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NON-STANDARD RISK MODEL FOR APPLICATIONS IN RAILWAY TRANSPORT

Summary. In risk management in railway transport, standard risk models are usually used based on its typical definition and discrete quantification. This approach allows for easy justification of the adopted model, most often by referring to appropriate norms or standards (such as IRIS). The scientific approach does not disqualify the practical use of standard risk models, but its disadvantages (especially typical risk matrices, including their subjectivity) are increasingly being pointed out. In risk management procedures, most frequently one model is used to assess the risk of all identified hazards. This may turn out to be a mistake, considering the specific characteristics of the hazards. A risk model applied to one hazard may not be adequate to assess the risk of another. Therefore, it should be individually adapted both in terms of variables and the ranges of their measurement values. For some hazards, it will even be necessary to develop or adopt non-standard models. The aim of the article is to present non-standard risk models that provide a base for their easy implementation in safety management procedures used by railway entities.

Keywords: railway, risk model, RAMS

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1. INTRODUCTION

In risk management in railway transport, standard risk models based on the typical definition of risk (see risk definition in subsection 2.1) and discrete mapping of the measures of risk components are usually used. Slightly more detailed models, i.e. those based on the FMEA method, are used equally frequently. An example in Poland may be the SMS/MMS-PR-02 Procedure – Technical and Operational Risk Assessment [25] used by the administrator of the national railway network, or certain research papers, for instance [32, 33] as well as the work [15], where FMEA was conducted on the example of the main railway station in Bielsko-Biala. The situation is also confirmed by cross-analyses available in literature (conducted, for instance, in papers [31, 40]), as well as (unpublished) documentation for projects carried out in cooperation with railway market entities. It should be noted, however, that risk management in railway transport based on standard risk models can be observed not only in Poland, which is evidenced by other research papers. For example, the authors of the paper [6] presenting a framework for risk management at railways, use a two-component risk model (consequences and frequencies of hazards). The authors of the paper [3], in their Hybrid Model for Optimizing Reliability, Risk and Maintenance of a Rolling Stock Subsystem, emphasize identifying critical failure modes using risk priority numbers. The authors of the paper [27], indicate that FMEA is an effective tool for the risk assessment of mechanical systems by applying its extended version to rolling stock operated in an iron ore mine in Sweden. Similarly, the authors of the paper [24], who present the implementation of a modified FMEA methodology in accordance with EU Commission Regulation 402/13 on a common safety method for risk assessment and evaluation in the railway sector.

Reasons for the more extensive use of the standard risk models can be assumed, taking into consideration the origin of the popularity of the FMEA method in the railway transport industry. The author of dissertation [39] associates it with IRIS (International Railway Industry Standard), which is the basis for quality management systems used by manufacturers of railway vehicles and railway vehicle equipment. In accordance with the guidelines provided for IRIS, the FMEA method is the preferred risk analysis method applicable at any stage of the product life cycle, in particular in the risk analysis procedure and the RAMS procedure [39]. Such a recommendation may turn out to be a sufficient reason, as it provides basis for references to legislative provisions.

In risk management procedures executed this way, one risk model is used for risk evaluation for all the identified hazards. This may turn out to be a mistake, taking into account the unique characteristics of the hazards, including [20] e.g.: the history and probability of hazard activation, the extent of losses/damage generated in the area of analysis. The values of hazard characteristics are used to determine the risk component, and because of such a broad spectrum of those, this provides the basis for a greater differentiation of risk models.

A risk model applied for one hazard may not be appropriate for the evaluation of the risk of another hazard. In this case, it should be individually adapted to the hazard, both in terms of the variables and the value ranges of their measures. The (theoretical) situation where risk management procedures consider as many risk models as there are hazards is therefore correct. Perhaps with some of them, it may be necessary to develop or adopt non-standard models. A number of needs, obstacles, and challenges related to risk assessment and risk management processes (including risk models), adapted to the current and future technological challenges, were mentioned by the authors of [5].

The problem in applying non-standard risk models may, however, be their excessively academic and abstract nature. At the same time, a considerable amount of input data is required for them, which is not always available in the practice of operating railway transport systems. Academic literature presents many detailed, but also relatively complex risk models that require a considerable amount of data (see subsection 2.2).

The validity of the application of risk models verified in practice (such as the FMEA) is not questioned. However, noticing their flaws (e.g., work [27]), and sometimes even their debatable value in the context of certain hazards [14], different authors are trying to develop risk models constituting an extension to the FMEA. Such a model was proposed, among others, by the authors of [14, 24]. At times, the FMEA or FMECA also becomes part of hybrid models (e.g. in [3]), constituting a combination of several methods used in safety engineering. A broader description of the models was included in subsection 2.2.

The inclination to use the already proven models (sometimes even in spite of their perceived invalidity for certain hazards) is related to the lack of inclusion of non-standard models in the norms. And although the application of approaches based e.g. on the FMEA is not imposed by legislation, it seems easier to justify for entities required to manage risk. Ultimately, a conclusion can be made that the lack of information about the existence of non-standard models simply contributes to their non-application.

In academic literature, other, relatively simple risk models are known which may turn out to be convenient in the risk assessment in railway systems. An example may be the model presented by Schöne i Mahboob in their book [29] or Aven's model provided in his publication [4]. Although example applications were provided for such models and the adopted variables were explained, in the perspective of their convenient implementation in risk management procedures, the need for their broader interpretation and discussion of the applied variables is observed.

The paper is aimed at presenting a non-standard risk model, providing grounds for convenient implementation in the safety management procedures used by entities in the railway industry. The article presents such a model in section 3. An example application of the model for the estimation of the risk of hazard of a collision between a railway vehicle and a road vehicle at category B level crossings was also presented.

2. MATERIALS AND METHODS

2.1. What a risk model is

A risk model is said to be a way of mapping the properties of the area of analysis (existing in hazard conditions), significant in terms of safety, with the use of a finite set of symbols and mathematical or logical relationships, including a function of transition from a set of hazards to a set of undesirable events, taking into account their effects (damage, losses) and uncertainty [20]. It is worth noting that the above definition clearly indicates the need to map the uncertainty measure in the risk model (which is also mentioned and applied in risk models e.g. by Aven [4, 35] or the Society for Risk Analysis [31]).

A risk model can be a set of symbols, i.e. it can be a graphical model without mathematical relationships. The geometric or topological properties of a graphic unit then serve to represent the geometric properties, logical relationships or functions of the executed process. A graphical risk model is often presented in regulations dedicated to risk management processes, for instance those related to RAMS specifications.

Graphical models, no matter how useful they may be for the visualisation of an issue or problem, are, however, usually converted into any other formal form – usually mathematical (deterministic, statistical or simulation). It might be said that risk as a measure of hazard severity is then expressed with the value of the relevant function (in generalised form provided in relationship (1)).

Mathematical risk models frequently contain several components whose values or levels are determined in the risk analysis process in accordance with the adopted criteria. What components a risk model should contain is specified by the definition of risk itself, for instance the one proposed by Vincoli [36] or a similar one, formulated by the Center for Chemical Process and Safety – New York [9]: "a measure of human injury, environmental damage, or economic loss in terms of both the incident likelihood and the magnitude of the loss or injury. A simplified version of this relationship expresses risk as the product of the likelihood and the consequences (i.e. Risk = Consequence x Likelihood) of an incident".

An example of a more detailed approach to a risk model, in particular in the context of expressing the likelihood and uncertainty of events, is presented e.g. by MacDonald in [12]. The risk model he proposes includes a coincidence of three different measures related to hazard activation: frequency and duration of exposure, probability of hazardous event, possibility to avoid or limit harm.

If a risk model is to be presented in mathematical form, its form may always be notated in generalised form as follows [21]:

$$R(z_k) = f[r_1(z_k), r_2(z_k), \dots, r_m(z_k)]\ , k = 1,2, \dots, l \quad (1)$$

where $r_i(z_k)$ is a component of the risk of the k-th hazard.

2.2. Literature review on risk models used in railway transport

An illustrative example of a risk model which is mathematically advanced and requires a considerable amount of data is the cloud model-based risk assessment [38]. It was developed for application with railway tunnels, more precisely in the risk assessment for the existing Guangzhou-Shenzhen-Hong Kong railway tunnel. In the adopted methodology, a risk assessment index is used, developed based on the tests of the geological condition, the condition of the natural environment, the tunnel design scheme, and construction management. The cloud model, in turn, is intended to provide a basis for the transformation of uncertainty between its qualitative concepts and quantitative expressions.

Another example is a risk model expressed with the probability of a hazardous event (dynamic hybrid model; DHM), presented by [2]. The DHM makes use of the Bayesian method of factorisation and network variable elimination as a complex aggregation of frequency and severity distributions. The DHM verifies the predicted risk using machine learning based on the Bayesian expectation-maximisation, evidence of expert knowledge propagation, and learned data [2].

An interesting example of a risk model which can be categorised as non-standard is one using the logistic regression method, presented in paper [8]. It was developed with reference to level crossings, but it seems flexible enough for it to be easily adapted to risk assessment and monitoring in different areas of the railway system. Another such example is the risk model presented by [13]. It is entirely a probabilistic model, i.e. it is based on an index constituting a relationship between the probability of an event calculated with Markov processes/models and statistical probability (based on real events).

A similar example is [34], constituting a risk model based on the estimated number of accidents on platforms. As a result of its development, 16 factors were defined, such as platform structure and passenger traffic. Poisson regression and negative binomial regression models were used to estimate and analyse the number of accidents from the station's database (158 platforms from 52 stations in Japan).

In academic studies on risk models, a trend of establishing risk models based on the fuzzy set theory emerges. Examples of such solutions (applicable to railway transport), intended for different stages of the systems' life cycle and their areas of application, can be identified. For instance, at the stage of designing railway structures – papers [16, 24], railway traffic control – paper [10] (using so-called fuzzy-AHP, i.e. the fuzzy analytical hierarchy process, which is a combination of the AHP and the fuzzy set theory; described in detail with reference to railway transport by An and Chen in book [1]), carriage systems – paper [14], as well as trespassing on the railway tracks – paper [19]. It is pointed out that the reason for such an approach lies in the flaws of the typical risk matrices, including their subjectivity. It was observed that they can be reduced by mapping the relationship between the risk assessment value and its category scale in a linear or logarithmic manner [10], or in a different way that is not discrete mapping. A significant degree of mapping discretisation may lead to low quality and usability of the results of risk assessments [10, 11].

Fuzzy logic finds application primarily in the elimination of the flaws of the FMEA models, in particular the RPN (risk priority number) index. Among the most criticised flaws of the RPN, Fu et al. [14] include: the algebraic product of the value of the index components may be debatable and introduce excessive sensitivity to the model, different combinations of the index component values may give the same value of the index, which is not effective in practical risk management, precisely determining the index component values may be difficult in many real scenarios, in the conventional FMEA approach, the relative significance of the index components may be overlooked.

In their article [14], they presented an extended FMEA model based on the cumulative prospect theory and the VIKOR method (with type-2 fuzzy sets) for determining the priority of hazards related to trains. Such an extension was aimed at eliminating the limitations of the traditional FMEA approach and examining the crucial types of damage to the elements of the operated train. The essence of the method they developed is the adoption of triangular intuition-based type-2 fuzzy numbers for mapping uncertainty in risk analysis. Similarly, Macura et al. [24] presented the use of a risk model with the FMEA method based on fuzzy logic. They used interval type-2 fuzzy logic which, by assumption (i.e. through the fuzzification of the membership function of fuzzy sets), provides better mapping of the degree of uncertainty, in this case – uncertainty resulting from risk assessment. The validity of the use of fuzzy logic is justified by the authors with the possibility to use data which is uncertain or vague. Many events (occurring during the construction or modernisation of railway infrastructure projects) are defined with more than just simple binary values. In this case, the fuzzy FMEA is the best choice, in particular with sensitive models. In order to illustrate the importance and the potential of the developed model, the presented approach was applied and demonstrated with reference to railway infrastructure projects in the Republic of Serbia.

The use of the fuzzy set theory and classical FMEA-based risk models results in the development of non-classical models (they may be called extended FMEA/FMECA). Meanwhile, the use of a standard model in combination with other techniques or methods leads to the development of hybrid models with structures dependent on the methods applied. One example may be paper [3], in which Appoh et al. use a standard risk model (FMECA) in the form of RPN in order to identify critical forms of damage. This is a classic definitional use of this index. However, they treat the procedure of identifying the form of damage and determining its criticality as one of the components of the hybrid model, integrating the issues of reliability, risk, and operating techniques in damage analysis and resource management. It might be said that their work constitutes an application of the risk management procedure according to the RBM (risk-based maintenance) idea.

Apart from the articles mentioned above, those which do not present risk models directly, but provide grounds for their development may be pointed out. These include papers [18, 22] concerning risk analysis or hazard identification processes. However, they will not be analysed in more detail in this article.

3. RESEARCH ISSUES

The model is based on the classical definition of risk and the principles of the RAMS standards [26], but its essence lies in the original mapping of the component related to hazard activation (“transformation” of undesirable system states into a hazardous event involving measurable losses). It was performed taking into consideration the assumptions and graphical risk model provided in the RAMS specification standards (Fig. 1). The distinctive feature of this risk model is the division of hazards into:

- hazards at the level of the analysed (or considered) system,
- hazards in the supersystem of the analysed system (hazards at the railway system level).

The relationship between the listed systems may be explained in simple terms as follows: the analysed/considered system is implemented in the railway system. In reality, the emergence of an undesirable state (a state which may lead to an accident) in a railway system is the development of an undesirable state in the analysed/considered system. This was shown symbolically in Fig. 1 and as a formal notation with relationship (2).

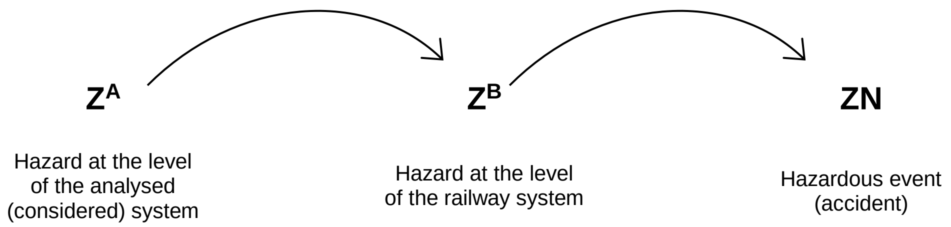

Fig. 1. The concept of hazard “development” in railway systems, presenting the division of hazards according to risk model as per the PN-EN 50126-2 standard

If we were to call a single event, event sequence, factors, or properties of the area of analysis conditions leading to an accident, then the set of conditions may be divided into subsets of conditions applicable to the considered system (called hazards at the level of the considered system), conditions applicable to the railway system (as the supersystem of the considered system), called hazards at the level of the railway system.

If we were to further mark the set of all the conditions leading to a hazardous event (accident) with a Z, then the relationships between the hazards at different levels of system decomposition can be notated as follows:

$$\mathbf{Z^A} \subset \mathbf{Z^B} \subset \mathbf{Z} \tag{2}$$

where $\mathbf{Z^A}$ is a subset of conditions leading to an accident at the level of the considered system, and $\mathbf{Z^B}$ is a subset of conditions leading to an accident, applicable to the railway system.

Using the assumptions adopted here and relationship (1), the mathematical form of the RAMS model can be expressed as follows:

$$R(z_k) = f[P(ZN_{wk}), S(ZN_{wk})], k = 1,2, \dots, l; w = 1,2, \dots \tag{3}$$

where:

$P(ZN_{wk})$ – risk component expressing the probability of the *w*-th type of a hazardous event resulting from the activation of the *k*-th hazard,

$S(ZN_{wk})$ – risk component expressing losses arising due to the occurrence of the *w*-th type of a hazardous event resulting from the activation of the *k*-th hazard.

In this risk model, it is assumed that the losses arising due to a hazardous event can be mapped in the form of one generalised measure (regardless of the number of loss categories or the size of the spectrum of these losses). A principle of maximum possible loss or most probable loss may be adopted here, yet still, the conditional probability of the occurrence of the given type of loss S_w is assumed to be certain, i.e.:

$$P(S_w|ZN_{wk}) \cong 1 => P(S_w) \equiv P(ZN_{wk}) \tag{4}$$

In the simplest, but also the most critical case, the hazard at the level of the analysed system may be caused by (may be the effect of) one factor, error, form of damage or – generalising – hazard source (ZZ). Such event sequences are analysed in the FMEA method or e.g. the Bowtie method. One type of damage/error or failure to fulfil a function leads to the occurrence of a local effect, primarily in the form of an undesirable state of the analysed system (i.e. definitionally, hazard at the level of the analysed system). In such a case, the relationships between the hazardous events, hazards, and their sources (hazard factors, types of damage, function error, etc.), can be notated as the following sequence: ZZ □ Z^A □ Z^B □ ZN.

If we assume that the probability of the occurrence of the state/hazard Z_j^A depends not only on the occurrence of its source, but also the “chance” that the given source is causing this state, then the relationship for the probability of this state/hazard may be expressed as follows:

$$P(Z_j^A) = P(ZZ_i) \cdot P(Z_j^A|ZZ_i), \quad i = 1,2, \dots, m; j = 1,2, \dots, n \tag{5}$$

where:

$P(ZZ_i)$ – probability of the occurrence of the *i*-th hazard source (form of damage, function error, etc.),

$P(Z_j^A|ZZ_i)$ – probability of the emergence of a hazard at the level of the analysed system provided that the *i*-th hazard source occurs (Willis calls this vulnerability with respect to the risk of terrorist threat [37]).

If we then, similarly to relationship (5), notate that:

$$P(Z_k^B) = P(Z_j^A) \cdot P(Z_k^B|Z_j^A) \tag{6}$$

$$P(ZN_{wk}) = P(Z_k^{\mathrm{B}}) \cdot P(ZN_{wk}|Z_k^{\mathrm{B}}) \tag{7}$$

where:

$P(HRL_k|HSL_j)$ – the (conditional) probability of the occurrence of the k-th hazard at the level of the railway system provided that the j-th hazard occurs at the level of the analysed system.

$P(AE_{wk}|HRL_k)$ – the (conditional) probability of the occurrence of the w-th hazardous event resulting from the activation of the k-th hazard at the level of the railway system provided that this hazard occurs,

then the probability of risk component $P(ZN_{wk})$ will be equal to:

$$P(ZN_{wk}) = P(ZZ_i) \cdot P(Z_j^{\mathrm{A}}|ZZ_i) \cdot P(Z_k^{\mathrm{B}}|Z_j^{\mathrm{A}}) \cdot P(ZN_{wk}|Z_k^{\mathrm{B}}) \tag{8}$$

The RAMS model, demonstrated with relationships (3) and (8), is so universal that giving the conditional probabilities appropriate interpretations will transform it into standard models. For instance, giving the conditional probabilities the interpretation of undetectability will cause a transformation of the RAMS model into the FMEA model and the RPN index, i.e.:

$$P(ZN_{wk}) = P(ZZ_i) \cdot [1 - W(ZZ_i)] \cdot [1 - W(Z_j^{\mathrm{A}})] \cdot [1 - W(Z_k^{\mathrm{B}})] \tag{9}$$

where $W(ZZ_i)$, $W(Z_j^{\mathrm{A}})$, $W(Z_k^{\mathrm{B}})$ is the detectability of: the hazard source, the hazard at the level of the analysed system, and the hazard at the level of the railway system, respectively. Other examples of conditional probability interpretations were adopted in the second risk model, presented further on in the article – relationship (12).

The interpretation of conditional probabilities (relationship (8)) as the efficacy or inefficacy of the fulfilment of the safety function, i.e. the effect of the risk reduction measure on the hazard source, the hazard at the level of the analysed system, and the hazard at the level of the railway system, respectively, is also valid. Such efficacy may be expressed and understood in various ways. It is a synthetic measure, i.e. it usually combines the component of probability of the effect (inclusion) of the measure and the component of certain susceptibility of the hazard source to the effect of the risk reduction measure. In literature on the subject, other examples of understanding and estimating efficacy are also proposed. Bianchini et al. [7] suggest determining the value of the *efficacy index* (EI), the value of which is obtained based on the costs of the consequences of the event and the costs of preventing these events. The works of Saracinoa et al., e.g. [28], presenting an index used to express the effect of the properties of the workplace on employee health in quantitative terms, are also worth noting.

Although it is difficult to express efficacy in measurable characteristics (which is why it is often mapped qualitatively with the use of linguistic variables or in other ways, verbally or descriptively), for the purpose of this model, it will be convenient to express it as a probabilistic measure. For its introduction, the following events are then defined:

Q – activation of risk reduction measure,
V – reaction of the hazard or undesirable event to the effect of risk reduction measure,
C – fulfilment of function by risk reduction measures.

In a statistical sense, event *V* is dependent on event Q. If $P(V|\bar{Q}) = Q$, then the probability of the product of events Q and *V* equals [17]:

$$P(Q \cap V) = P(C) = P(V|Q) \cdot P(Q) \tag{10}$$

If we mark the efficacy further with *E*, i.e.:

$$P(Q \cap V) = P(V|Q) \cdot P(Q) = E \tag{11}$$

then the inefficacy of or failure to fulfil the safety function by the risk reduction measure having an effect on the hazard sources, hazards at the level of the analysed system, and hazards at the level of the railway system, can be expressed, respectively, as: $1 - E(ZZ_i)$, $1 - E(Z_j^{\mathrm{A}})$, $1 - E(Z_k^{\mathrm{B}})$ $(i = 1,2,\dots,m; j = 1,2,\dots,n;\ k = 1,2,\dots,l; w = 1,2,\dots)$. The RAMS risk model will then be a function of five variables:

$$R(z_k) = f\left[P(ZZ_i), E(ZZ_i), E\left(Z_j^{\mathrm{A}}\right), E\left(Z_k^{\mathrm{B}}\right), S(ZN_{wk})\right] \tag{12}$$

It should be noted that undesirable system states (hazards both at the level of the analysed system and at the level of the railway system) may be the consequence of a number of causes. Moreover, various relationships may occur between these causes. A hazard at the level of the considered system Z_j^{A} may be, for instance, a coincidence of several hazard sources ZZ_i. If we want to map such relationships in the RAMS model presented herein, then appropriate interpretations should be given to individual (non-conditional) probabilities. In the case of a conjunction of events:

$$P\left(Z_j^{\mathrm{A}}\right) = P\left(ZZ_{1j} \cap ZZ_{2j} \cap \dots \cap ZZ_{mj}\right) \text{ and } P\left(Z_k^{\mathrm{B}}\right) = P\left(Z_{1k}^{\mathrm{A}} \cap Z_{2k}^{\mathrm{A}} \cap \dots \cap Z_{nk}^{\mathrm{A}}\right) \tag{13}$$

In the following example of using the method, road user errors, resulting in entering the trackage, are taken into account. The reason for this is people's limited susceptibility to the effects of safety systems in the form of light signals which remain switched on while the barriers are closed. This is primarily due to road users' mechanisms of making errors (including violations). Based on literature, e.g. [29], it may be concluded that the probability of a human making an error may be as high as 2e-02 (assuming actions based on knowledge and an unusual/stressful situation).

The results of the estimation of the risk of a collision between a railway vehicle and a road vehicle at the level crossing for the assumed exemplary probability values described were presented in Tables 1.

Tab. 1

Adopted exemplary values of the measures of the RAMS risk model components

Risk model component	**Symbol and numerical value**	**Remarks**
Hazard source probability	$P(ZZ_1) = 1e - 03$	
Hazard probability at the level of the analysed system	$P\left(Z_1^{\mathrm{A}}\right) = P(ZZ_1) \cdot P\left(Z_1^{\mathrm{A}} \middle| ZZ_1\right) = 1e - 03$	Assuming that: $P\left(Z_1^{\mathrm{A}} \middle| ZZ_1\right) \cong 1$

Hazard probability at the level of the railway system	$P(Z_1^{\mathrm{B}}) = P(Z_1^{\mathrm{A}}) \cdot P(Z_k^{\mathrm{B}}\vert Z_j^{\mathrm{A}}) = 2e-04$	For $P(Z_k^{\mathrm{B}}\vert Z_j^{\mathrm{A}}) = 2e-1$
Hazardous event probability	$P(ZN_{wk}) = P(Z_k^{\mathrm{B}}) \cdot P(ZN_{wk}\vert Z_k^{\mathrm{B}}) = 2e-06$	Assuming that $P(ZN_{wk}\vert Z_k^{\mathrm{B}}) = 0{,}01$ as in the risk model [29]
Losses resulting from the hazardous event	$S(ZN_{wk}) = 5$	Assuming a passenger vehicle with up to 5 people
Risk value	$R(ZN_{wk}) = 1e-05$	Assuming an algebraic product of the components

For the purpose of the RAMS model, the following states and events were formulated:

- hazard source (ZZ_1): *damaged barrier driver,*
- hazard at the level of the level crossing (Z_1^{A}): *barriers blocked in the upper end position due to barrier drive failure,*
- hazard at the level of the railway system (Z_1^{B}): *possibility of road vehicles entering the level crossing while the light signals are on,*
- hazardous event (ZN): *collision between a railway vehicle and a road vehicle,*
- losses related to the hazardous event: *death of a few people.*

4. FINAL REMARKS

In risk management in railway transport, standard risk models are usually used, based on the classical definition of risk and discrete mapping of the measures of risk components. Slightly more detailed models, i.e. those based on the FMEA method, are used equally frequently. Such an approach has a number of advantages, mentioned in this article, yet it does also have a good many flaws demonstrated in academic literature and observed due to the article author's professional experience. The major flaws of such an approach include the following: the models are multiplicative, highly sensitive, the combinations of the input values give the same output value, there are no scales in the form of continuous functions, and the model components/variables are inadequate for the hazards. This is why the need for choice and the presentation of mathematical risk model, which is not the typical ones, included in risk management norms or standards. At the same time, it provides grounds for easy implementation in safety management procedures used by railway entities.

First of all, the reasons for the attractiveness of the standard models, as well as the issues with applying non-standard models, were analysed. In the first category, the relatively simple structure of the standard models should be mentioned, enabling their easy understanding and application. Moreover, what is extremely important in this case is the legislative foundation. Referring to standards or norms, it is easier to justify the choice of methods and execution of risk assessments. The identified issues with the application of non-standard models include their excessively academic and abstract character, a considerable amount of input data or resources required, lack of inclusion in the standards, and sometimes also simply unavailability of information about non-standard risk models. For this reason, an academic literature review was carried out next, focused on risk models applied in railway transport. The analysis has shown that the risks elaborated in academic literature are very frequently an extension to the FMEA resulting from the perceived faults of this analysis, or they are hybrid models, i.e. combining several different methods of hazard identification or risk analysis. There are also models which are very mathematically advanced and require large amounts of data. Their description, due to the adopted principle of easy implementation in risk management systems of railway entities, was limited for the purpose of this article. As evidenced by the literature review, the extension of the classic FMEA usually consists in the application of type-2 fuzzy sets.

In order to provide a proper description and interpretation of these models, a generalised mathematical risk model was first adopted. Risk treated as a measure of hazard severity is mapped with a function with multiple components (variables). The model which was elaborated, called the RAMS model, is a two-component risk model based on the classical definition of risk. Its non-standard character consists in original mapping of the component related to hazard activation. It stems from the assumptions of the RAMS standards and the graphical risk model presented there (which was, however, never presented in mathematical form). Thanks to expressing the hazard activation component with a sequence of probabilities, including conditional probabilities, the RAMS model provides numerous calculation possibilities, depending on the available information. For instance, if the probability of a hazardous event is known, the application of a risk model with two components will be the easiest (even if other probabilities are also known). Certainly, when (apart from the hazardous event probability) the probability of the occurrence of the hazard source is known, the value of detectability can be calculated and a model with three components can be developed (such as RPN, for instance). Additionally, the RAMS model is so universal that giving the conditional probabilities appropriate interpretations makes it possible to transform it both into standard models and other non-standard ones.

The models presented herein are not intended to replace those currently in use, but complement the resources of available tools for risk assessment. Perhaps a temporary problem which will emerge in the first applications of the models will be mastering them properly and applying them with ease. Even though the presented risk models do not use an advanced mathematical apparatus, the notations are (and should remain) properly formalised in order to ensure their clarity and lack of ambiguity. Moreover, there will always be the issue of the input data – it would be best if it was not just a result of the exploration of expert knowledge, but constituted statistical analyses based on the quantitative data collected. It is for the application of such data that the proposed models (particularly the RAMS model) will prove to be useful.

Summing up the work carried out, it may be concluded that there is a possibility to easily extend the currently used risk assessment procedures with the proposed non-standard models. In their structures, they draw on the well-known and legislatively accepted models. But they do introduce additional components and ways of expressing them (measures and mathematical forms) referring to the characteristics of hazards identified in railway systems.

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