employees' skills index Haring and reporting knowledge Employees' cooperation rate in teams Succession rate of training programs Success likelihood index Number of errors and omissions Absenteeism rate Injuries rate
Organizational	Training Procedures, instructions Job safety analysis (JSA) Planning Coordination Control Design Preventive maintenance program	Proportion of process technicians having formal system training Average number of years of experience in total for relevant personnel Proportion of relevant personnel having received JSA training Number of controls of JSA preparation and application Number of hours inspection of accidents Efficiency in management of safety resources
Environmental	Legislation Standardisation Protection Technologies Social Environmental Economic Environment Competitive Environment Perceptions and values of stakeholders	Level of application of legislation Number of implemented standards Level of social responsibility Level of technology protection Number of available databases on accidents Number of available funds Degree of innovation Degree of networking

MCDA METHODS IN SAFETY MANAGEMENT SYSTEMS

Multi-criteria decision analysis (MCDA) methods have become increasingly popular in decision-making for safety management systems because of the multi-dimensionality of the goal and the complexity of socio-economic and technical systems [17].

MCDA is an integrated evaluation. Compared to single criteria approach, the distinctive advantage of MCDA methods is to employ multi-criteria or attributes to obtain an integrated DM result.

Generally, the MCDA problem for safety management decision making involves *m* alternatives evaluated on *n* criteria. The grouped decision matrix can be expressed as follows:

$$\begin{array}{rl} \textit{criteria} & C_1 \quad C_2 \quad \cdots \quad C_n \\ \textit{weights} & w_1 \quad w_2 \quad \cdots \quad w_n \\ \textit{alternatives} & =============== \end{array}$$

$$X = \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix}_{m\,x\,n} \quad (1)$$

where x_{ij} is the value of *j*-th criteria with respect to the *i*-th alternative, w_j is the weight of *j*-th criterion, *n* is the number of criteria and *m* is the number of alternatives.

Based on the Eq. (1), corresponding decision making process can be described by means of algorithm presented in Fig. 4. It includes four main stages: formulation of alternatives and criteria selection, criteria weighting, evaluation, and final aggregation.

Measuring effectiveness of the safety management systems is a problem. Developing evaluation criteria and methods that reliably measure effectiveness and efficiency is a prerequisite for selecting the best alternative, informing design-makers on performances of the alternatives and monitoring impacts on the social environment. The development and selection of criteria require parameters related to the reliability, appropriateness, practicality and limitations of measurement.

These indexes are restricted and/or impacted each other. For example, the number of technical and societal possibilities are wanted to increase, but sometimes are blocked by economic and political interests [18]. Also, the advanced system may reduce the number of accidents, but excessive cost is needed to invest and/or maintain the system meanwhile. So the decision-maker is difficult to select the optimal system from options well.

However, the weight values of evaluation indexes influence the evaluation results. Different weight values lead to different evaluation results. There are two methods: the equal weights and the rank-order weights.

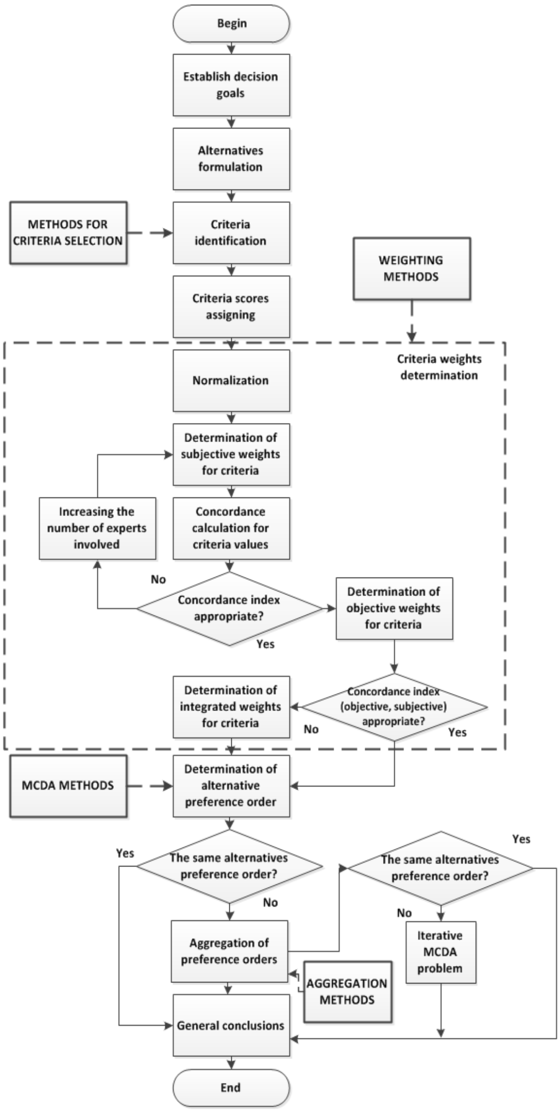

Figure 4. *MCDA process in safety management systems decision-making (based on [18])*

There are also subjective and objective weighting methods (Tab.3). Subjective weighting methods such as pair-wise comparison were the most used methods in safety decision making. The objective weighting method elicits the criteria weights using the measurement data and information and reflects the difference degree.

After determining the criteria weights it is necessary to determine the preference orders of alternative so that MCAD methods are employed to get the ranking order in Eq. (1). MCDA methods are divided into three categories, as presented in Table 4.

Outranking methods allow incomparability between alternatives. This characteristic is important in situations where some alternatives cannot be compared to each other.

The decision maker selects the best alternative based on the ranking orders after the calculation in a selected MCDA method. The application of various MCDA methods of calculation may give different preference ranking order.

Table 3. *Weighting methods in MCDA decision making [18]*

Categories	Weighting methods
Subjective weighting	Simple multiple-attribute rating technique (SMART), SMARTER, Swing, Trade-off, SIMOS, Consistent matrix analysis, AHP, Least-square method, Delphi method, PATTERN, Eigenvector method, Pair-wise comparison
Objective weighting	Least mean square (LMS) method, Minmax deviation method, Entropy method Principal component analysis, Multiple correlation coefficient, TOPSIS method, Variation coefficient, Vertical and horizontal method, Multi-objective optimization method
Combination weighting	Multiplication synthesis Additive synthesis (Optimal weighting based on relational coefficient of gradation, Optimal weighting based on sum of squares, Optimal weighting based on minimum bias)

Table 4. *MCDA methods [18]*

Categories	Weighting methods
Elementary	Dominance, Maximin, Maximax, Conjunctive, Disjunctive, Lexicographic, Elimination by aspects, Linear assignment, Weighted additive, Weighted product
Unique synthesizing criteria	Analytical hierarchy process (AHP), TOPSIS, SMART, Grey relational analysis, Data envelopment analysis, Multi-attribute value theory (MAVT), Multi-attribute utility theory (MAUT), Utility theory additive (UTA), Fuzzy weighted sum, Fuzzy maximum
Outranking	ELECTRE (I, IS, II, III, IV, TRI), PROMETHEE (I, II), ORESTRE

Methods used to aggregate the preference orders are called aggregation methods, and they are divided into two categories: voting method and mathematical aggregation method. General approach to aggregate alternatives' preferences is the voting methods. The winning alternative in voting methods depends on which voting rule is used. Generally, Borda rule and Copeland rule are the most common voting rules. The mathematical aggregation methods are classified to two sub-categories, ''hard aggregation method'' and ''soft aggregation method'' based on including the decision-makers.

CONCLUSION

Managing occupational risk allows organizations to maintain and develop intellectual capital, which is fundamental for the development of the organization. Safety management system consists of a safety policy (principles and the responsibilities of all organization members), that encourage employees' participation, training, continuous communication and collaboration, planning of the activities and adequate control of the activities. It has positive effect on: safety performance - by reducing the accident rate, and improving working conditions; and competitiveness - due to its positive influence on the organizational image, productivity, reputation and innovation.

When the research on developing indicators or metrics for major hazards started, the focus was on direct or lagging indicators (after-the-event type of indicators). This approach counts the number of accidents or incidents or near misses, however, these indicators are not very useful as pre-warnings or early warnings. For early warnings, one needs to analyse causes of dangerous events and the condition of the factors that leads to accidents. This is achieved by indirect or proactive indicators (leading indicators) that provide performance feedback before an accident or incident occurs.

Defining safety performances and indicators, according to the specific organization, is the basis for application of multi-criteria decision-making in the safety management system.

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