Journal of civil engineering and transport **transEngin**

2022, Volume **4** Number **2** **ISSN 2658-1698, e-ISSN 2658-2120**

DOI: 10.24136/tren.2022.006

THE USE OF THE SEMI-QUANTITATIVE CLASSIFICATION METHOD OF ASSESSMENT OF THE EFFICACY OF SAFETY SYSTEMS FOR THE RAILWAY TECHNICAL RESCUE SYSTEM

Adrian **Gill** [1,*], Piotr **Smoczyński** [2]

[1] Poznan University of Technology, Faculty of Civil and Transport Engineering, Piotrowo 3, 60-965 Poznan, Poland, e-mail: adrian.gill@put.poznan.pl, https://orcid.org/0000-0002-2655-4584

[2] Poznan University of Technology, Faculty of Civil and Transport Engineering, Piotrowo 3, 60-965 Poznan, Poland, e-mail: piotr.smoczyński@put.poznan.pl, https://orcid.org/0000-0003-3824-3764

* Corresponding author

Reviewed positively: 09.08.2022

Information about quoting an article:
Gill A., Smoczyński P. (2022). The use of the semi-quantitative classification method of assessment of the efficacy of safety systems for the railway technical rescue system. Journal of civil engineering and transport. 4(2), 23-35, ISSN 2658-1698, e-ISSN 2658-2120, DOI: 10.24136/tren.2022.006

Abstract – Much research shows that over-expansion of safety systems can be irrational and counter-effective. To avoid this, it is necessary to define a method for assessing the effectiveness of the implemented risk reduction measures. This article presents the adaptation of a previously developed method of this type to the nature of the operation of the railway rescue teams. It uses a hierarchical classification system of safety measures that is used as a basis on which their effectiveness is determined. The way how the method should be implemented is presented on the example of 28 selected tools used by rescue teams operating within the Polish railway infrastructure manager. Although the obtained results do not constitute a comprehensive solution to the problem of assessing the effectiveness of safety systems, they can nevertheless be used to support decisions taken in this area.

Key words – efficacy, rescue system, safety system

JEL Classification – R41, J28

INTRODUCTION

A system is a combination of people, procedures, facilities, and/or equipment, all functioning within a given or specified working environment to accomplish a specific task or set of tasks [17]. When the objective of the system is the reduction or optimisation of risk, it may be referred to as a safety system. The safety system can therefore be defined by three components [2, 7]: objective of the systems, elements of the system (man, technical elements, organizational elements) and structure of the system.

It was observed already over a dozen years ago that an irrational approach to safety system management leads to their excessive expansion and considerable maintenance costs. In his work, Głodek [3] gives an example of the Shell Global Solutions company, which carried out an analysis of the safety measures used based on the IEC 61508 standard. As a result of this analysis, the company found that 65% of these safety measures were overinvested. Summers found in 1998 that in order to avoid problems with ensuring safety, many companies introduce measures with the highest level of operational reliability without conducting proper analyses [16]. Vincoli points out that efforts related to system safety sometimes exceed the minimum compliance standards in order to ensure the highest level of safety (i.e. the lowest level of acceptable risk) possible to achieve for the given system.

System safety has often been used to demonstrate that some compliance requirements can be excessive while providing insufficient risk reduction to justify the costs incurred [17]. What is worse, safety system expansion does not always guarantee that the value of risk will come down to the acceptable level. What the risk management entity is left with is the use of the ultimate tactics towards risk, i.e. its retention [5].

Reasons for the lack of rationality in creating safety systems include:

- introduction of elements based on the events that have occurred – accidents, instead of risk analysis/assessment results,
- ignoring complex interrelationships between individual system elements, as well as between system elements and hazard sources/hazards,
- lack of sufficient resources (time, information) to understand the integration of risk analysis results with the process of dealing with risk,
- lack of tools enabling easy configuration of safety system structures, as well as the identification and documentation of the effects of these changes.

Designing safety systems primarily consists in selecting their elements while guided by the characteristics of system operation and the effects related to adverse events. The role of these elements is to perform safety functions, which can be defined as a technical, organizational or combined function that can reduce the probability and/or consequences of accidents and other unwanted events in a system [4]. Both probability and consequences are included in many mathematical models of risk, therefore they can be also called risk reduction measures (RRM). When RRM fulfil these functions, the possibility (likelihood) of the occurrence of certain adverse events in the supersystem of the safety system is reduced or the extent of losses is limited.

A justified approach to designing safety system is to make a choice based on the degree of the achieved "good performance" of the solution. For instance, it is reasonable to achieve a safety system structure that changes the degree of exposures coming from hazard sources in the most favourable manner or makes it possible to achieve the largest possible value of risk reduction. Although mathematically reducing risk through lowering either probability or negative consequences can be equivalent, it is usually better to stop the hazard from emerging than to limit the associated losses. In order to achieve it, the RRM has to have an effect on hazard sources.

The hazard sources are also called hazard factors, risk factors, as well as dangerous, harmful or onerous factors. They can be defined as factors of physical, chemical, biological, psychophysical, organisational or personal nature; their presence, state, attributes etc. in an indicated analysis domain is a reason (source) of formulating a hazard [7]. The effect mentioned before, may occur in different ways and to a different extent. It may consist in the elimination of these sources, limiting the exposures that come from them, and sometimes only in informing about the possibility of their occurrence.

In accordance with the analyses carried out, among others, that a satisfactory manner of expressing the extent of the effect of safety system elements on hazard sources is their *efficacy*. This measure should be distinguished from *efficiency*, which also includes the outlays incurred and the resources used [10]. Most studies on system management in general are – more or less intentionally – dedicated to the efficiency measure. A clear example of such an application of efficiency in railway transport systems is presented e.g. in [15]. It is to a much smaller extent that papers are dedicated to the efficacy measure. According to the Scopus database, in 2022, about fifty articles in the field of engineering were dedicated to this measure in connection with the topic of safety. The primary domains of these works included medicine and healthcare engineering. None of the papers published this year focused on the efficacy of safety systems, railway transport systems or railway rescue systems.

Therefore, a certain research gap emerged regarding the form of efficacy measures, in particular in the case of safety systems, such as rescue systems, as to which outlays or resources used should not be taken into consideration, as the extent of operation execution and results achieved is more important.

The purpose of the article is therefore to present a method of assessing the efficacy of safety system elements and the results of its application for the railway technical rescue system. Chapter two describes the method, whereas the results of the application of the method for part of the railway technical rescue system were presented in chapter three.[1]

1. Material and Methods

Components of the railway technical rescue system

In the railway technical rescue system, the following groups of risk reduction measures can be distinguished: (1) personal protective equipment, (2) devices and tools, (3) vehicles, (4) instructions and regulations, and (5) people. Each group constitutes a certain rescue subsystem, i.e. it may consist of a number of interoperable elements.

[1] The research was conducted with subsidy for the support and development of research potential for the Faculty of Civil and Transport Engineering at Poznan University of Technology

Within each group, corresponding subgroups can additionally be distinguished. For instance, in the personal protective equipment subsystem/group, the following subgroups can be distinguished: eye or face protection, head protection (separate), lower or upper limb protection, and body protection. A detailed list of risk reduction measures in individual subsystems of the railway technical rescue system was drawn up and presented in [18].

Examples of risk reduction measures in the personal protective equipment subsystem/group include various safety goggles (impact goggles, gas-tight goggles, sun protection goggles), safety helmets with or without lining, masks, filtering half masks, breathing apparatuses, raincoats and waterproof clothing, flame retardant and anti-static reflective vests, various types of gloves (insulated drill, dielectric, rubber nitrile, acid-resistant, anti-vibration gloves), and shoes (insulated boots with protective [steel] toes or waders). This type of equipment may also include some less formal items, such as mouthguards or knee braces and supports.

The devices and tools subsystem primarily includes items constituting the minimum and standard list of technical rescue equipment for basic rescue operations. The list was presented in Table 1.

Risk reduction measures in the vehicles subsystem/group include all kinds of technical and service wagons, road-rail vehicles, and special rescue trains. Road-rail vehicles constitute the largest subgroup. Examples in the railway technical rescue system include: road-rail vehicles (STAR type USm and USC, Uniroller, Tarpan, Unistar-k, Iveco type IVC), tractors (Ursus, Crystal), excavators, and ploughs. Among the technical and service wagons, the following should be noted: the technical equipment wagon and the technical and service staff wagon, whereas special rescue trains are mainly the so-called maintenance trains (e.g. WM-15A/PRT-00, PS-00.M/d) and recovery vehicles on wagons (flatcars).

Examples of instructions as risk reduction measures in subsystem 4 of the railway technical rescue system include all kinds of instruction and operating manuals. According to analyses carried out in [18], they can be divided into at least two subgroups: railway vehicle and device operating and maintenance manuals and procedures in case of railway incidents. Examples of such measures in the first subgroup include the Itw-3 Railway vehicle brake operating and maintenance manual or the Ir-5 Train radio communication device user manual, and in the second subgroup: the Ir-8 Procedure in the event of serious accidents, accidents, and incidents in railway transport, the Ir-16 Procedure for the railway transport of hazardous materials, and the Ir-15 Railway technical rescue manual.

Examples of people as risk reduction measures in subsystem 5 of the railway technical rescue system, with a division into subgroups, were presented in Table 2.

This article focuses on the technical risk reduction measures which perform safety functions with reference to the receivers of exposures not constituting elements of the rescue system (i.e. people, property, environment, which are the subject of the rescue operations). The rescuers' personal protective equipment is therefore excluded from the area of analysis.

Table 1. Examples of risk reduction measures in subsystem (2) – Devices and tools of the technical rescue system, which constitute the minimum and standard list of equipment for basic rescue operations

Item no.	Name of risk reduction measure
2.1.	Hydraulic spreader with accessories (2 chain locks, 2 chains with hooks)
2.2.	Hydraulic rescue cutters
2.3.	Telescopic rescue rams with a set of attachments (cross head, wedge piece, conical tip) of various lengths
2.4.	Power unit for hydraulic tools with at least the ATO operating mode
2.5.	Set of hydraulic hoses at least 5 metres long
2.6.	High-pressure air cushions for lifting with a load capacity of 50-300 kN
2.7.	Air cushion pneumatic control equipment for inflating with a compressed air cylinder
2.8.	Compressed air cylinder for air cushions with a capacity of at least 6 litres
2.9.	Petrol chainsaw for cutting wood
2.10.	Petrol circular saw for cutting steel and concrete
2.11.	Spring-loaded punch for safety glass
2.12.	Seatbelt cutter
2.13.	Shackle and cable attachment kit for a winch

Source: prepared based on [11]

Table 2. Examples of people as risk reduction measures in subsystem 5 of the railway technical rescue system

Item no.	Examples of risk reduction measures (RRM)	Examples of risk reduction subgroups
5.1.1.	Crane operator qualified to operate railway vehicles	5.1. Railway employees qualified to operate technical rescue team equipment
5.1.2.	Crane operator acting as rigger	
5.1.3.	Employee with a train driver's licence and certificate (wm-15a/prrt)	
5.1.4.	Driver – operator of the recovery vehicle	
5.1.5.	Work and service train manager	
5.1.6.	Employee with qualifications to drive in road traffic and to drive railway vehicles	
5.1.7.	Employee qualified to direct road traffic within a level crossing area	
5.2.1.	Organisational unit for technical rescue	5.2. Personnel responsible for supervising technical rescue teams
5.2.2.	Head of the organisational unit in which a technical rescue team was established	
5.2.3.	Head of the executive organisational unit	
5.2.4.	Director of the railway track development and construction unit	

Source: prepared based on [18]

POSSIBILITIES OF ASSESSING THE EFFICACY OF RISK REDUCTION MEASURES

Efficacy can be understood as a synthetic measure, i.e. combining the component of probability of the safety system element having an effect (becoming activated) and the component of vulnerability of the hazard source to the effect of this element. In literature on the subject, other examples of understanding and estimating efficacy are also proposed. Authors of [1] suggest, for instance, determining the value of the efficacy index, the value of which is obtained based on the costs of event results and the costs of preventing these events. In the works of Saracinoa et al. [12], an index used to express the effect of the properties of the workplace on employee health in quantitative terms.

An efficacy index closest to the subject matter of this article is presented by the authors of [13]. They analyse the efficacy of a newly developed online training program for learner drivers regarding the prediction of hazards. The efficacy of the training program is estimated based on the drivers' assessment of their self-efficacy and their attitudes in terms of road safety. The drivers' sense of self-efficacy and road safety attitudes were assessed with the use of measurements registered in the preliminary test. In spite of the conclusions that the difference between the pre- and post-test variables does not correlate with either the sense of self-efficacy or with the attitudes in terms of road safety, article [13] indicates potential efficacy measures. In order to assess self-efficacy in driving, the 12-element Adelaide Driving Self-Efficacy Scale was used. Road safety attitudes were assessed with the use of the 25-element Attitudes toward risky driving scale. The efficacy of the program was verified by improving the accuracy of the hazard prediction test from the preliminary to the post-test stage.

A similarly good example of efficacy assessments, yet based on experimental research, is article [6]. It deals with the efficacy of personal protective equipment in the form of earplugs. The concept of estimating efficacy is similar to that in [13] (online driver training program), i.e. it is based on preliminary measurements of personal assessment of sound muffling. The efficacy assessment assumed binary values of "success" or "failure", depending on whether the earplug managed to muffle 22 dB. It should be noted here that although an approach to testing risk reduction measure efficacy based on experimental research involving people is attractive, as it decreases the subjectivity of the results, it will not always be possible with reference to rescue system elements.

Therefore, Harms-Ringdahl approaches the issue of estimating efficacy in a slightly different manner, proposing three qualitative criteria [4]: importance, efficiency, and intention (intentional or unintentional action, affecting or not affecting safety). However, he uses it with reference to the safety function. Due to the fact that safety functions are performed by safety system elements, it is possible to use the values of score measures used as part of these criteria in order to estimate the efficacy of safety system elements.

There is also a possibility to adapt the formalised approach to determining the efficiency of safety systems in railway transport proposed as part of the EN 50126-2 standard [9]. It is a qualitative approach based on four criteria: the possibility (frequency) of damaging a system component, the extent of its use in different types of applications, the applicability (as a type of application) of the component, and the maintainability criterion. The flaw of the safety system efficiency assessment based on this approach is its limitation to systems characterised by low values of hazard risk. Moreover, the degree of formalisation of the method was limited to the provision of a general description of the levels of efficiency according to individual criteria and the general interrelationships (product) of the variables expressing the individual efficiency components. There are no quantitative measures which could be used to express the levels of efficiency within individual criteria and the total efficiency of the system.

Summing up the content of the studies referred to above, it should be noted that efficacy may be expressed in a linguistic, qualitative or quantitative manner, with the use of score measures or probability measures. The values of score measures are usually attributed to linguistic values. Values specifying the efficacy of safety systems may also be obtained through expert assessment or with the use of detailed calculation algorithms, including simulation algorithms. Expert assessment is usually used in the case of non-measurable attributes of safety systems or a lack of data on the measurable attributes.

2. Results

Method description

Risk reduction measures have specific characteristics (attributes). It is suggested that among these characteristics, qualities and properties should be distinguished. With reference to safety systems, qualities can be described as characteristics which are invariable and independent of relationships with other elements, e.g. system environments. Examples include qualities resulting from the structure of the given element, such as: activity or passivity, automatic or non-automatic operation, materiality or non-materiality. Properties, in turn, can be described as characteristics in the case of which the values of the measures that describe them are variable. This results from the interactions of risk reduction measures with different components of the safety system environment, with interactions with hazard sources being particularly interesting.

The method proposed in this article is based on the use of the qualities of risk reduction measures and their classification in line with these qualities. The measures are divided into thirty classes/layers (Fig. 1) created through appropriate combinations of fifteen qualities of safety system elements. The diagram presenting these combinations (Fig. 1) has a distinctive, hierarchical layout. The first classes (on top of the diagram) are classes (or system layers) corresponding to the most efficacious risk reduction measures. The last classes (at the bottom of the diagram) are classes/layers of risk reduction measures with the lowest efficacy.

In order to use the diagram correctly, proper understanding of the individual qualities of risk reduction measures is required. Therefore, their brief description is presented below.

Reduction measures treated as material are those of technical nature, whose task is to eliminate hazard sources or limit exposures coming from these sources by physically blocking the flow of energy, materials or information. Non-material measures, on the other hand, are those of organisational nature, whose task is to eliminate hazard sources or limit exposures coming from these sources through properly sanctioned procedures.

Internal risk reduction measures are both material – placed inside the object/facility (usually integrated with it), and non-material, concerning or referring only to the protected object/system. External risk reduction measures are material measures placed outside of the object/system or non-material measures planned for a larger group of objects or systems which are not a domain under the effect of the given safety systems.

Risk reduction measures introduced by the designer are material measures placed inside (usually integrated with the object/facility) or procedures (instructions) planned and introduced by the object/facility designer. Risk reduction measures introduced by the user are those used by the user (e.g. personal protective equipment).

Automatic hazard risk reduction measures are material measures placed inside or outside the object/facility, which activate and perform the safety function automatically. No interaction with a human controlling their operation is necessary for their proper functioning. Non-automatic risk reduction measures are the opposite of the automatic ones, i.e. there is a human serving as a sensor or a decision-making or controlling element.

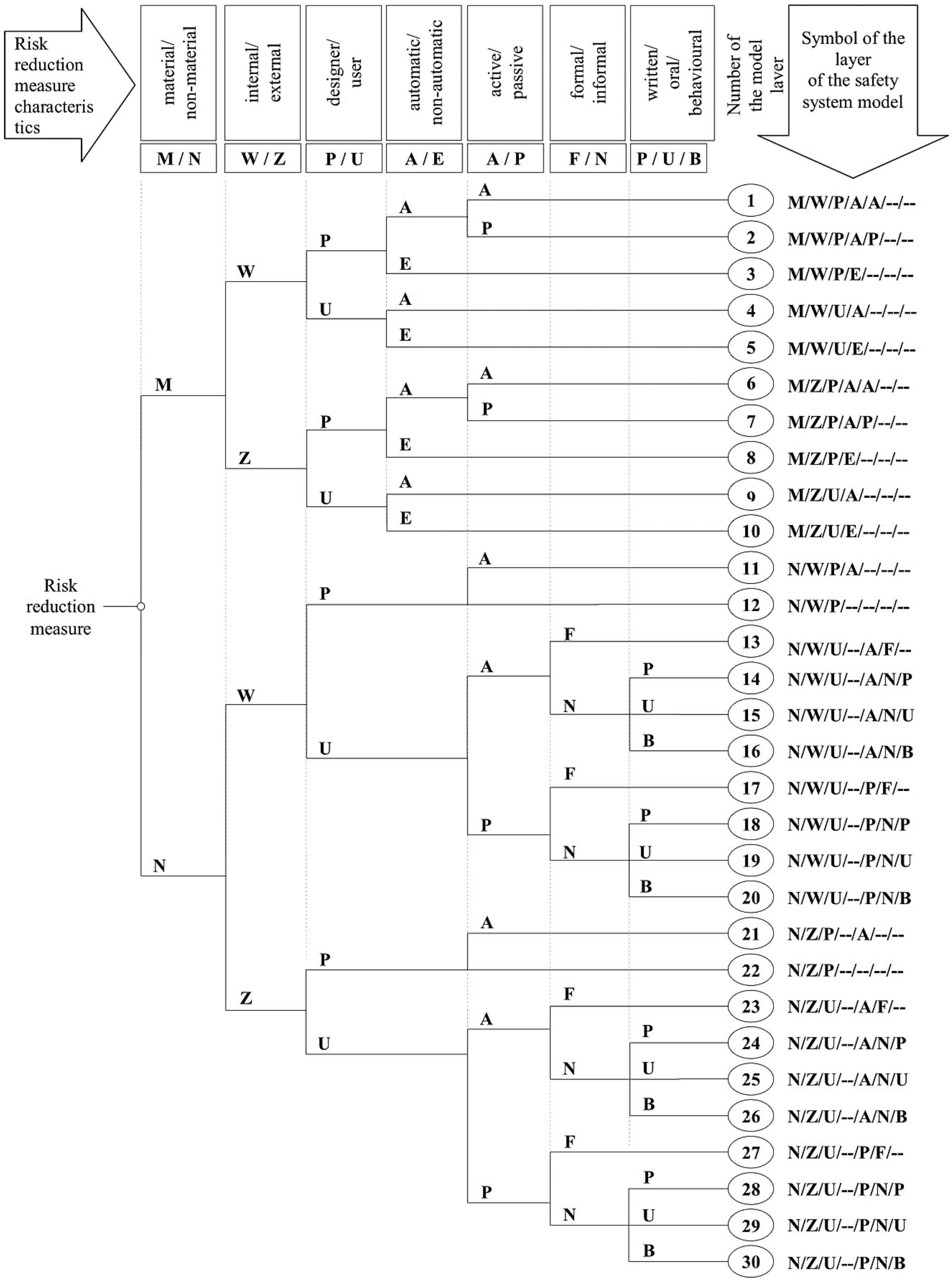

Fig. 1. Diagram of risk reduction measure qualification for safety system model layers [2]

Active risk reduction measures (also called entities) are material or non-material measures which change their state and the state of the safety system in order to perform the safety functions. They are usually organised in the form of people's, processes' or devices' actions that generate energy, material or information flow. Passive risk reduction measures are material measures which perform the safety functions without changing their state.

Formal hazard risk reduction measures are understood as organisational measures (models and criteria, operators' actions in transport systems, rescuers' actions, etc.) compliant with the applicable regulations and safety standards. Informal hazard risk reduction measures are organisational measures in the form of requirements imposed on themselves by the management or working group members. Sometimes, these requirements are even "stricter" than the regulations and standards would suggest.

Written and oral messages are both formal and informal messages from the management or working group members. Similarly, behavioural hazard risk reduction measures are organisational measures specifying detailed methods of work (so-called execution models) and defining behaviours not directly related to the tasks performed (so-called behaviour models).

Technical measures operating automatically are characterised by high efficacy and as such, they are the most frequently used ones. Organisational measures, i.e. legal, media-related, etc. are characterised by much lower efficacy. The situation is reflected in the hierarchy of the safety system layers. On this basis, it may be concluded that each layer (of which there are thirty) signifies a certain efficacy class of the given risk reduction measure.

Therefore, in [2] suggests that the efficacy measure of the effect of the given risk reduction measure should be a value inversely proportional to the number of the class used in the classification under discussion. This means that a risk reduction measure with a lower number in the classification (higher class) has a higher efficacy, which can be expressed as follows:

$$E_i = \frac{1}{k} \tag{1}$$

where:

E_i - efficacy of the effect of the i-th risk reduction measure on the hazard sources against which it was intended,

k - number of the safety system class/layer, assigned based on the risk reduction measure classification (Fig. 1).

ADAPTATION OF THE KNOWN CLASSIFICATION OF RISK REDUCTION MEASURES

Due to the specificity of the functioning of the rescue system elements, it was decided that the diagram of risk reduction measure qualification presented above (Fig. 1) should be modified. Above all, it was concluded that material risk reduction measures cannot be informal measures or measures used in a behavioural manner, but they can be passive measures even if the performance of their function is automatic. The modified part of the qualification diagram was presented in Figure 2 and Figure 3.

A significant change concerning the value of efficacy, related to the active/passive quality, was introduced. It was assumed that active measures will be less efficacious than passive measures due to the lower likelihood of activation caused by their need to change their state in order to perform the safety function. For passive measures, it may be assumed that the likelihood of their activation is a certain event. This change is reflected in the classification graph as a swap in the order of letters denoting the qualities of the risk reduction measures (e.g. A/P for P/A).

Other important modifications included changes to the following characteristics, which were considered to be more valid for manufacturing devices and machines, i.e.:

- designer/user was changed to mechanical / manual characteristics,
- internal/external was changed into direct / indirect characteristics.

Mechanical measures are understood here as those having their own or connected source of power supply, e.g. electric or pneumatic, and not powered by human-generated energy. Manual measures, on the other hand, are those powered by human muscles, used in places where there is a risk of explosion or there is no access to other power supply sources. Examples of mechanical measures include hydraulic power units, inflatable rescue boats with a motor, telescopic rams or megaphones with a microphone, whereas manual measures include: hand pumps, inflatable rescue boats without a motor, crowbars or whistles. It should be noted here that both the mechanical and manual measures may have automatic features, e.g. hand pumps may be equipped with an automatic pressure switch.

The "direct" characteristic is commonly used to describe measures directly used to perform the safety functions, i.e. used in direct contact with the rescued human or object. Indirect risk reduction measures, which can also be called supporting measures, do not perform these functions in direct contact with the rescued human or object or ensure the performance of the safety functions through other measures. For instance, hydraulic power units will be mechanical, indirect, automatic, active measures, whereas tools such as crowbars will be manual, direct, non-automatic, passive measures.

The last modification of the known risk reduction measure classification (presented in Figure 1) is the change of only the name of the characteristics from material/non-material to technical/organisational (T/O).

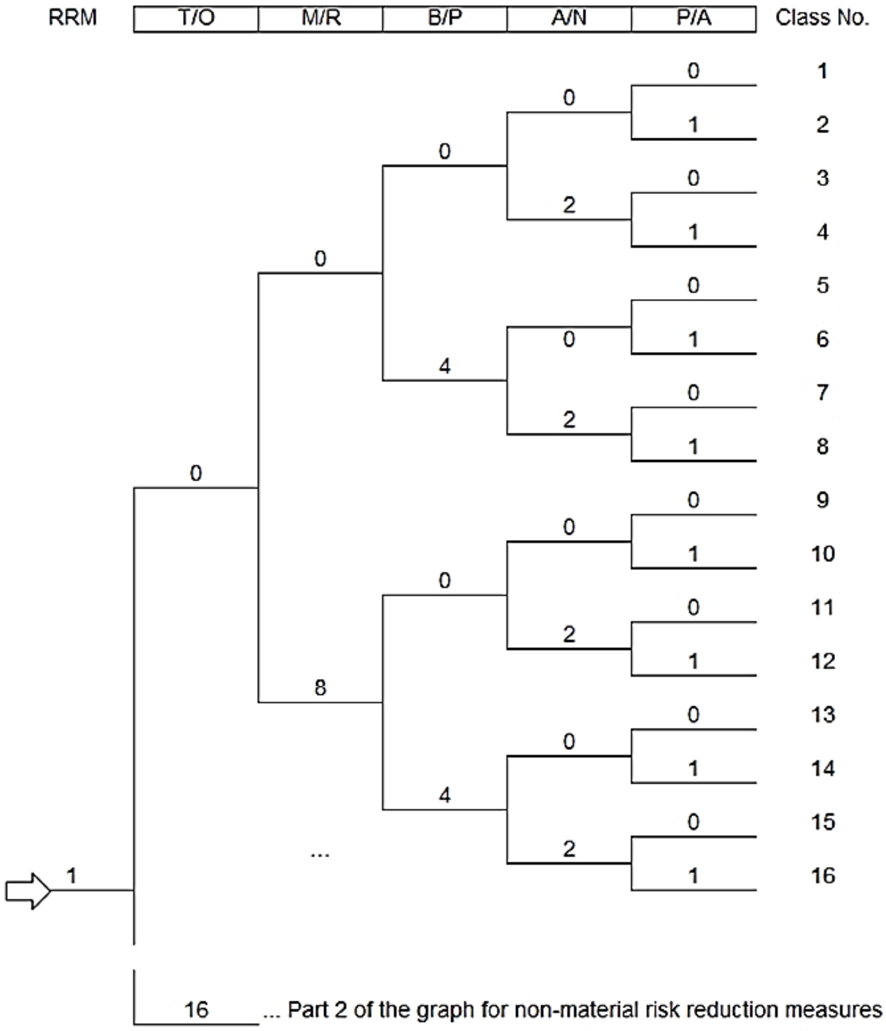

Fig. 2. Part of the risk reduction measure classification diagram concerning technical measures with rank numbers of their qualities, where: RRM – risk reduction measure; T/O, M/R, B/P, A/N, P/A – symbols of risk reduction measure characteristics: technical/organisational, mechanical/manual, direct/indirect, automatic/non-automatic, passive/active, respectively

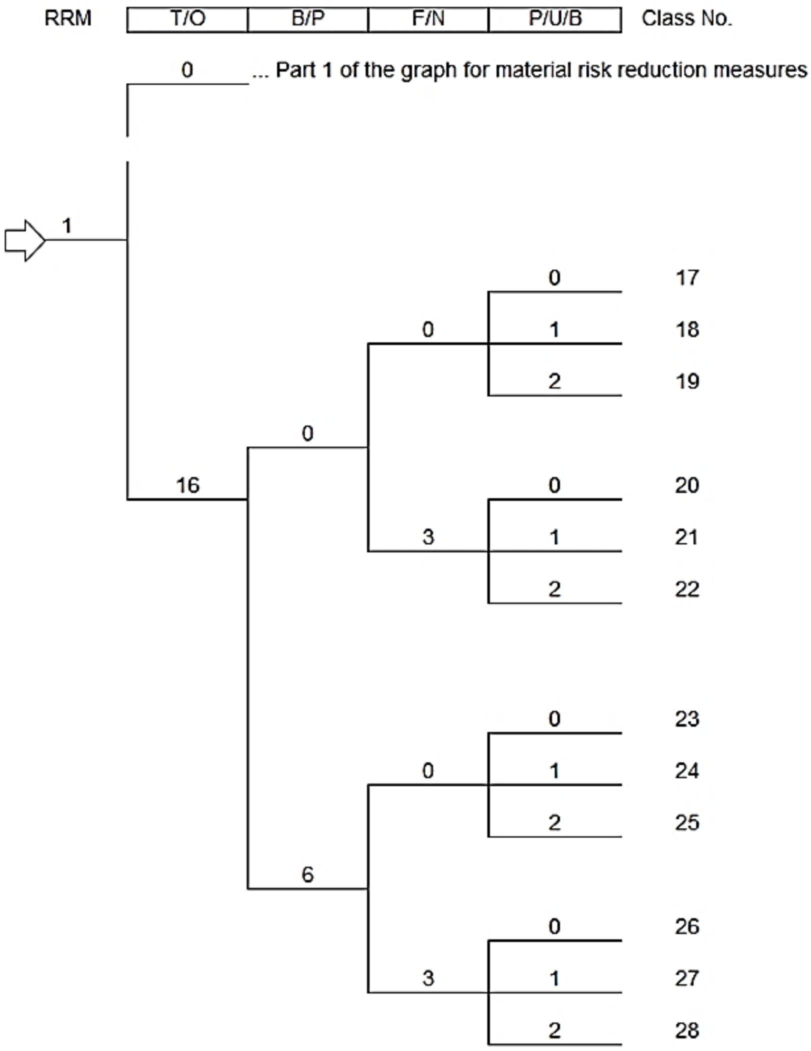

Fig. 3. Part of the risk reduction measure classification diagram concerning organisational measures with rank numbers of their qualities, where: RRM – risk reduction measure; T/O, B/P, F/N, P/U/B – symbols of risk reduction measure characteristics: technical/organisational, direct/indirect, formal/informal, written/oral/behavioural, respectively

As part of the adaptation of the known classification of risk reduction measures (Fig. 1), the manner of determining the extent of efficacy was also algorithmised, in accordance with formula (1). Appropriate ranking of individual qualities of safety system elements was introduced. Rank numbers – integers, not series of natural numbers – are related to the number of branches at the successive levels (columns) of the graph. If each level has two branches, a binary system may be used. The next rank number, starting from the right side of the graph, i.e. the last level or column of the graph, is twice the value of the previous one. If there are more branches, the multiplicative manner of determining rank numbers does not apply.

It was also assumed that the number of the risk reduction measure class shall be determined as the sum of the rank numbers. The components of this sum may be calculated after identifying and noting the successive risk reduction measure qualities (e.g. according to the T/M/P/N/A notation) or they may be read off the classification diagrams. For instance, using the diagram presented in Figure 2, a technical risk reduction measure that is a mechanical and non-automatic measure performing its functions indirectly as a result of a change of its state (T/M/P/N/A) will receive the following class number: 1 + 0 + 0 + 4 + 2 + 1 = 8.

METHOD PROCEDURE EXECUTION

As indicated above, the measures selected for assessment are the technical measures of the railway technical rescue system, which perform the safety functions with reference to the rescued objects. Below (Table 3), estimation results of their efficacy were presented for selected technical risk reduction measures. The measures chosen for analysis were measures included in the minimum and standard list of technical rescue equipment (equipment and technical measures), but the list was supplemented with measures from different subsystems of the rescue system.

In order to determine the total efficacy of the system, the use of simple measures is suggested, such as the sum of the efficacy of the individual elements of the system or the average efficacy. As the structure of the system (the number and type of relationships between the elements) or the principles of its operation become more complex, it is certainly possible to use more advanced efficacy measures, which is mentioned in the "Discussion" section.

Table 3. Results of efficacy assessment of selected technical risk reduction measures in technical rescue systems

ID	Abbreviated name of risk reduction measure (RRM)	Characteristic symbol					Class no.	Efficacy
2.1.	Hydraulic spreaders	T	M	B	N	A	3	0.333
2.2.	Hydraulic rescue cutters...	T	M	B	N	A	3	0.333
2.3.	Telescopic rams	T	M	B	N	A	3	0.333
2.4.	Hydraulic power units	T	M	P	A	A	5	0.200
2.5.	Hydraulic hose set...	T	R	P	N	P	14	0.071
2.6.	High-pressure air cushions...	T	M	P	A	A	5	0.200
2.7.	Control equipment for inflating with a compressed air cylinder...	T	R	P	N	P	14	0.071
2.8.	Compressed air cylinder...	T	R	P	N	P	14	0.071
2.9.	Chainsaw...	T	M	B	N	A	3	0.333
2.10.	Circular saw...	T	M	B	N	A	3	0.333
2.11.	Spring-loaded punch for safety glass	T	R	B	N	P	10	0.100
2.12.	Seatbelt cutter	T	R	B	N	P	10	0.100
2.13.	Shackle and cable attachment kit for a winch	T	R	P	N	P	14	0.071
D.1	Hydraulic spreader-cutters	T	M	B	N	A	3	0.333
D.2	Hand pumps	T	R	B	N	A	11	0.091
D.3	Stabilizing blocks and wedges	T	R	B	N	P	10	0.100
D.4	Rescue platforms	T	R	B	N	P	10	0.100
D.5	Steel supports	T	R	B	N	P	10	0.100
D.6	Quick stabilisation system SW-350	T	M	B	N	A	3	0.333
D.7	Hydraulic door opener	T	M	B	N	A	3	0.333
D.8	Glass management accessories	T	M	P	N	P	6	0.167
D.9	Handsaw	T	R	B	N	A	11	0.091
D.10	Semi-automatic glass punch	T	R	B	A	P	8	0.125
D.11	Transparent shield	T	R	B	N	P	10	0.100
D.12	Protective equipment (mats, covers)	T	R	P	N	P	14	0.071
D.13	Halligan Bar	T	R	B	N	P	10	0.100
D.14	Axes/hammers/crowbars/hooks	T	R	B	N	P	10	0.100
D.15	Hydraulic pipe clamp	T	M	P	N	A	7	0.143

Table 4. Results of safety system efficacy estimation with the use of the semi-quantitative classification method of efficacy assessment provided for two sample risk reduction measure lists

List 1		List 2	
Abbreviated name of the measure (RRM)	**Efficacy**	**Abbreviated name of the measure (RRM)**	**Efficacy**
2.1. Hydraulic spreaders	0.333	2.3. Telescopic rams	0.333
2.4. Hydraulic power units	0.200	D.6. Quick stabilisation system SW-350	0.333
2.6. High-pressure air cushions...	0.200	D.2. Hand pumps	0.091
2.11. Spring-loaded punch for safety glass	0.100	D.10. Semi-automatic glass punch	0.125
D.4. Rescue platforms	0.100	D.4. Rescue platforms	0.100
Total:	0.933	Total:	0.982

In order to present the efficacy estimation results, two sample risk reduction measure lists were prepared. The selection of only some of the available measures is due to the fact that the use of the method is anticipated, among others, in the case of specific rescue tasks or operations where not all of the system resources are necessary. In the example, some of the measures constituting the minimum standard equipment list were replaced with different types of measures, but performing similar functions. The estimation results were presented in Table 4.

In the presented example (Table 4), the aim was to make the risk reduction measure lists similar, so that they would include similar types of measures (performing similar functions) and the number of the measures would be the same. In spite of that, as well as the low number of measures, differences in the total efficacy of the safety system based on the given lists can be observed. It would therefore be reasonable to base the safety system structure on the risk reduction measures included in the second list.

3. Discussion

Treating the sample list of risk reduction measures as a specific safety system, a simple measure of its efficacy was adopted, i.e. the sum of the values of efficacy of its individual elements. It should be noted, however, that the total efficacy assessment of the system may be carried out based on more advanced models. This depends on the complexity of the system or the principles of its operation, and in some cases, also on the available information. Examples of advanced efficacy estimation models were presented in detail, among others, in [2, 6]. Which model should be selected (coincidence, diversification, reinforcement) depends on the relationships between the risk reduction measures within one subsystem or even subsystem subgroup. In the case of a subgroup, it will usually be diversification or exclusion models (assuming, for example, that the rescuer has several types of clothing at their disposal and can use each type, even inappropriate for the surrounding conditions, but at the same time, they will not put on each type of clothing). Within subsystems or systems, it will generally be reinforcement and sequence models.

Diversification models constitute an interesting group. They reflect the effect of two or more risk reduction measures as a certain outcome of their performance of the safety functions with not entirely understood mechanisms of interoperation between the measures. It may, however, be assumed that along with an increase of the size of the group of risk reduction measures coexisting in this manner, the efficacy of its effect on hazard sources will increase. Therefore, in order to determine the efficacy of a group of measures, different average value measures can be used, for instance: the weighted average, centre of gravity or centroid, as well as the so-called diversity measures. In the most general sense, diversity includes a finite set of mutually exclusive events occurring with specific probabilities or proportions [8]. In applications in biology and ecology, the problem usually involves a sample or population of different species. Literature proposes many measures of diversity, such as Simpson's Diversity Index [14] or the measure of Shannon's Entropy. By marking the simplest form of this measure as Z1, diversity can be expressed as the following relationship [8]:

$$Z_1(P_n)=n \qquad (2)$$

where:

P_n is understood as a probability distribution of the presence of the n-th entity (unit, element) in a specified group.

In the case of estimating the efficacy of the entire system, the use of reinforcement models is proposed. A reinforcement relationship is a basic type of relationship between risk reduction measures performing one safety function. This means that the effect of one measure increases the possible effect on hazard sources of the other measure or supports limiting the results of hazard activation by the other measure. One of the measures is, for instance:

$$E_j = 1 - \prod_{i=1}^{n} \left(1 - p_i v_{ij}\right), \ j = 1,2,\ldots,m \qquad (3)$$

where:

E_j - efficacy of risk reduction measures connected by reinforcement relationships, having an effect on the j-th hazard source.

p_i - value of the probability of an event that the i-th risk reduction measure is in the state of usability.

v_{ij} - vulnerability of the j-th hazard source to the i-th risk reduction measure.

CONCLUSIONS

For rational management of safety systems, the use of a good, comprehensive measure making it possible to determine the efficacy of such systems (and/or the efficacy of their elements), is necessary. At the same time, it is reasonable to use the simplest possible methodology for its determination, which will bring the following benefits:

- rationality of the effects of the method (financially attractive for entities implementing safety policies),
- possibility to use the method in the case of a lack of experimental research or the impossibility to conduct such research with the participation of people,
- limitation of human resources involvement in the preparation of the safety system configuration,
- possibility to adapt the method to the changing conditions (also legal conditions), usually with limited resources and information,
- formal documentation of the results of the process of dealing with risk with the use of the safety systems.

The method presented in the article is intended to initiate a search for safety system efficacy measures meeting the above-mentioned conditions. The results obtained based on the application of the method to railway technical rescue systems are intended to constitute an example of a presentation (picture) of the results of a formalised approach to the safety system efficacy assessment. They do not, however, constitute a comprehensive solution to the problem of efficacy assessment of the analysed safety systems in this sense, as we treat them as one of many possible solutions. Yet this does not exclude the fact that the example results provided may already in this form aid decisions concerning technical rescue systems.

It should be noted that the determined efficacy assessments are not intended to be used to compare risk reduction measures. This is not possible primarily because the measures perform different safety functions. It is, however, possible to compare alternative lists of risk reduction measures, which was demonstrated in this article.

The estimation of the efficacy of individual risk reduction measures according to the adopted classification will bring considerable benefits in the case of specific combinations of characteristics, as to which the efficacy assessment will be difficult or doubtful.

Another advantage of the method is the fact that it makes it possible to generate the final result of the safety system assessment in quantitative form and creates the possibility of formal presentation of the principles of the assessment, which increases its transparency and enables its repetition. At the same time, the assessment is obtained regardless of the degree of complexity of the given risk reduction measure.

The original solution in the form of rank numbers makes the use of the method easy, which is not without significance with usually limited human, time, and in particular information resources available in the process of preparation of the safety system configuration.

The use of the method is anticipated e.g. in the case of assessments of specific rescue tasks or operations during which not all of the system resources are necessary and the assessment has to be conducted very quickly.

A significant advantage of the method is the possibility of easy modifications and calibration, e.g. by changing the interpretation of the qualities and their location in the graph structure or only by changing the order of the occurrence of the qualities in the classification diagrams.

Further activities planned in connection with the development of the method include researching different forms of classification diagrams and conducting efficacy assessment studies with the use of a group of experts.

ABBREVIATIONS

1. **RRM** – Risk Reduction Measures;
2. **T/O** – technical/organisational;
3. **M/R** – mechanical/manual;
4. **B/P** – direct/indirect;
5. **A/N** – automatic/non-automatic;
6. **P/A** – passive/active;
7. **F/N** – formal/informal;
8. **P/U/B** – written/oral/behavioural

ZASTOSOWANIE KLASYFIKACYJNEJ PÓŁILOŚCIOWEJ METODY OCENY SKUTECZNOŚCI ELEMENTÓW SYSTEMÓW BEZPIECZEŃSTWA DO SYSTEMU KOLEJOWEGO RATOWNICTWA TECHNICZNEGO

Wiele badań pokazuje, że nadmierna rozbudowa systemów bezpieczeństwa może być nieracjonalna i nieefektywna. Aby tego uniknąć, konieczne jest określenie metody oceny skuteczności implementowanych środków redukcji ryzyka. W artykule przedstawiono adaptację opracowanej wcześniej metody tego typu, do charakteru działania kolejowych zespołów ratowniczych. Metoda wykorzystuje hierarchiczny system klasyfikacji środków bezpieczeństwa, który stanowi podstawę do określenia ich skuteczności. Sposób wdrożenia metody przedstawiono na przykładzie 28 wybranych narzędzi/sprzętu wykorzystywanego przez zespoły ratownicze, działające w ramach polskiego zarządcy infrastruktury kolejowej. Choć uzyskane wyniki nie stanowią kompleksowego rozwiązania problemu oceny skuteczności systemów bezpieczeństwa, to jednak mogą być wykorzystane do wsparcia decyzji podejmowanych w tym obszarze.

Słowa kluczowe: skuteczność, system ratowniczy, system bezpieczeństwa

REFERENCES

[1] Bianchini A., Donini F., Pellegrini M., Saccani C. (2017) An innovative methodology for measuring the effective implementation of an Occupational Health and Safety Management System in the European Union. *Safety Science*, 92, pp 26–33. https://doi.org/10.1016/j.ssci.2016.09.012

[2] Gill A. (2018) *Warstwowe modele systemów bezpieczeństwa do zastosowań w transporcie szynowym [Layered models of safety systems for rail transport applications]*. Wydawnictwo Politechniki Poznańskiej, ISBN: 978-83-7775-517-4

[3] Głodek W. (2003) Automatyka zabezpieczeniowa w przemyśle procesowym – przegląd unormowań, *Warsztaty SIPI61508*, 3, pp 1–10

[4] Harms-Ringdahl L. (2013) *Guide to safety analysis for accident prevention*. IRS Riskhantering AB: Stockholm, Sweden, ISBN 978-91-6373-164-8

[5] Hubbard D. W. (2009) *The Failure of Risk Management: Why It's Broken and How to Fix It.* ISBN 978-04-7038-795-5, John Wiley & Sons Inc.

[6] Lee K. H., Benke G., Mckenzie D. (2022) The efficacy of earplugs at a major hazard facility. *Physical and Engineering Sciences in Medicine*, 45(1), pp 107-114. https://doi.org/10.1007/s13246-021-01087-y

[7] Kadziński A. (2013) *Studium wybranych aspektów niezawodności systemów oraz obiektów pojazdów szynowych [Study on selected dependability aspects of systems and rail vehicles objects]*. Wydawnictwo Politechniki Poznańskiej, ISBN: 978-83-7775-289-0

[8] Lovric M. (Ed.). (2011). *International Encyclopedia of Statistical Science* (1st ed.). ISBN 978-3-642-04897-5, Springer-Verlag Berlin Heidelberg.

[9] PN - EN 50126-2:2018. Zastosowania kolejowe. Specyfikowanie niezawodności, dostępności, podatności utrzymaniowej i bezpieczeństwa (RAMS). Część 2: Sposoby podejścia do bezpieczeństwa. Polski Komitet Normalizacyjny.

[10] PN - EN ISO 9000:2015-10. Systemy zarządzania jakością - Podstawy i terminologia. PKN, 58 (2015)

[11] Podlasiński, R. (2018). *Skrypt do szkolenia ratownictwa technicznego realizowanego przez KSRG w zakresie podstawowym*. Komenda Główna Państwowej Straży Pożarnej

[12] Saracinoa A., Curcurutob M., Pacinic V., Spadoni G., Guglielmib D., Saccanic C., Boccid V. M., Cimarellie M. (2012) IPESHE: an Index for Quantifying the Performance for Safety and Health in a Workplace. *Chemical Engineering*, 26, pp 489–494.

[13] Šeibokaitė L., Endriulaitienė A., Markšaitytė R., Slavinskienė J. (2022) Improvement of hazard prediction accuracy after training: Moderation effect of driving self-efficacy and road safety attitudes of learner drivers. *Safety Science*, 151, https://doi.org/10.1016/j.ssci.2022.105742

[14] Simpson E. H. (1949) Measurement of Diversity. *Nature*, 163, pp 688. http://dx.doi.org/10.1038/163688a0

[15] Sobczak P. (2020) The efficiency of the selected polish regional rail carriers in the years 2017-2020. *Journal of Civil Engineering and Transport*, 2(4), pp 203–213. https://doi.org/10.24136/tren.2020.015

[16] Summers A. E. (1998) Techniques for assigning a target safety integrity level. *ISA Transactions*, 37(2), pp 95–104. https://doi.org/10.1016/S0019-0578(98)00010-X

[17] Vincoli J. W. (2014) Basic Guide to System Safety, Third Edition. John Wiley & Sons Inc. https://doi.org/10.1002/9781118904589

[18] Zjawińska W. (2021) Komunikowanie o ryzyku z wykorzystaniem warstwowych modeli systemów bezpieczeństwa. Master's dissertation (thesis supervisor: Adrian Gill); unpublished