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THE USE OF THE RISK MATRIX METHOD FOR ASSESSING THE RISK OF IMPLEMENTING RAIL FREIGHT SERVICES

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Abstract:

The article presents a proposal for the use of a risk matrix for assessing the safety of the implementation of rail freight transport. The starting point for considerations related to risk assessment is the conditions arising from the business need and the obligation of entities operating in the railway market to ensure the safety of the implementation of freight tasks. The authors presented selected literature within the framework of the issues discussed. The layers of risk assessment, which include the analytical layer, the decision layer and the elimination layer, indicate the possibility of considering the problem of risk assessment from different perspectives. The identification of direct causes and consequences of undesirable events during the implementation of rail freight transport was also made. The article describes one of the methods of risk management which is the risk matrix.

The authors stressed that the construction of a risk matrix should be preceded by an analysis of the factors that affect the safety of rail transportation. This is possible by determining their probability of occurrence and setting values for the consequences of adverse events. The article divides the assignment of levels of adverse events to a five-level risk matrix (slight, low, medium, high, very high). Also presented is a case study considering the risk assessment of rail freight transport in Poland using the risk matrix method for railway accidents in the area of railway lines. Thanks to the development of the risk matrix, a risk management strategy can be used. The last part of the article is a summary, which highlights the possibility of applying the presented approach to risk assessment among entities operating in the rail transport market.

Keywords: *risk matrix, adverse events, freight transport*

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1. Introduction

Analyzing processes in transportation, it can be assumed that the implementation of both freight and passenger transportation is affected by many factors. An important issue in this context is risk issues, which can relate to many areas of the organization's operation. Risk assessment is also an indispensable part of the railway safety system. Under the Railway Transport Law (UTK, 2003) managers, rail carriers, users of railway sidings and infrastructure management companies are designated as entities that guarantee the safe operation of railway traffic and the safe operation of railway vehicles. In addition, railway managers and carriers ensure that safety is maintained and strive to continuously improve it. The obligation imposed on infrastructure managers and railway operators relating to the implementation of the necessary risk control measures is key. One of the primary tasks of the designated entities is to act as a priority to prevent rail accidents. An increase in the level of risk to the safety of the implementation of rail transportation can result in actions to reduce this risk by halting or limiting rail traffic.

Risk in the literature is presented in various aspects, including through: the criteria for division (e.g., risk – technical, personal, individual, social, economic), reliability and safety or the methods used to identify, analyze and evaluate it. At risk can be also looked from various perspectives. One instance considers risk as an entropy (Duffey & Saull 2002, Duffey 2020). We however stick to more traditional perspective which has been established for multidisciplinary purposes and is defined e.g. in (ISO 31000 Risk management, 2018), (ISO 31010 Risk managment, 2020), (ISO Guide 73, 2010). Based on these boundary conditions we also understand the composition of risk in following form. Risk (R) consists minimally from probability (P) of some undesired even happening and consequences (C) of such event. Therefore, we consider following minimalistic analytic form for risk calculations R = P x C. With this form we further work both for risk analysis as a whole as well as when considering and assessing its individual components. When defining the area related to transportation security, the point is emphasized that it is a state that gives a sense of certainty of existence and a guarantee of its preservation. In transport terms, it means assessing the risk of loss of health or life due to communication events (accidents) related to the implementation of the transportation process (Bałuch et al., 2011) . Relevant in this context is the EU Commission Implementing Regulation No. 402/2013 of April 30, 2013 on a common safety assessment method for the valuation and evaluation of risk (EU, 2013). This document defines the basic definitions related to the risk management process and indicates, among other things, such elements as: general description of the risk assessment process, indication of compliance with safety requirements, management of hazards.

The article focuses on presenting issues related to risk, pointing out its multifaceted nature. The purpose of this article is to present the risk matrix as a method to assess risks in rail transportation. In order to apply it, the causes and consequences of undesirable events during the implementation of rail freight transport were specified. The risk matrix can assist rail freight operators to take measures to reduce or mitigate medium and high levels of risk. The entire content of the article is divided into three main parts. The first one presents the general approach to risk in the literature of the problem. The essence of the issues raised from the point of view of risk assessment as well as risk management is indicated. The second part is a description of the risk assessment tool and a general notation of the model with an indication of defining the scope of the risk matrix. The last part is a case study that considers the risk assessment of rail freight transport in Poland using the risk matrix method for railway accidents in the area of railway lines.

2. Literature review

As mentioned in the introduction, entities operating within the rail transportation system should conduct risk assessments related to the activities they perform. It should be noted that the perception of risk has changed over the years. As the authors of the work note (Dvorak et al., 2020), (Bernatik et al., 2021), (Tubis & Werbińska-Wojciechowska, 2017), (Lahuta, Kardoš & Hudáková, 2021) risk assessment is the subject of research in many transportation industries. The article (Sobota et al., 2018) emphasizes that the functioning of the transport system is also determined by the quality of the services provided by the infrastructure of various transport branches. Within the framework of EU regulations and the rationale for merging business areas, it is necessary to create audit structures in organizations.

Audit departments are based on risk analysis. This trend has triggered research in the field of risk management. The indicated subject area is analyzed for both rail and road transport, which have a lot in common in terms of their approach to risk. Issues related to risk in road transportation of dangerous goods are presented in the works of, among others. (Ambituuni et al., 2015), (Izdebski et al., 2022), (Batarliene, 2020), (Conca et al., 2016). In the article (Ambituuni et al., 2015) analyzed accidents taking into account causal factors of accidents, frequency, consequences and financial impact. In turn, in (Izdebski et al., 2022) the author's model taking into account the minimization of the probability of accidents in the transportation of dangerous cargoes was determined, along with a case study conducted in the area of the Mazovian province. The authors of the study (Batarliene, 2020) showed that the main factors affecting the probability of an accident during the transportation of dangerous goods are improper loading of cargo, the condition of the vehicle, and weather and surface conditions. According to the risk management methodology presented in, for example (ISO 31000 Risk management, 2018), (ISO 31010 Risk managment, 2020), (ISO Guide 73, 2010) issue of risk assessment is presented alongside risk analysis and risk valuation as one of the stages of risk management in the entire system, including railways. It should be emphasized that risk assessment of the implementation of rail transportation, like other transportation services, requires decision-making (cf. (Karoń & Żochowska, 2020), (Jacyna & Szaciłło, 2017) under conditions:

– Certainty - when the effects of the risks are known,
– Uncertainty - when the probabilities of risk effects are unknown or the effects of risks are difficult to determine,
– Risks - when the probabilities of the effects of risks are known.

National and international literature items presenting risk assessment methodologies for rail transportation highlight several important areas. The inclusion related to risk assessment for terrorist events at railway stations is detailed in (Luxton & Marinov, 2020, (Marrone et al., 2013), (De Cillis et al., 2013). For example, the work (Luxton & Marinov, 2020) distinguished a five-step methodology for dealing with adverse events (identification of hazards, prioritization of hazards in terms of the most severe effects, development of mitigation strategies, evaluation of strategies, implementation of strategies). In the case of research related to hazards caused by atmospheric phenomena, the work should be mentioned (Sanchis et al., 2020). An original approach related to a mathematical model for assessing the safety of school bus travel is included in the paper (Murawski et al., 2022). In the work of (Grenčík et al., 2020), (Grenčík, 2018) an assessment of the risks associated with freight cars in the operation and maintenance phase of the rolling stock was carried out . In the work (Grenčík, 2018) indicated feasible methods of risk assessment with types of risks divided into categories of their sources – individual, technical, environmental, social, economic and other. In the articles (Berrado et al., 2011), (Abioye et al., 2020), (Burdzik et al., 2017), (Bureika et al., 2017) much attention was paid to the issues of risk assessment at level crossings. In turn, the problem of risk assessment of the transport of dangerous cargoes by rail was presented in the papers (Cafiso et al., 2006), (Liu, 2016), (Huang et al., 2021), (Rahbar & Begheri, 2014). In addition, accidents and incidents during the transportation of dangerous goods by rail transport were the subject of research in the article (Batarliene & Jarasuniene, 2014) (Batarliene, 2020). It indicates how respondents estimate the main factors associated with risk in rail transportation, describes starts resulting from accidents, and offers recommendations for measures to reduce accidents. W (Huang et al., 2020) interpretive structural modeling approach and Bayesian networks are presented as methods that can be used to quantitatively analyze the relationship and strength of interactions between risk factors or causes of rail accidents in the rail hazardous goods transportation system. Safety assessment in rail systems has been defined, among other things, in the standard (PN-EN, 2018), which provides general guidelines to reduce the risk of a hazard to a minimum level according to the ALARP (As Low As Reasonably) principle.

On the other hand, in the items (Sitarz et al., 2011), (Cieśla et al., 2020) listed risk assessment methods used in the rail transportation system, such as:

– Checklists – organizations starting to execute the process in the transport market,
– Failure Mode and Effect Analysis (FMEA), Hazard and Operability Study (HAZOP (IEC, 2016), (PN-EN, 2018), COSO II - an organization with

extensive experience in the process (e.g., Polish carriers with a minimum of 2 years of experience),
– FTA (Fault Tree Analysis) - an organization with extensive experience in the process, with a large amount of incident data - major freight and passenger carriers, major infrastructure managers.

In the study (Kycko & Zabłocki, 2019) the authors point out the necessity of risk assessment at each stage of a railway investment, starting from the feasibility study stage, through design and construction to the operation stage, without ignoring the impact of human factors and equipment reliability. In addition, they note that it is very important to select the appropriate methodology, from the many available, for the stage being evaluated. Of the methods not previously mentioned, the authors cited the following:

– Delhi method - applicable at any stage of the project, but not applicable to assessing human factors or equipment reliability,
– Event tree analysis - a universal methodology that can be applied to all analyzed cases,
– Unfitness tree analysis - useful only at the stage of assessing the service life and reliability of equipment,
– Human reliability analysis - applicable only to the evaluation of human factors.

The above-mentioned list of risk assessment techniques of course is not exhaustive. We are aware that some of the risk assessment techniques are successfully applied in other fields (e.g. reliability) and also have individual standardized form. Therefore, for much more relevant list of techniques for different purposes of risk assessment we can refer to (ISO 31010 Risk managment, 2020). It is also inherent in rail systems to ensure and then assess the reliability of the systems. The higher the system reliability, the lower the probability of adverse events. This paper (Kornaszewski & Pniewski, 2016) shows how the use of simulation can help assess the reliability of railway traffic control equipment. The paper (Grabowska–Bujna, 2016) analyzed the defectiveness of individual components of the railway traffic control system, based on real data collected, taking into account the geographical location of each station, traffic volume and year of construction. The analysis shows that isolated sections are the most fault-prone component of the signaling systems, which may give an indication of what should be focused on to increase their reliability. Based on the analysis, a forecast for the future is also provided.

It is crucial that the application of the risk assessment method be done based on the identified research objective and input data, which should come from reliable sources. The literature analysis shows that the issue of risk assessment is multifaceted and requires an individual approach to solving specific problems.

3. Characteristics of risk assessment layers

Risk assessment in rail transportation can refer to both freight and passenger transportation. Within the framework of this article, a systematic approach to risk assessment during the implementation of rail freight transportation is proposed. Assumptions related to risk assessment in this context are presented in the paper (Szaciłło et al., 2021), it proposes a description taking into account various aspects, conventionally called layers. The basis for risk assessment in rail freight transport can be provided by statistics on serious accidents, accidents and incidents, which are collected as part of the activities of bodies such as the Railway Transport Authority (*Urząd Transportu Kolejowego*) and the State Commission for Investigation of Railway Accidents (*Państwowa Komisja Badania Wypadków Kolejowych*). A train accident is an unwanted or unintended sudden event or series of such events that have severe consequences. They are divided into: collisions, derailments, level crossing accidents, accidents involving persons caused by rolling stock in motion, fires and others. A serious accident is an accident with at least one fatality or at least five seriously injured people, or causing significant damage (which can be immediately estimated by the investigator at least €2 million) to rolling stock, infrastructure or the environment. An incident, on the other hand, is any event other than an accident or serious accident affecting railway safety (Bałuch et al., 2011), (UTK, The Railway Transport Act (2022), 2003).

Considering the range of data that are published in publicly available reports (for example, in the (UTK, The Office of Rail Transport, 2020), it is possible to identify three layers that can be subject to risk assessment (Figure 1).

As part of the analytical layer, statistical data can be used to study the current status of adverse events on rail lines and rail sidings. Data on these events can be included, for example, in tabular summaries, which are updated at specific intervals and contain all information about disruptions during the implementation of rail freight transport. The selected information can be used to determine parameters such as the probability of occurrence of adverse events and the severity of the consequences of adverse events. On this basis, it is possible to make a risk assessment for the route of travel from the moment when the train is loaded at the railway siding through the sending station, intermediate station (if any), destination station up to the unloading point located, for example, on the railway siding. The collection of information in the analytical layer facilitates the statistics necessary to determine the risk assessment of the rail transportation system. A general diagram for the process involved in the implementation of rail freight transportation is shown in Figure 2.

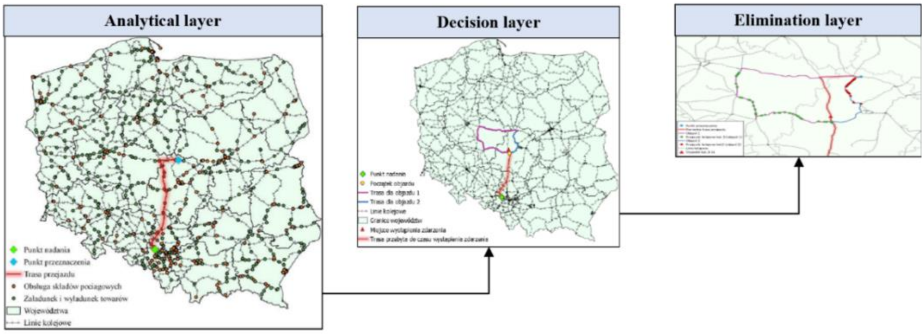

Fig. 1. Layers of risk assessment during rail freight operations

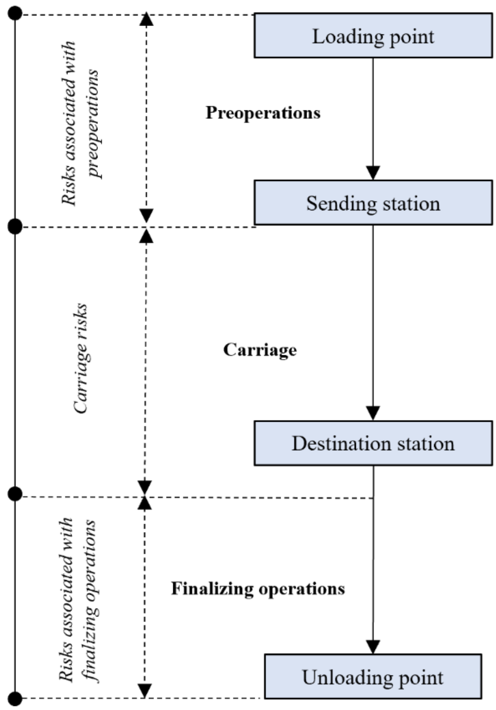

Fig. 2. General view of the process involved in the implementation of rail freight transportation

During the implementation of rail freight transport, adverse events occur, the consequences of which often prevent the continuation of the freight task. In order for cargo to be delivered to recipients with the least possible delay, it may be necessary to determine alternative routes. When doing this, you can be guided by the criterion of minimizing the risk associated with the effect of an accident or incident (e.g., injured persons, financial implications). This layer, called the decision layer, supports decision-makingin selecting alternative routes with given selection criteria relating to the consequences of incidents defined by the decision-maker.

The last layer is the elimination layer. During the analysis of alternative crossing routes for the decision layer, it may be crucial in the evaluation of the influencer to determine the crossing route to identify specific factors that can cause an undesirable situation. In such a case, it is necessary to examine all possible points along the travel route where an undesirable event may occur, such as the selected category of level crossings. When an undesirable event occurs as a result of which it is necessary to choose an alternative route, in addition to the criterion presented in the decision layer, an additional criterion may also be the determination of a specific category of direct cause. Adverse event data and routes of travel are indicated based on the information in Table 1.

4. Causes and consequences of adverse events in the rail transport system

The basis for the risk management process is to specify the cause of adverse events. Data on adverse events (i.e., serious accident, incident) are collected and analyzed at three levels (UTK, The Office of Rail Transport, 2020):

– European within the framework of the European Union Railway Agency (data is related to the European Union's publicly accessible rail network),
– national within the Railway Transport Authority and the State Commission for Investigation of Railway Accidents (the data is related to the public railway network, railway sidings and narrow-gauge railways),
– as part of the activities of railway operators, infrastructure managers or entities responsible for maintenance (data includes activities covered by the safety management system).

A division of the causes of accidents and incidents is presented in Figure 3.

In Poland, the classification of a serious accident, accident or incident into a specific category is indicated by a specially appointed commission based on the determination of the direct cause of its occurrence (Figure 4). The classification of the direct cause of serious accidents, accidents and incidents is detailed in the (MIiB, 2016).

Table 1. Scope of data characterizing adverse events

Lp.	Group	Subgroup	Scope of data	Source
1	Railway infra-structure	Railway lines	Line number, starting kilometer, final kilometer	(PKP PLK S.A., 2022)
2		Points where train service takes place	Geographical coordinates	(UTK, The Office of Rail Transport., 2022)
3		Points where loading and unloading of goods takes place	Geographical coordinates	(UTK, The Office of Rail Transport., 2022)
4	Adverse events in rail freight transport	Serious accidents	Geographical coordinates, locations of the adverse event, date of occurrence, category and number of the event, description of the cause of the event, consequences of the event	Obtained data from the Railway Transport Authority and the State Commission for Investigation of Railway Accidents
5		Accidents		
6		Incidents		
7	Itinerary	Starting point of the travel route	Geographical coordinates	Own data based on assumed parameters
8		End point of the driving route	Geographical coordinates	
9	Detour route	Starting point of the detour route	Geographical coordinates	Own data based on assumed parameters and (GUGiK, Head Office of Geodesy and Cartography., 2022), (GUGiK, Head Office of Geodesy and Cartography., 2022).
10		End point of the detour route	Geographical coordinates	
11		Rail-road crossings along the route of the trip	Transit category, geographic coordinates	

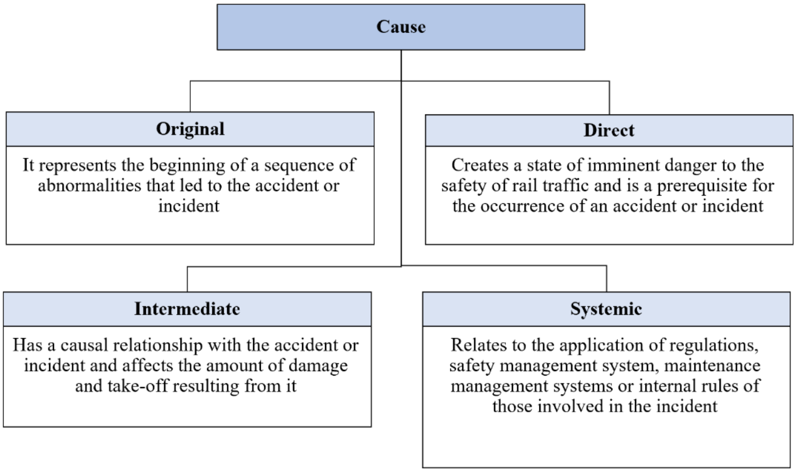

Fig. 3. Types of causes of adverse events in the rail transport system
Source: own elaboration based on (MIiB, 2016).

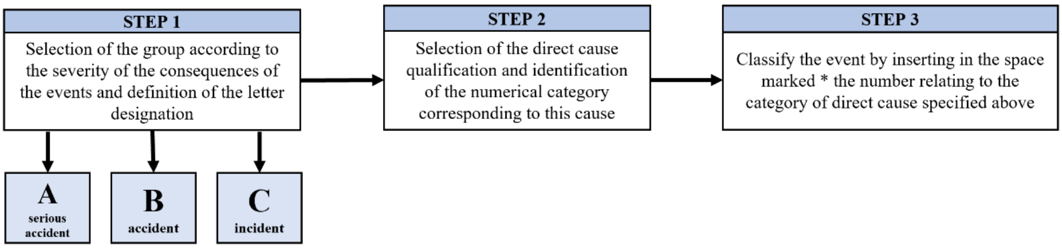

Fig. 4. The process involved in categorizing serious accidents, incidents and accidents into an established direct cause
Source: own elaboration based on (MIiB, 2016).

Some of the most common causes of disruptions during rail operations include (Placido, 2017):
– poor condition of infrastructure: tracks, points, subgrades, sleepers, bridges and flyovers, as well as sudden emergency damage to these elements,
– track work plans carried out,
– lack of service or damage to horns, or reduced visibility at points of contact between different branches of the same transportation system,
– failure of rolling stock in the course of the transportation task,
– no power supply on electrified lines,
– atmospheric and environmental factors, such as snow blizzards, washout of tracks due to heavy precipitation, buckling of rails due to high summer temperatures,
– the human factor related to the transportation system or outside the transportation system.

5. Assumptions of risk assessment model using risk matrix

This article focuses on the risk assessment aspect by identifying the most important assumptions and constraints. The model of risk assessment of the implementation of rail freight transport includes elements related to the upstream and downstream operations, which include: loading points (tracks of general use, station sidings, trail sidings other points designed to perform loading and unloading of goods), the station of shipment, the station of destination. On the other hand, the output determines the risk assessment of rail freight transport. A general view of the risk assessment model is shown in Figure 5.

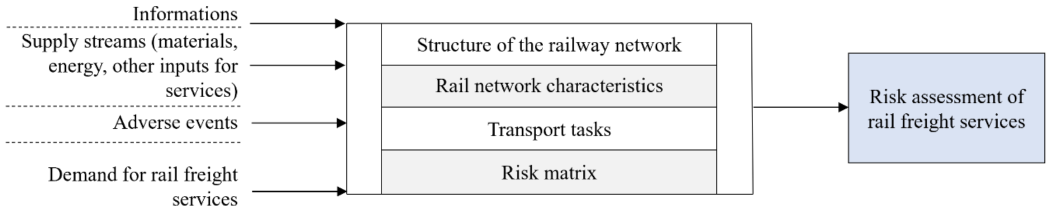

Fig. 5. General scheme of the risk assessment model

In the work (Szaciłło, 2021) the model is based on an approach to modeling transportation systems with respect to aspects presented in the works of (Jacyna i Semenov, 2020), (Jacyna et al., 2020), (Tavasszy i De Jong, 2013) and on a risk management approach based on the definition of a risk matrix. The model of risk assessment for the implementation in rail freight transport (***MORKPT***) is defined as an ordered four:

$$\boldsymbol{MORKPT}=\langle \boldsymbol{GK},\boldsymbol{ZF},\boldsymbol{ZP},\boldsymbol{MR}\rangle \quad (1)$$

In order to build a model for risk assessment of the realization of rail freight transport, it is necessary to know the structure of the ***GK*** rail network, the characteristics defined on the elements of the ***ZF*** structure, the ***ZP*** transport tasks, the ***MR*** risk matrix described in, among others (ISO 31010 Risk management, 2020), (IEC 60812, 2019).
In order to conduct a risk assessment, the direct causes of adverse events must be specified and described accordingly. In order to identify the causes of adverse events in the rail transportation system, a nationwide classification of direct causes of accidents and incidents was used (MIiB, 2016).
Table 2 shows the direct causes of railway accidents in rail transportation.

Table 2. direct causes of railway accidents

Lp.	Description of the direct cause	Category	Symbol
1	Other than the causes listed below, or an overlap of several causes at the same time, creating equivalent causes	0	*W00*
2	Launching a railway vehicle on an occupied, closed or opposite to the main track or in the wrong direction	1	*W01*
3	Acceptance of a railway vehicle into a station on a closed or occupied track	2	*W02*
4	Launching, receiving or driving a railway vehicle on an improperly laid unprotected route or improper operation of traffic control devices	3	*W03*
5	Failure of a railway vehicle to stop before the signal "Stop" or at the place where it should stop, or starting a railway vehicle without the required authorization	4	*W04*
6	Failure to exercise caution after a railway vehicle has passed an automatic clearance semaphore indicating a "Standstill" signal or a doubtful signal after stopping before these signals	5	*W05*
7	Exceeding the highest speed limit	6	*W06*
8	Performing a maneuver that poses a traffic safety risk trains	7	*W07*
9	Runaway railway vehicle	8	*W08*
10	Damage to or poor maintenance of a structure, such as a pavement, bridge or overpass, including improper execution of work, such as improper unloading of materials, pavement, leaving materials and equipment (including road machinery) on the track or in the gauge of a railway vehicle, or invading elements of the structure by a railway vehicle	9	*W09*
11	Damage or poor condition of powered railway vehicle, special-purpose railway vehicle (including invasion of the an object that is a structural part of a powered railway vehicle, a special-purpose railway vehicle) and the failure or malfunction of the on-board part of the equipment that enables the control of railway vehicle guidance (ERTMS)	10	*W10*
12	Damage or poor condition of the wagon (including raiding a structural part of the wagon)	11	*W11*
13	Failure or malfunction of railway traffic control equipment	12	*W12*
14	Railing over a railway vehicle or other obstacle (e.g., brake skid, baggage cart, mail cart)	13	*W13*
15	Criminal assassination	14	*W14*

Lp.	Description of the direct cause	Category	Symbol
16	Premature dissolution of the route or abrogation of the closure and flipping of the switch under the railway vehicle	15	*W15*
17	Incorrect combination of train or shunting yard formation	16	*W16*
18	Improper loading, unloading, irregularities in cargo securing or other irregularities in loading operations, or improper train or shunting combination	17	*W17*
19	Invasion of a railway vehicle on a road vehicle (other road machinery, agricultural machinery) or vice versa at level crossing with turnpikes (cat A according to the crossing metric)	18	*W18*
20	Invasion of a railway vehicle on a road vehicle (other road machinery, agricultural machinery) or vice versa at a level crossing equipped with an automatic crossing system with traffic lights and horns (cat. B).	19	*W19*
21	Invasion of a railway vehicle into a road vehicle (other road machinery, agricultural machinery) or vice versa at a level crossing equipped with an automatic crossing system with traffic lights and without horns (cat. C).	20	*W20*
22	Invasion of a rail vehicle on a road vehicle (other road machinery, agricultural machinery) or vice versa at a level crossing not equipped with a crossing system (Cat. D)	21	*W21*
23	Invasion of a railway vehicle into a road vehicle (other road machinery, agricultural machinery) or vice versa at a level crossing of private use (cat. F)	22	*W22*
24	Invasion of a railway vehicle on a road vehicle (other road machinery, agricultural machinery) or vice versa outside of level crossings at stations and routes or on a communication and access track to a siding	23	*W23*
25	Fire in a train, shunting yard or railway vehicle	24	*W24*
26	Fire in a building structure, etc. within the boundaries of the railway area, forest fire within the boundaries up to the end of the fire lane, grain, grass and track fires arising within the boundaries of the railway area	26	*W26*
27	Explosion in a train, shunting yard or railway vehicle	27	*W27*
28	Natural disasters (e.g., floods, snowdrifts, ice jams, hurricanes, landslides)	28	*W28*
29	Construction disasters in the immediate vicinity of railway tracks on which normal train traffic runs	29	*W29*
30	Malicious, hooligan, or reckless misconduct (e.g., throwing rocks at a train, stealing cargo from a moving train or shunting yard, placing an obstruction on the track, vandalizing power, communications, traffic control, or track surface equipment, and interfering with such equipment)	30	*W30*
31	Invasion of persons by a railway vehicle while crossing the tracks at a level crossing or a guarded crossing	31	*W31*
32	Invasion of persons by a railway vehicle while crossing the tracks at a level crossing with an automatic crossing system (cat. B, C)	32	*W32*
33	Invasion of persons by a railway vehicle while crossing the tracks at other level crossings and road crossings	33	*W33*
34	Invasion of persons by a railway vehicle while crossing the tracks outside level crossings or crossings at stations and routes	34	*W34*
35	Incidents with persons related to the movement of the railway vehicle (jumping, falling out of the train, railway vehicle, strong approach or sudden braking of the railway vehicle)	35	*W35*
36	Disregard by the driver of a road vehicle of signals prohibiting entry to a level crossing and damage to the turnpike or traffic signals	36	*W36*
37	Train or shunting yard breakup that resulted in runaway cars	37	*W37*
38	Improper tripping of structures and equipment intended for railway traffic or railway vehicles caused by theft	38	*W38*
39	Entry of a railway vehicle using catenary power supply on unoccupied non-electrified track	39	*W39*
40	Uncontrolled release of dangerous goods from a wagon or package requiring the intervention of authorities or the application of measures to eliminate fire, chemical, biological hazards at a station or on a route	40	*W40*

Source: (MIiB, 2016).

For the purpose of building the risk assessment model, it was assumed that adverse events of realized freight transportation could occur on:
– railway (lkol),
– railway siding (bk).

As indicated earlier, in each of the areas mentioned, there may be multiple causes of accidents or incidents that could result in an adverse event, i.e. the risk of cargo damage, for example. For each type of adverse event determined, the causes of the occurrence of this type of event have been identified.

Therefore, in order to determine the probability distributions of the occurrence of an adverse event, a set of $\boldsymbol{ZN}$ categories of causes of adverse events of the form was defined:

$$\boldsymbol{ZN}=\{zn: zn=1,\dots,\mathrm{ZN}\} \tag{2}$$

An adverse event may occur for the following categories of direct causes:
– accidents for the railway line area,
– incidents for the railway line area,
– accidents for the railway siding area,
– incidents for the railway siding area.

In each of the categories listed in each area, there may be multiple causes of accidents or incidents that could result in an adverse event, such as the risk of damage to a freight car. For each type of adverse event determined, the cause of the occurrence of that type of event was identified. These causes are denoted by the subscript p, while the vector of factors influencing the type of risk is written as follows:

$$\mathbf{ZN}=[(zn,1),(zn,2),\dots(zn,p),\dots,(zn,\mathrm{P})] \tag{3}$$

where the pair (zn, p) denotes the p-th factor influencing the occurrence of the *zn-th* adverse event category.

With this in mind, the vector of factors for each area was written as follows:
– for the causes of direct accidents or incidents identified on the railway:

$$\mathbf{R}(lkol)=[((lkol,(zn,1)),((lkol,(zn,2)),\dots,((lkol,(zn,m)),\dots,((lkol,(zn,\mathrm{M}))] \tag{4}$$

– for the causes of direct accidents or incidents identified on the railway siding:

$$\mathbf{R}(bk)=[((bk,(zn,1)),((bk,(zn,2)),\dots((bk,(zn,c)),\dots,((bk,(zn,\mathrm{C}))] \tag{5}$$

The probabilities of adverse events are in the <0,1> range. On the other hand, the five-point scale according to the risk matrix can be written as in Table 3.

Table 3. Adverse event occurrence levels allowing risk assessment for direct causes

Level		**Slight**	**Low**	**Medium**	**High**	**Very high**
The value of the level of occurrence of an adverse event		1	2	3	4	5
Probability of occurrence of an event (lower limit- upper limit)						
Area	**Accidents for the railway Line**	0,000 - GGNZ (*w*,*lkol*)	DGNS(*w*,*lkol*) - GGNS(*w*,*lkol*)	DGSD(*w*,*lkol*) - GGSD(*w*,*lkol*)	DGW(*w*,*lkol*) - GGW(*w*,*lkol*)	≥ DGBW(*w*,*lkol*)
	Incidents for the railway line	0,000 - GGNZ (*i*,*lkol*)	DGNS(*w*,*lkol*) - GGNS(*i*,*lkol*)	DGSD(*w*,*lkol*) - GGSD(*i*,*lkol*)	DGW(*w*,*lkol*) - GGW(*i*,*lkol*)	≥ DGBW(i,*lkol*)
	Accidents for the railway siding	0,000 - GGNZ (*w*,*bk*)	DGNS(*w*,*bk*) - GGNS(*w*,*bk*)	DGSD(*w*,*bk*) - GGSD(*w*,*bk*)	DGW(*w*,*bk*) - GGW(*w*,*bk*)	≥ DGBW(*w*,*bk*)
	Incidents for the railway siding	0,000 - GGNZ (*i*,*bk*)	DGNS(*i*,*bk*) - GGNS(*i*,*bk*)	DGSD(*i*,*bk*) - GGSD(*i*,*bk*)	DGW(*i*,*bk*) - GGW(*i*,*bk*)	≥ DGBW(*i*,*bk*)

Indications:
DGBW - lower limit for cause or effect category very high; DGNS - lower limit for cause or effect category low; DGSD - lower limit for cause or effect category medium; DGW - lower limit for cause or effect category high GGNS - upper limit for cause or effect category low; GGNZ - upper limit for cause or effect category insignificant; GGSD - upper limit for cause or effect category medium; GGW - upper limit for cause or effect category high.

For each type of adverse event determined, the s-th effects of occurrence (SZ) of that type of event were identified. For the unambiguousness of further research, the effects of adverse events were labeled with the index s, respectively, and it is assumed that the set of SZs will be a set of the form:

$$\boldsymbol{SZ}=\{s\colon s=z,cr,ra,dp,pd,o,f\} \quad (6)$$

where:
z - killed,
cr - seriously injured,
ra - injured,
dp - invasion of a road vehicle on a train,
pd - the invasion of a train on a road vehicle,
o - freight train delays,
f - financial implications.

6. Risk matrix for risk assessment in rail freight transportation

The risk matrix is a method of concisely presenting the result of risk assessment. The analysis of undesirable events in the rail transport system makes it possible to determine the risks so that those involved in the implementation of rail freight transport can effectively counteract them (Szaciłło et al., 2021). Risk assessment during the performance of freight tasks is currently a management challenge for railway companies. Appropriate methods must be used to assess risks. One of the methods that can support risk assessment during the implementation of rail freight operations is the risk matrix method. Its main task is to classify risks, prioritize sources of risk and deal with risks. As indicated in (ISO 31000 Risk management, 2018), (ISO 31010 Risk managment, 2020), (IEC 60812, 2019) these methods provides support in the process of determining which risks require further analysis and against which preventive measures should be taken. Examination of the consequences of events, taking into account the probability of their occurrence, makes it possible to assess whether a given level of risk meets the criteria for acceptability. The risk matrix method uses two basic factors that affect the value of the determined risk see e.g. (ISO 31010 Risk management, 2020), (IEC 60812, 2019) and (Elmontsri, 2014):
– the probability of a given adverse event,
– the effects (consequences) of an adverse event.
The risk matrix method is represented by a two-dimensional matrix on a scale of several levels. Data on adverse events in 2019 obtained from the Railway Transport Authority and the National Railway Accident Investigation Commission became the basis for creating a model risk matrix for the sums of cause and effect values shown in Figure 6. It also made it possible to determine the percentage of each field of the risk matrix.
Since adverse event data occurred in reality, it was decided that the insignificant level would reflect a marginal percentage of all events. The numerical ranges of the individual risk level values were established with the following assumption:
– the slight level is a range between 0.0% – 1.3%,
– the low level represents a range between 1.3% – 13, 3%,
– the average level represents a range between 13.3% – 46.7%,
– the high level represents a range between 46.7% – 81.3%,
– very high level occurs above 81.3% of all adverse events, for a given direct cause and effect.

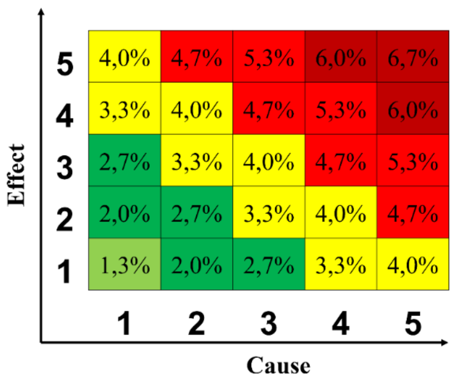

Fig. 6. Percentage of each field of the risk matrix Source: (Szaciłło, 2021).

Quantification of the ranges of risk assessment levels is shown in Figure 7.
Risk assessment levels may reflect the following activities:
– **Slight level** – current activities are acceptable, adverse events in the implementation of rail freight should be monitored,
– **Low level** – organization of training courses and workshops to address adverse events. Develop alternative scenarios for adverse events including, for example, making organizational, functional changes, etc.

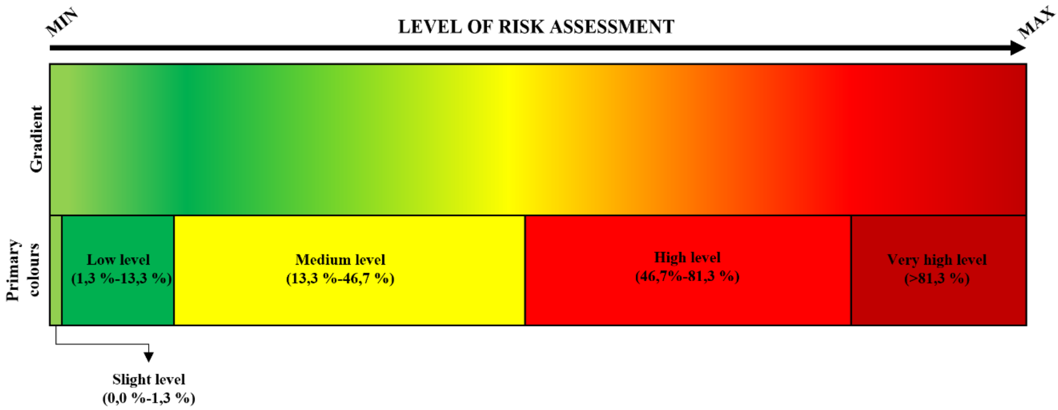

Fig. 7. Risk assessment levels for causes and consequences of adverse events

- **Medium level** – incidents should be reported in annual reports and railway company reports. Additional safety measures should be introduced.
- **High level** – a recovery plan should be drawn up and immediate action taken to reduce the level of risk.
- **Very high level** – the need for intervention of a body authorized to prevent undesirable events (such as the Railway Transport Authority). Take immediate action to eliminate undesirable events.

The developed risk matrix is a universal tool to support the decision-making process in assessing the risk of freight transportation on the rail network. It can be used to analyze scenarios of adverse events for both railway lines and railway sidings.

7. Application of the risk matrix for railway accidents on railway lines

In order to assess the risk of carrying out rail freight transport, data obtained from the Railway Transport Office and the State Commission for Investigation of Railway Accidents were analyzed. To determine the probability relating to the occurrence of accidents on railway lines in Poland for direct causes, the number of accidents per accident category was related to the number of accidents in the calendar year under review. The numerical ranges for the effects of railway accidents were determined based on the following assumptions:

- it was considered that a given category of effects would be subject to analysis when their number exceeded three events in the calendar year under review,
- for the categories: killed, seriously injured and injured - the upper limit was determined based on the definitions contained in the (MIiB, 2016),
- for the categories: invasion of a road vehicle by a train, invasion of a road vehicle by a train – the upper limit was set as the sum of all adverse events in the calendar year under review,
- for the categories: freight train delays, financial impact - the average for a single incident per accident or incident category that occurred in the calendar year under review was considered as the upper limit.

The values of the risk of the cause of the accident for the accident category (in the figures, the values presented on the x-axis), together with the determination of measures of the risk of the consequence effect for the accident category on the railway (in the figures, the values presented on the y-axis), made it possible to present the risk assessment in the form of a risk matrix.

Based on the numerical ranges for the probability of direct causes and for the consequences of adverse events, risk assessments were made for accidents in the railway lines area (see Figures 8 – 14).

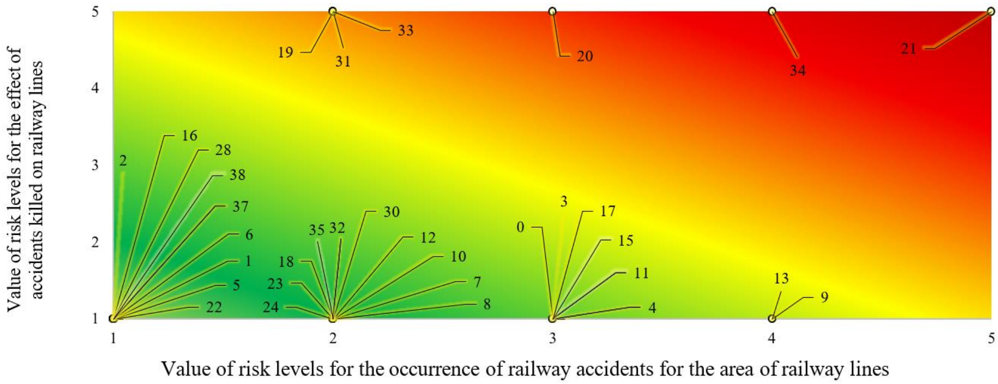

Fig. 8. Risk assessment of rail freight implementation for the effect of killed
Source. based on (Szaciłło, 2021).

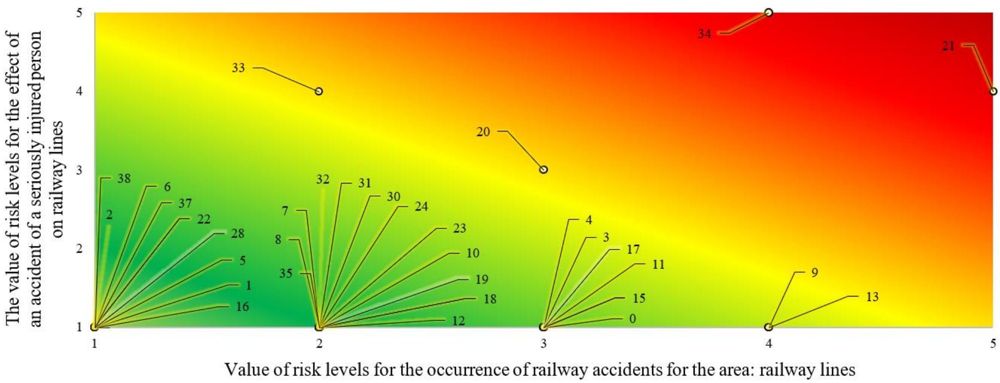

Fig. 9. Risk assessment of the implementation of rail freight for the effect of severely injured
Source: based on (Szaciłło, 2021).

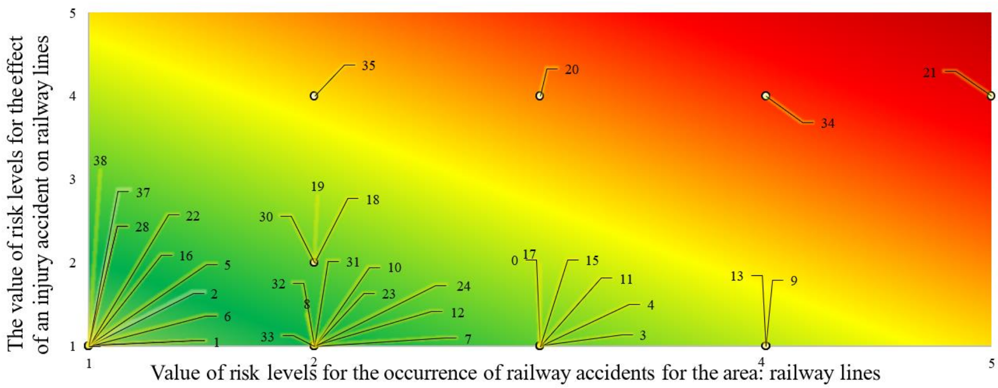

Fig. 10. Risk assessment of the implementation of rail freight for the effect of the injured
Source: based on (Szaciłło, 2021).

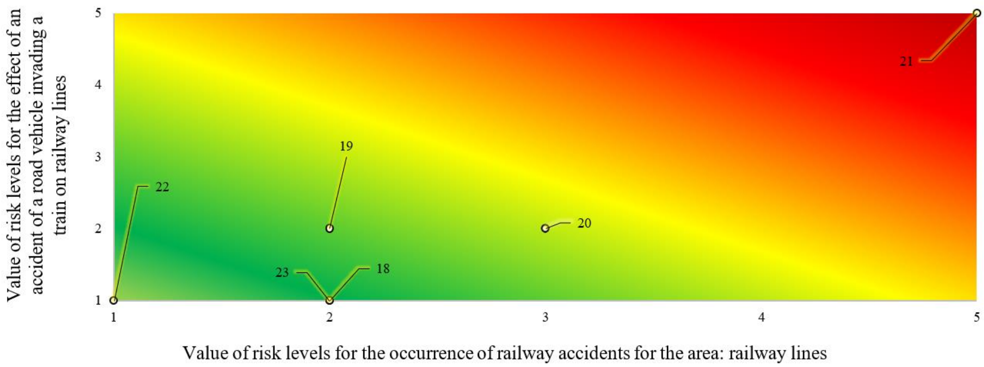

Fig. 11. Risk assessment of the implementation of rail freight services for the effect of a road vehicle invading a train
Source: based on (Szaciłło, 2021).

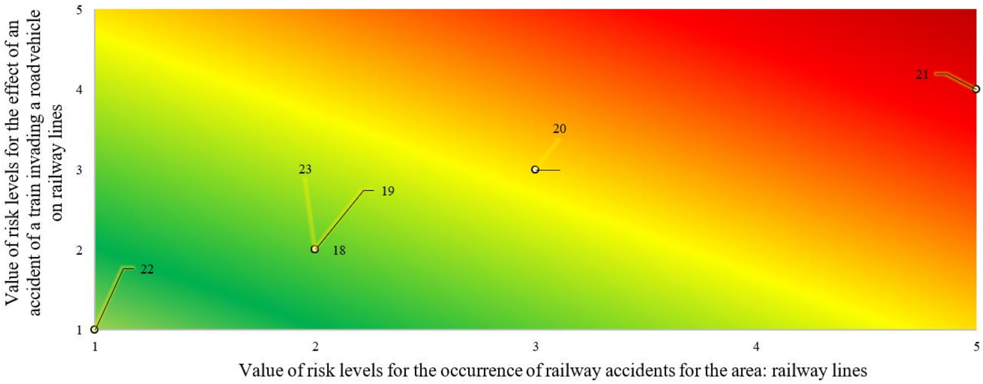

Fig. 12. Risk assessment of the implementation of rail freight services for the effect of a train invading a road vehicle
Source: based on (Szaciłło, 2021).

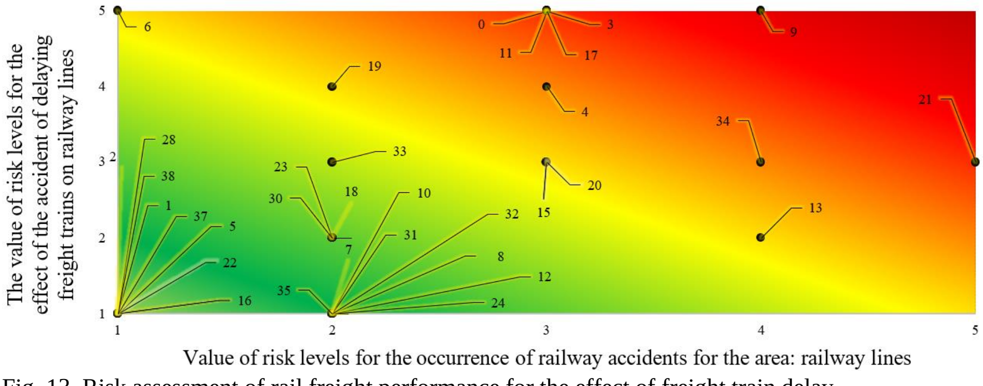

Fig. 13. Risk assessment of rail freight performance for the effect of freight train delay
Source: based on (Szaciłło, 2021).

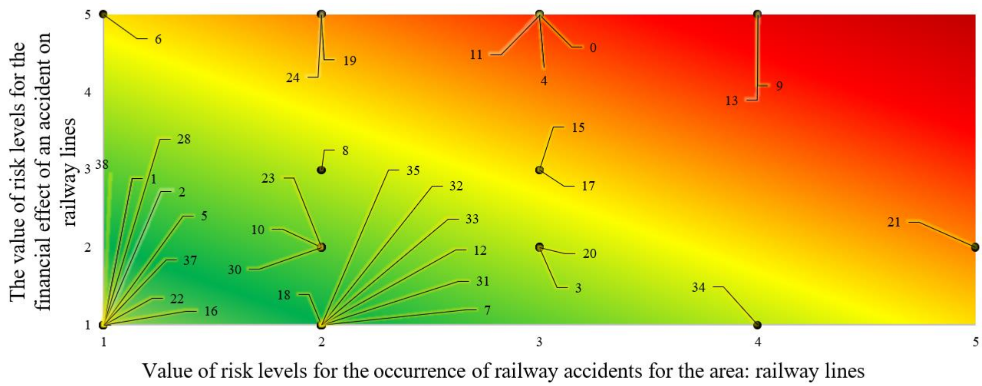

Fig. 14. Risk assessment of rail freight implementation for financial impact
Source: based on (Szaciłło, 2021).

Table 4. Aggregate risk assessment of rail freight implementation for selected impacts

Effect	Slight (2)	Low (3-4)	Medium (5-6)	High (7-8)	Very high (9-10)
Killed	1, 2, 5, 6, 16, 22, 28, 37, 38	0, 3, 4, 7, 8, 10, 11, 12, 15, 17, 18, 23, 24, 30, 32, 35	9, 13	19, 20, 31, 33	21, 34
Severely injured	1, 2, 5, 6, 16, 22, 28, 37,38	0, 3, 4, 7, 8, 10, 11, 12, 15, 17, 18, 19, 23, 24, 30, 31, 32, 35	9, 13, 20, 33	-	21, 34
Injured	1, 2, 5, 6, 16, 22, 28, 37,38	0, 3, 4, 7, 8, 10, 11, 12, 15, 17, 18, 19, 23, 24, 30, 31, 32, 33	9, 13, 35	20, 34	21
Invasion of a train by a road vehicle	22	18, 19, 23	20	-	21
Invasion of a road vehicle by a train	22	18, 19, 23	20	-	21
Delay of a freight train	1, 2, 5, 16, 22, 28, 37,38	7, 8, 10, 12, 18, 23, 24, 30, 31,32, 35	6, 13, 15, 19, 20, 33	0, 3, 4, 11, 17, 21, 34,	9
Financial	1, 2, 5, 16, 22, 28, 37, 38	7, 10, 12, 18, 23, 30, 31, 32, 33, 35	3, 6, 8, 15, 17, 20, 34	0, 4, 11, 19, 21, 24	9, 13

Source: own elaboration based on (Szaciłło, 2021).

8. Summary

The issue of assessing the risk of carrying out transportation on the rail network is very important due to the role of rail transport in cargo transportation. Transmission of cargo by rail is carried out using various transport technologies, and this causes the occurrence of various adverse events. Determining the risk assessment of the realization of rail freight transport, requires solving a complex decision-making problem. The presented assumptions of the model for the risk assessment of the realization of rail freight transport indicate a universal approach to support the decision-making process for the risk assessment of the realization of freight transport on the rail network. They can be used to analyze adverse event scenarios for both railways and rail sidings. The developed approach to risk assessment using a risk matrix enables risk management.

Of decisive importance in the correctness of the model's operation and the possibility of its use in practical solutions is the quality of the input data. The presented approach is primarily driven by the need for business practice, i.e. to align the reliability and safety of freight transportation by rail with customer expectations.

The risk matrix is a useful tool for presenting the results of risk analysis to support risk assessment for various event scenarios that may occur in the system under study, including in rail freight. Risk estimation, if not based on historical data or statistical analysis, requires expert judgment. The risk matrix method can be considered a universal method to support risk management. Among other things, it can be applied to rail freight operators and rail infrastructure managers to identify the most dangerous locations of adverse events.

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Bibliography

[1] Abioye, O., Dulebenets, M., Pasha, J., Kavoosi, M., Moses, R., Sobanjo, J., Ozguven, E. (2020). Accident and hazard prediction models for highway–rail grade crossings: a state-of-the-practice review for the USA. Railway Engineering Science 28 (3), 251-274. DOI: 10.1007/s40534-020-00215-w
[2] Ambituuni, A., Amezaga, J., Werner, D. (2015). Risk assessment of petroleum product transportation by road: A framework for regulatory improvement. Safety Science, 79, 324-335. DOI: 10.1016/j.ssci.2015.06.022
[3] Bałuch, H., Starczewska, M., KOW Sp. z o. o. (2011). Leksykon terminów kolejowych. Warszawa: KOW media & marketing.
[4] Batarliene, N., Jarasuniene, A. (2014). Analysis of the accidents and incidents occurring during the transportation of dangerous goods by railway transport. Transport (Vilnius, Lithuania), 29(4), 395-400. DOI:10.3846/16484142.2014.983967
[5] Batarliene, N. (2020). Essential Safety Factors for the Transport of Dangerous Goods by Road: A Case Study of Lithuania. Sustainability (Basel, Switzerland), 12(12), 4954. DOI:10.3390/su12124954
[6] Bernatik, A., Rehak, D., Cozzani, V., Foltin, P., Valasek, J., Paulus, F. (2021). Integrated Environmental Risk Assessment of Major Accidents in the Transport of Hazardous Substances. Sustainability (Basel, Switzerland), 13(21), 11993. DOI:10.3390/su132111993
[7] Berrado, A., El-Koursi, E., Cherkaoui, A., Khaddour, M. (2011). A Framework for Risk Management in Railway Sector: Application to Road-Rail Level Crossings. The Open Transportation Journal, 5(1), 34-44. DOI: 10.2174/1874447801105010034
[8] Burdzik, R., Rozmus, R., Nowak, B., Młyńczak, J. (2017). Analysis of the safety of railway level crossing in the aspect of traffic ratio. Scientific Journals of the Institute of Vehicles, 4(113), 23-31.
[9] Bureika, G., Gaidamauskas, E., Kupinas, J., Bogdevičius, M., Steišūnas, S. (2017). Modelling the assessment of traffic risk at level crossings of Lithuanian railways. Transport (Vilnius, Lithuania), 32(3), 282-290. DOI: 10.3846/16484142.2016.1244114
[10] Cafiso, S., A. Di Graziano, N. Di Blasi. (2006). Risk Assessment On Railway Transportation Of Hazardous Materials. WIT Transactions on Ecology and the Environment, 91, 97-106. DOI:10.2495/RISK060101
[11] Cieśla, M., Sobota, A., Jacyna, M. (2020). Multi-Criteria Decision Making Process in Metropolitan Transport Means Selection Based on the Sharing Mobility Idea. Sustainability (Basel, Switzerland), 12(17), 7231. DOI:10.3390/su12177231
[12] Conca, A., Ridella, C., Sapori, E. (2016). A Risk Assessment for Road Transportation of Dangerous Goods: A Routing Solution. Transportation Research Procedia, 14, 2890-2899. DOI:10.1016/j.trpro.2016.05.407
[13] De Cillis, F., De Maggio, M., Pragliola C., Setola, R. (2013). Analysis of Criminal and Terrorist Related Episodes in Railway Infrastructure Scenarios. Journal of Homeland Security and Emergency Management, 10(2), 1-30. DOI: 10.1515/jhsem-2013-0003
[14] Duffey, R., Saull, J. (2002). Know the Risk : Learning from Errors and Accidents: Safety and Risk In Today's Technology, Elsevier Science & Technology.
[15] Duffey, R. (2020). Learning About Risk : Life, Death...and Money, Independently Published.
[16] Dvorak, Z., Rehak, D., David, A., Cekerevac, Z. (2020). Qualitative Approach to Environmental Risk Assessment in Transport. International Journal of Environmental Research and Public Health, 17(15), 5494. DOI:10.3390/ijerph17155494
[17] Elmontsri, M. (2014). Review of the Strengths and Weaknesses of Risk Matrices. Journal of

Risk Analysis and Crisis Response, 4(1), 49. DOI:10.2991/jrarc.2014.4.1.6
[18] European Union. (2013). Commission Implementing Regulation (EU) No 402/2013 of 30 April 2013 on the common safety method for risk evaluation and assessment and repealing Regulation (EC) No 352/2009. (L 121/8).
[19] Grabowska–Bujna, B., Wieczorek, S., Mikulski, J. (2016). Rail Traffic Remote Control Systems Within the Areas Affected by the Occurrence of Mining Damage and Railway Safety. Tools of Transport Telematics, 264-273. DOI:10.1007/978-3-319-24577-5_26
[20] Grenčík, J., Galliková, J., Volna, P. (2020). A novel methodology of risk assessment for railway freight wagons. Scientific Journals of the Maritime University of Szczecin, 63(135), 17-22. DOI:10.17402/435
[21] Grenčík, J., Poprocký, R., Galliková, J., Volna, P. (2018). Use of risk assessment methods in maintenance for more reliable rolling stock operation. MATEC Web of Conferences, 157, 4002. DOI:10.1051/matecconf/201815704002
[22] GUGiK. (2022). Head Office of Geodesy and Cartography. Access: https://mapy.geoportal.gov.pl/wss/service/sdi/Przejazdy/get
[23] GUGiK. (2022). Head Office of Geodesy and Cartography. Access: https://services.gugik.gov.pl/uug/
[24] Huang, W., Zhang, Y., Kou, X., Yin, D., Mi, R., Li, L. (2020). Railway dangerous goods transportation system risk analysis: An Interpretive Structural Modeling and Bayesian Network combining approach. Reliability Engineering & System Safety, 204. 107220. DOI:10.1016/j.ress.2020.107220
[25] Huang, W., Zhang, Y., Yu, Y., Xu, Y., Xu, M., Zhang, R., Liu, Z. (2021). Historical data-driven risk assessment of railway dangerous goods transportation system: Comparisons between Entropy Weight Method and Scatter Degree Method. Reliability Engineering & System Safety, 205, 107236. DOI:10.1016/j.ress.2020.107236
[26] IEC. (2016). International Standard 61882, Hazard and Operability Studies (HAZOP) Application Guide.
[27] ISO 31010 Risk management - Risk assessment techniques. 2.0. Geneva: IEC. (2020).
[28] ISO Guide 73: Risk management - Vocabulary. 2.0. Vienna: ISO (2010).
[29] IEC 60812 Failure modes and effects analysis (FMEA and FMECA). 2.0. Geneva: IEC (2019).
[30] Izdebski, M., Jacyna-Gołda, I., Gołda, P. (2022). Minimisation of the probability of serious road accidents in the transport of dangerous goods. Reliability Engineering & System Safety, 217, 108093. DOI:10.1016/j.ress.2021.108093
[31] Jacyna, M., Szaciłło, L. (2017). Selected aspects of risk management in railway transport. WUT Journal of Transportation Engineering, 119, 163-178.
[32] Jacyna, M., Semenov, I. (2020). Models of vehicle service system supply under information uncertainty. Eksploatacja I Niezawodnosc - Maintenance and Reliability, 22(4), 694-704. DOI:10.17531/ein.2020.4.13
[33] Jacyna, M., Jachimowski, R., Szczepański, E., Izdebski, M.. (2020). Road vehicle sequencing problem in a railroad intermodal terminal – simulation research. Bulletin of the Polish Academy of Sciences. Technical Sciences, 68(5), 1135-1148. DOI:10.24425/bpasts.2020.134643
[34] Karoń G., Żochowska, R. (2020). Problems of Quality of Public Transportation Systems in Smart Cities-Smoothness and Disruptions in Urban Traffic. In book: Modelling of the Interaction of the Different Vehicles and Various Transport Modes, 383-414. DOI:10.1007/978-3-030-11512-8_9
[35] Kornaszewski, M., Pniewski. (2016). Pedicting reliability of railway traffic control devices using simulation methods. WUT Journal of Transportation Engineering, 113, pp. 241-253.
[36] Kycko, M., Zabłocki, W. (2019). Risks in Investment Processes Covering Railway Traffic Control Systems. Railway Reports, 184, 85-91.
[37] Lahuta, P., Kardoš, P., Hudáková, M. (2021). Integrated Risk Management System in Transport. Transportation Research Procedia, 55, 1530-1537. DOI:10.1016/j.trpro.2021.07.142
[38] Liu, X. (2016). Development of a Risk Assessment Tool for Rail Transport of Flammable Energy Resources. Final report (CAIT-UTC-NC16). New Jersey: Department of Civil and Environmental Engineering Rutgers. The State University of New Jersey.

[39] Luxton, A., Marinov, M. (2020). Terrorist Threat Mitigation Strategies for the Railways. Sustainability (Basel, Switzerland), 12(8), 3408. DOI:10.3390/su12083408
[40] Marrone, S., Nardone, R., Tedesco, A., D'Amore, P., Vittorini, V., Setola, R., Mazzocca, N. (2013). Vulnerability modeling and analysis for critical infrastructure protection applications. International Journal of Critical Infrastructure Protection, 6(3-4), 217-227. DOI:10.1016/j.ijcip.2013.10.001
[41] MIiB. (2016). Rozporządzenie Ministra Infrastruktury i Budownictwa z dnia 16 marca 2016 r. w sprawie poważnych wypadków, wypadków i incydentów (369, Dz.U. 2016 poz.).
[42] Murawski, J., Szczepański, E., Jacyna-Gołda, I., Izdebski, M., Jankowska-Karpa, D. (2022). Intelligent mobility: A model for assessing the safety of children traveling to school on a school bus with the use of intelligent bus stops. Eksploatacja i Niezawodność - Maintenance and Reliability, 24(4), 695-706. DOI: 10.17531/ein.2022.4.10
[43] PKP PLK S.A. (2022). PKP Polish Railway Lines S.A., Access: http://mapa.plk-sa.pl/.
[44] Placido, A., Petito, C., Gallo, M., D'Acierno, L. (2017). Managing disruptions and disturbances on railway services: A real-scale case study. International Journal of Transport Development and Integration, 1(4), 695-710. DOI:10.2495/TDI-V1-N4-695-710
[45] PN-EN. (2018). 50126-2:2018 Railways Applications - The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) - Part 2: Systems Approach to Safety.
[46] Rahbar, M., Bagheri, M. (2014). Risk Assessment Framework for the Rail Transport of Hazardous Materials. Transportation Research Record. Journal of the Transportation Research Board, 2411, 90-95. DOI:10.3141/2411-11
[47] Sanchis, I., Franco, R., Zuriaga, P., Fernández, P. (2020). Risk of increasing temperature due to climate change on operation of the Spanish rail network. Transportation Research Procedia, 45, 5-12. DOI:10.1016/j.trpro.2020.02.056
[48] Sitarz, M., Chruzik., Wachnik, R. (2011). The integrated managing system for safety in railway transport. Part 8. estimation of risk. TTS Technika Transportu Szynowego, 5-6, 89-93.
[49] Sobota, A., Żochowska, Szczepański, E., Gołda, P. (2018). The influence of tram tracks on car vehicle speed and noise emission at four-approach intersections located on multilane arteries in cities. Journal of Vibroengineering, 20(6), 2453-2468. DOI:10.21595/jve.2018.20087
[50] Szaciłło, L. (2021). Model Oceny Ryzyka Realizacji Kolejowych Przewozów Towarowych: Rozprawa Doktorska. (Risk assessment model for the implementation of raił freight).
[51] Szaciłło, L., Jacyna, M., Szczepański, E., Izdebski, M. (2021). Risk assessment for rail freight transport operations. Eksploatacja i Niezawodność - Maintenance and Reliability, 23(3), pp. 476-488. DOI:10.17531/ein.2021.3.8
[52] Tavasszy, L., De Jong, G. (2013). Modelling Freight Transport (1st ed., Elsevier insights). Saint Louis: Elsevier. DOI:10.1016/C2012-0-06032-2
[53] Tubis, A., Werbińska-Wojciechowska, S. (2017). Risk assessment issues in the process of freight transport performance. Journal of KONBiN, 42(1), 235-253. DOI:10.1515/jok-2017-0027
[54] UTK. (2003). The Railway Transport Act of March 28, 2003. Access: https://utk.gov.pl/en/market- regulation-and-l/railway-transport-act/19018,Nonbinding-Translation-of-the- Railway-Transport-Act-2003.html (2022).
[55] UTK. (2022). The Office of Rail Transport. Access: https://dane.utk.gov.pl/sts/infrastruktura/obiekty-infrastruktury/18003,Obiekty- infrastruktury-uslugowej-z-podzialem-na-rodzaj-swiadczonych-uslug.html.
[56] UTK. (2020). The Office of Rail Transport. Access: https://utk.gov.pl/pl/dokumenty-i- formularze/opracowania-urzedu-tran/19252,Sprawozdanie-ze-stanu-bezpieczenstwa- ruchu-kolejowego-2021.html.