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Risk assessment for rail freight transport operations

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Highlights

- Risk assessment for freight train delays on railway lines.
- Identification of causes of accidents on railway lines and railway sidings in Poland.
- Determination of the probability of a cause resulting in a railway accident.
- Risk analysis of potential costs of delays resulting from accidents in Poland in 2019.

Abstract

The aim of this article is to assess the risk of performance of rail freight transport on the basis of an analysis of identified risk areas based on statistical data on the causes of accidents that occurred on the lines of railway transport in Poland. A critical review of selected scientific studies relating to the risk assessment process for identified areas of the railway system has been undertaken. Based on statistical data, the authors analysed the causes of accidents on railway lines in 2019 in Poland and determined the probability of occurrence of a given cause. In addition, the article calculates the probability of vehicle delays for different emergency situations occurring in the performance of rail freight transport operations. This enabled the authors of the article to carry out a risk assessment of freight train delays on railway lines.

Keywords

risk assessment, railway transport risk, train delay risk level, causes of railway accidents.

1. Introduction

The problem of risk assessment in railway transport is presented next to risk analysis and risk evaluation as one of the stages of risk management in the whole railway system. The level of generality in dealing with adverse events in the process of freight transport by rail often results in an inadequate and insufficient response to the upsetting of the acceptable level of risk by those involved in the process. It is common practice to react to the effects of rail incidents rather than prevent them from occurring. The groups of entities involved in ensuring safety in railway transport include rail operators, infrastructure managers, users of sidings, rolling stock manufacturers, manufacturers of devices and railway traffic control systems, designers and entities responsible for maintenance of rolling stock and railway infrastructure facilities.

Risk assessment in the rail transport system can be seen as an approach aimed at identifying risks at junctions and on railway lines, including risks arising from operational processes and the actions of other actors in the system whose task is to provide rail freight transport operations. Risk assessment also consists of risk analysis and evaluation.

Particularly relevant in this context is the risk profile *R* the so-called risk scenario representing the pattern of the risk distribution probability and its consequences written in the form of the following pairs [53]:

$$R=\{(P_1, S_1), (P_2, S_2), \ldots,(P_i, S_i),\ldots, (P_n, S_n)\} \quad (1)$$

where:

- R – risk,
- P_i – probability of risk due to *i-th* factor,
- S_i – effects of risk due to *i-th* factor,
- i – risk factor number; $i = 1,\ldots n$.

Risks can come from internal sources resulting from the transport system under study and from external sources resulting from causes in its environment. A single risk may consequently generate multiple negative effects with varying degrees of impact. At the same time, one effect of risk implementation may have several causes.

Identification and analysis of adverse events allow for understanding and improving the weaknesses of the organisations operating within the railway system where such situations have been diagnosed. Positive aspects of studying this type of situations include:

- effective accident prevention by learning from mistakes,
- minimising the risks involved through proactive management,
- elimination of repetition of potentially dangerous situations,

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– detecting dangerous situations and behaviours,
– raising awareness, both among employees and subcontractors,
– developing a culture of safety,
– reducing the organisation's losses.

In case of risk, the level of which is acceptable to the evaluating entity, periodical risk analyses are performed. On the other hand, when the level of risk is unacceptable, actions necessary to reduce the risk are determined. In the last stage, changes are made to the system to reduce the level of risk (Fig. 1).

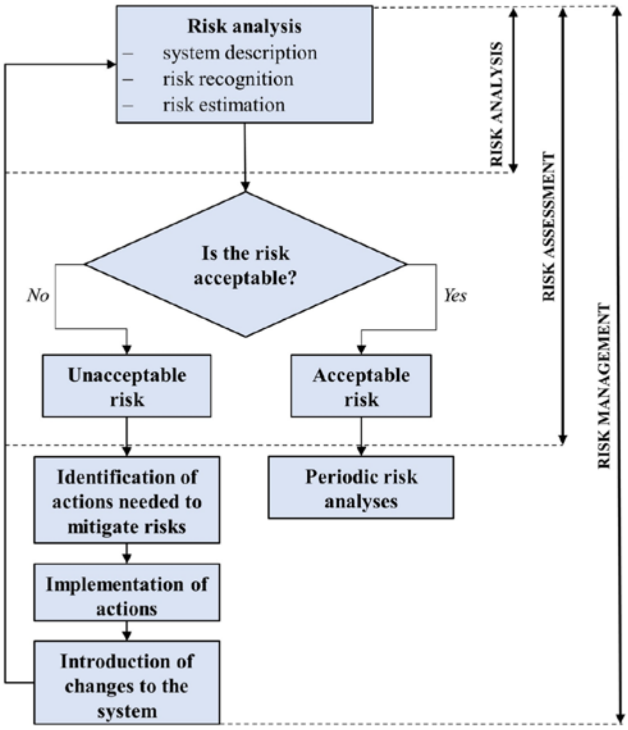

Fig. 1. Decision-making process related to risk management
Source: own study.

The aim of this article is to assess the risk of performance of rail freight transport on the basis of an analysis of identified risk areas based on statistical data on the causes of accidents that occurred on the lines of railway transport in Poland. Identification of risks is a starting point for further research in the area of risk assessment for performance of rail freight transport operations.

The article is divided into four parts. In the first one, a critical analysis of the literature on selected areas of risk assessment in the rail transport system and on tools and methods for risk assessment in other areas is carried out. The second part is the identification of the research area. The authors have presented the process of performance of rail freight transport operations, defining their scope and characteristics of the quantities describing the rail freight transport in Poland. The next section analyses conditions related to accidents and incidents in the railway transport system based on 2019 data occurring on both railway lines and sidings. The last part of the article is a case study detailing the causes of train accidents and their numbers. Based on the statistical data on the causes of railway accidents in the railway transport system on railway lines and railway sidings in 2019, the probability of occurrence of a particular cause was determined. The determination of the probability of vehicle delay in each emergency situation allowed for the determination of the risk associated with the occurrence of delays in rail freight transport.

In the discussion of results and conclusions, the authors pointed out the conditions of risk occurrence during performance of rail freight transport operations on the railway lines in Poland and indicated the directions of further research.

2. Literature review

Research studies have largely focused on the process of risk assessment in rail transport for infrastructure elements from two perspectives. The first one concerns research related to risk assessment with multiple facilities and their interrelationships. In contrast, the second approach presents a risk assessment that focuses on single facilities or multiple facilities without their interrelationships.

The risk management process for rail transport is outlined in both national and European legislation. The Railway Safety Directive [11] in conjunction with the Interoperability Directive [10] and the Single European Railway Area Directive [12] introduced a coherent system in which full responsibility for the safety of products and services lies with a specific undertaking which acts in a systemic way and uses uniform procedures and tools [20].

Commission Implementing Regulation (EU) of 2013 [8] presents the risk management process for determining whether a change has an impact on the safety of the railway system. There are, among others, criteria of independent changes, i.e.:

– effect of failure – a plausible worst-case scenario in the event of failure of the assessed system, taking into account the existence of protective barriers outside the assessed system,
– innovation used in implementing the change – this criterion covers innovation relevant to both the whole railway sector and the organisation implementing the change,
– complexity of change,
– monitoring – the inability to monitor an implemented change throughout the system life cycle and intervene accordingly,
– reversibility of change – the inability to return to the system before the change,
– additionality – assessment of the significance of change taking into account all recent changes to the system under assessment, which were related to safety and were not judged to be significant.

Much emphasis is placed on risk assessment of rolling stock during the operational phase. For example, the paper [16] focuses on presenting the reliability of rolling stock using the Weibull reliability model. The risk value formula was based on classical risk theory viewed as a combination of the probability of a negative event occurring and the severity of its consequences. Whereas possible methods of risk assessment together with types of risks divided into categories of their sources – individual, technical, environmental, social, economic were presented in the paper [15]. A rather interesting approach to system performance evaluation and operational process evaluation using fuzzy logic is presented by the author of the paper [28]. The proposed model allows combining inconsistent system and process characteristics, e.g.: punctuality, probability of no further delays, quantitative performance of planned processes or reconfiguration level. Many authors point out that the assessment of risk and the effectiveness of system operation in different aspects is a multi-criteria decision making (MCDM) problem [9], [28], [57]. In the paper [48] the MCDM aspect related to risk assessment of railway infrastructure has been pointed out, while the paper [35] presents the risk assessment of infrastructure investment projects on the railway network. The performance of the systems in terms of environmental aspects and minimisation of the number of exhaust gases has been extensively presented in [4].

The paper [13] presents a model of railway accident occurrence and the use of fault tree analysis method. A breakdown of studies of reliability and safety of the railway transport system in four areas is presented, i.e.:

– transport, in which the infrastructure is analysed with respect to minimising life-cycle costs, the performance of dispatching tasks after the occurrence of disruptions and the cause-effect sequences during the transition of individual elements to an inoperable state,
– reliability, including: vehicles, individual facilities or subsystems within the infrastructure, process reliability, punctuality,

– security, analysing the minimisation of negative effects of system operation and occurring errors,
– critical infrastructure – of a general nature that does not take into account certain features of the railway, e.g. the power supply system.

The risk assessment methodology for the railway infrastructure network was investigated in the DESTination RAIL project. Authors of the study [39] presented the process of risk assessment supporting railway network infrastructure managers in risk reduction for selected facilities by applying unified probability of failure connected with different state of infrastructure facilities and consequences of occurrence of such failures. The risk assessment is presented at four levels – facility, section, route and network taking into account the different types of failures and their impact on stakeholders.

At this point, it is also worth pointing to the INFRARISK project (2013-2016) whose subject of research was, among others, risk assessment of the implementation of both railway infrastructure investment projects on the road infrastructure [2], [17]. The objective of the project was to develop a process for assessing infrastructure network risks resulting from natural hazards (e.g. floods, landslides, earthquakes). This process illustrates the functional interdependencies between multiple facilities in the network and indicates the impact and consequences of individual risks. The main tasks of the research project were to initiate, conduct tests under extreme conditions to determine whether there is an acceptable level of risk associated with natural hazards and to prepare an intervention programme aimed at reducing the risk to an acceptable level by decision makers.

Many studies also address the aspect of modelling reliability analysis of railway infrastructure. Infrastructure maintenance and management play a major role in ensuring the reliability and availability of railway transport [38]. Managing infrastructural assets also means managing their exploitation [57] and functional reliability [31]. The article [45] determined the correlations between the type of infrastructure elements used and the number of incidents, as well as the correlation between the type (and age) of infrastructure elements used and the number of failures.

Other areas of research on rail freight transport risk assessment have been touched upon in the works [1], [3], and they concern risk assessment on level crossings and risk assessment of transport of dangerous goods by rail [6], [37], [43]. The organisation of the transport process[27] as well as the use of modern traffic control devices [26], [29], [54] are important. In the case of a risk assessment model for a railway accident at work [34], classification of five main causes of accidents (collision, derailment, fire, accident at level crossing, accidents related to train movement) was made and the process of creation of risk assessment model in railway system was presented and its application on Slovak railways was indicated. The management of risks to the railroad surface is presented in [49]. The safety of train traffic is influenced by many factors [7] such as type of track: classic or jointless [14], the state of stress in the rails [33]. The type of track and the quality of its maintenance also affect the better smoothness of driving and less noise emission [50]. There is also significantly less wear and tear on vehicles and traction energy consumption [55]. In order to increase the degree of level crossing safety, the supporting system should be independent of the currently used traffic control devices, as indicated by the authors of the paper [5]. Therefore, as the authors point out [25], the occurrence of an adverse event should be analysed and used to improve safety procedures.

Important documents in risk analysis and assessment include the international standards related to risk management [21], [22], [23] which relate to the identification, analysis and evaluation of risks. The application of techniques in the risk management process according to ISO 31000 is shown in Figure 2.

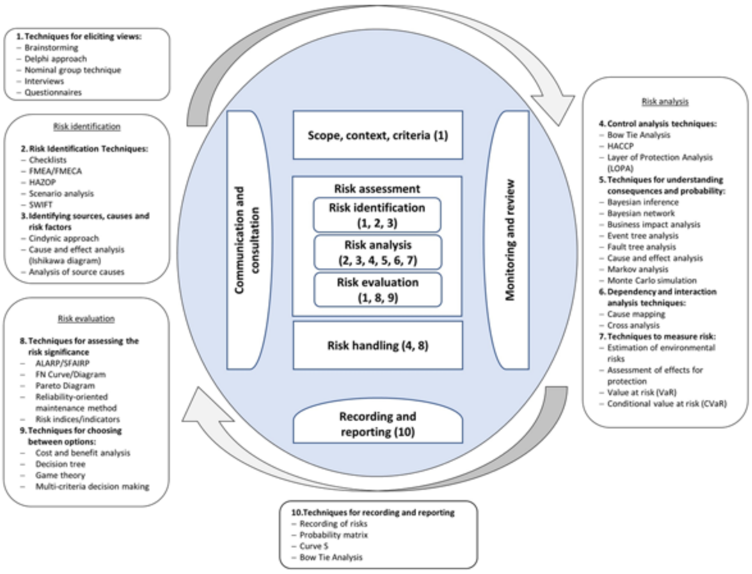

Fig. 2. Application of techniques in the risk management process according to ISO 31000
Source: own study based on [21]

Dedicated to any organisation regardless of its type, size and location, standard ISO 31000:2018 presents principles and guidelines for risk management in a systematic and transparent way within any issue and context. Although it cannot be part of a certification, it provides guidelines for internal or external audit programmes. In addition, it points to three main stages of risk management:
– adoption of risk management principles,
– development, introduction and continuous improvement of the framework structure,

Table 1. Specification of selected research areas related to the risk assessment of rail freight transport operations in relation to bibliographic sources

No.	Research area	Sources of issues
1	Legislation relevant to safety of railway systems	[8], [10], [11], [12], [20], [47]
2	International standards and internal procedures related to risk management	[21], [22], [23]
3	Risk assessment of rolling stock	[15], [16]
4	Risk assessment at level crossings	[1], [3]
5	Risk assessment for the transport of dangerous goods by rail	[6], [18], [19], [37], [43]
6	Risk assessment for infrastructure investment projects	[35]
7	Multi-criteria decision making in the area of reliability and risk assessment	[4], [9], [28], [48]
8	Causes of railway accidents	[34], [41], [52]
9	Reliability of railway infrastructure	[13], [39], [40], [45]
10	Research projects related to risk assessment in railway transport	[2], [17], [39]

Source: own study.

– implementation of a risk management process.

Given these considerations, it should be noted that the main areas for risk assessment include (Table 1):

– legal and organisational conditions of risk management and assessment,
– risk assessment for maintenance, operation and management of railway infrastructure,
– assessment of the causes of railway accidents and analysis of the reliability of the railway infrastructure,
– methods and tools for risk analysis, assessment and management,
– risk assessment studies undertaken in research projects.

Analyses conducted indicate to the lack of extensive research in the field of comprehensive analysis and risk assessment of railway transport operations based on the analysis of statistical data of undesirable situations occurring during transport on the Polish railway network.

3. The research problem and its evaluation

Many factors influence the freight transport process. One of them is the location of raw material sources, as well as the location of intermediate and final markets. Among other factors, there are also operational factors, which include: the size of the organisation, distribution channels and geographical dispersion [27].

The rail freight transport process is a set of structured and interrelated activities which involve moving a specific cargo batch (shipment) from a forwarding station to a destination station and delivering it to the recipient (direct or indirect) [26], [27]. From a technological point of view, the rail freight transport process should be understood as those elements of the transport process that involve freight cars – from the start of their loading at the forwarding station to the end of their unloading at the destination station (Fig. 3). Cars can be moved

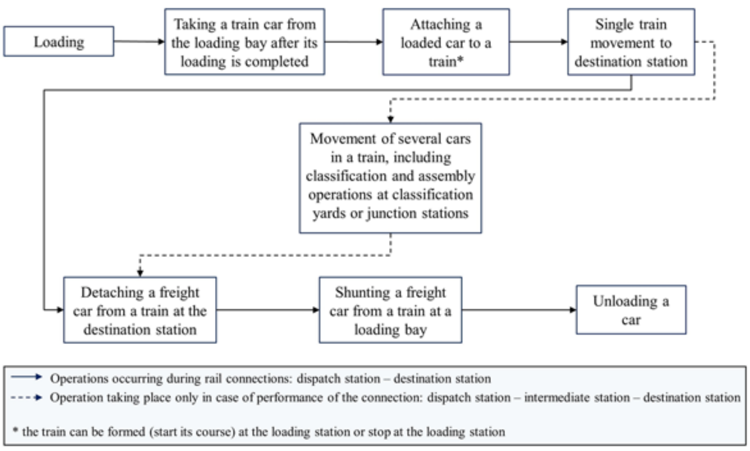

Fig. 3. Basic activities in the rail freight transport process (technological approach)
Source: own study.

in a direct transport process (when a certain cargo batch is only moved from a forwarding station to a destination station by one train) and in an indirect transport process (cargo is moved from a forwarding station to a destination station by two or more freight trains).

In rail freight transport, the type of cargo transported will be an important factor that affects the entire process of movement. In 2019, the main commodity groups (according to the simplified standard classification of goods for transport statistics) carried by rail freight transport operators included [51]:

– hard coal, lignite, crude oil and natural gas – 91.1 million tonnes,
– metal ores and other mining and quarrying products – 64.8 million tonnes,
– coke, briquette, refined petroleum products – 27.8 million tonnes,
– chemicals, chemical products, man-made fibres, rubber and plastic products, nuclear fuel 10 million tonnes,
– metals and finished metal products (excluding machinery and equipment) – 9.2 million tonnes.

The total weight of cargo transported by rail freight transport in 2019 at the territory of Poland amounted to 236.4 million tonnes

The Office for Railway Transport and the European Railway Agency (ERA) commonly use the terms “accident”, “serious accident” and “incident” in their reports and studies. The Railway Transport Act [56] defines the concept of an accident, a serious accident and an incident as follows:

a) accident – unintended sudden event or sequence of such events with the participation of a railway vehicle, causing negative consequences for human health, property or the environment; accidents include in particular: collisions, derailments, incidents on level crossings, incidents with the participation of persons caused by a railway vehicle in motion, fire of a railway vehicle;
b) serious accident – any accident caused by collision, derailment or any other event with an obvious impact on railway safety or the safety management, i.e. resulting in at least one fatality or at least 5 seriously injured persons or causing significant damage to a railway vehicle, the railway infrastructure or the environment, which can be immediately estimated by the accident investigation committee to cost at least EUR 2 million;
c) incident – any event, other than an accident, associated with railway traffic and affecting its safety.

The regulation on serious accidents, accidents and incidents [47] indicates that in order for a serious accident or an accident to be classified in a specific category depending on the established immediate cause, the following should be done:

– select a group according to the severity of the consequences of the event and specify the letter designation corresponding to that group as follows: A – serious accident, B – accident (other than serious),
– select the immediate cause qualification and determine the corresponding numerical category,
– qualify the event by inserting in place of the * a number relating to the category of the immediate cause specified above.

In order to qualify an incident to a specific category depending on the determined immediate cause of its occurrence, it is necessary to make a qualification of the cause and to specify a letter and number category corresponding to this cause (for an incident a letter designation C).

Adverse events in railway transport system coming from infrastructure manager (PKP PLK S.A.) or State Commission for Examination of Railway Accidents include, among others [20]:

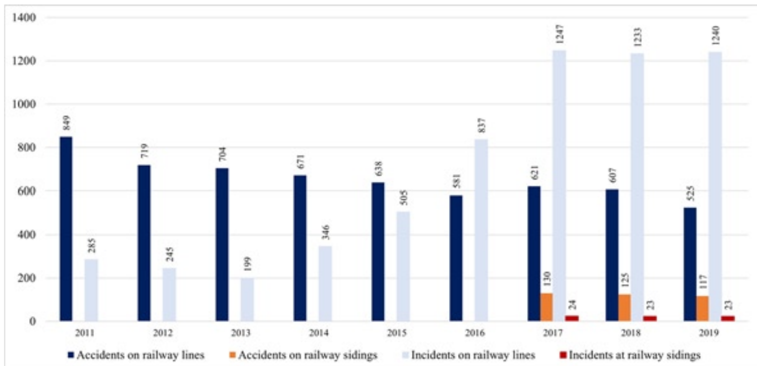

Fig. 4. Accidents and incidents on railway lines and railway sidings
Source: own study based on [52]

Table 2. Causes of accidents occurring on railway lines in 2019

No.	Cat (A, B)	Description of the cause	Number of causes	Pp
1	00	causes other than those listed below or the overlapping of several causes at the same time, creating equivalent causes	10	0.019048
2	03	dispatching, accepting or driving of a railway vehicle on an incorrectly planned, unsecured route or incorrect operation of traffic control devices	13	0.024762
3	04	failure of a railway vehicle to stop before a "stop" signal or in a place where it should stop, or starting a railway vehicle without required authorisation	22	0.041905
4	06	exceeding the maximum permissible speed	1	0.001905
5	08	inadvertent starting of a railway vehicle	3	0.005714
6	09	damage or poor maintenance of the surface, bridge or overpass, including also improper execution of works, e.g. improper unloading of materials, surface, leaving materials and equipment (including road machines) on the track or within the clearance of the railway vehicle, or running the railway vehicle over elements of the structure	28	0.053333
7	10	damage to or poor technical condition of powered railway vehicle, special-purpose vehicle (including running over an object which is a structural part of powered railway vehicle, special-purpose vehicle) and damage to or malfunction of the on-board part of ERTMS (European Rail Traffic Management System)	5	0.009524
8	11	damage or poor technical condition of a car (including running over a structural part of the car)	20	0.038095
9	13	collision of a railway vehicle with a railway vehicle or other obstacle (e.g. brake skid, luggage trolleys, postal cart, etc.)	23	0.04381
10	15	premature termination of the route or release and shifting of the railway point under the railway vehicle	13	0.024762
11	17	improper loading, unloading, irregularities in securing the cargo or other irregularities in cargo operations	7	0.013333
12	18	collision of railway vehicle with road vehicle (other road construction equipment, agricultural machinery) on a level crossing with grade-crossing gate (cat. A according to the transit metric)	8	0.015238
13	19	collision of railway vehicle with road vehicle (other road construction equipment, agricultural machinery) on a level crossing equipped with automatic crossing system with traffic lights and grade-crossing gate (cat. B)	14	0.026667
14	20	collision of railway vehicle with road vehicle (other road construction equipment, agricultural machinery) on a level crossing equipped with automatic crossing system with traffic lights and without grade-crossing gate (cat. C)	27	0.051429
15	21	collision of railway vehicle with road vehicle (other road construction equipment, agricultural machinery) on a level crossing not equipped with a crossing system (cat. D)	123	0.234286
16	23	collision of railway vehicle with road vehicle (other road construction equipment, agricultural machinery) outside level crossings in stations and routes or on the communication and access track to the siding	7	0.013333
17	24	fire in a train, marshalling train or railway vehicle	1	0.001905
18	30	malicious, hooligan or reckless misconduct (e.g. throwing stones at a train, stealing cargo from a train or marshalling train in motion, placing an obstacle in the track, devastation of power, communication, signalling or track surface equipment and interfering with such equipment)	9	0.017143
19	31	collision of a railway vehicle with persons when crossing the tracks at level crossings or guarded crossings	12	0.022857
20	32	collision of a railway vehicle with persons crossing the track at a level crossings with an automatic crossing system (cat. B, C)	5	0.009524
21	33	collision of a railway vehicle with persons when crossing the tracks at other level crossings and crossings	10	0.019048
22	34	collision of a railway vehicle with persons when crossing the tracks at level crossings or crossings at stations or on the routes	142	0.270476
23	35	events with persons related to the movement of a railway vehicle (jumping, falling from a train, railway vehicle, strong approach or sudden braking of a railway vehicle)	19	0.03619
24	41	the category has not been established or the cause of the incident is still being determined	3	0.005714

Source: own study based on: [41], [52].

- notification of an event,
- report of visual inspection of the scene,
- sketch of the scene of the accident or incident,
- report on final findings of the State Commission for Railway Accident Investigation,
- documents concerning the implementation of preventive measures,
- summary of proceedings,
- facts directly related to a serious accident,
- description of test and hearing records,

– analysis and conclusions
– description of ad hoc preventive measures,

recommended preventive measures to avoid such accidents or incidents in the future or to limit their consequences.

Figure 4 shows the number of accidents and incidents occurring on railway lines (2011-2019) and on railway sidings (2017-2019).

Since 2011 there has been a downward trend in the number of accidents on railway lines in Poland. In 2019 there were 525 accidents on railway lines and for the corresponding group on railway sidings – 117.

As indicated in many publications [41]a serious accident is only possible if the following factors occur simultaneously:

– a conscious or unconscious decision to misuse the system,
– continuation of the system misuse,
– disrupted train traffic (mainly serious accidents caused by the traffic dispatcher),
– human error (driver or traffic dispatcher).

For incidents on railway lines (Fig. 4), an increasing trend has been noticeable since 2014. This is due, among other things, to supervision activities that revealed the misclassification of some events which may have resulted in them not being included in official statistics. In 2019, 1240 incidents were recorded on railway lines while 23 incidents were recorded for the same group of incidents on railway sidings.

4. Risk analysis and assessment based on adverse events – case study

4.1. Identification of adverse events on the rail transport network

Publicly available statistical data on adverse events in the Polish railway transport system, provided by the Office for Railway Transport, do not distinguish between passenger and freight transport. Based on an analysis of documents [41], [52] causes of railway accidents for categories A (serious accident) and B (other than serious accident) on railway lines in 2019 (Table 2) and for railway sidings (Table 3) were identified.

The probability of occurrence of a given cause in the railway transport system in 2019 (P_p) and the probability of effect, i.e. occurrence of train delay generated by a given emergency situation (P_o) were determined on the basis of data analysis.

Out of all adverse events in the railway transport system, those reported by the Office for Railway Transport were singled out. The probability of causes listed in Tables 2 and 3 was calculated assuming that the number of train accidents in the system under study represents the same event space.

Table 3. Causes of accidents occurring on railway sidings in 2019

No.	Cat (A, B)	Description of the cause	Number	
1	00	causes other than those listed below or the overlapping of several causes at the same time, creating equivalent causes	3	0.026315789
2	03	dispatching, accepting or driving of a railway vehicle on an incorrectly planned, unsecured route or incorrect operation of traffic control devices	17	0.149122807
3	04	failure of a railway vehicle to stop before a “stop” signal or in a place where it should stop, or starting a railway vehicle without required authorisation	6	0.052631579
4	07	carrying out a manoeuvre that creates a risk for the safety of train traffic	1	0.00877193
5	08	inadvertent starting of a railway vehicle	1	0.00877193
6	09	damage or poor maintenance of the surface, bridge or overpass, including also improper execution of works, e.g. improper unloading of materials, surface, leaving materials and equipment (including road machines) on the track or within the clearance of the railway vehicle, or running the railway vehicle over elements of the structure	24	0.210526316
7	10	damage to or poor technical condition of powered railway vehicle, special-purpose vehicle (including running over an object which is a structural part of powered railway vehicle, special-purpose vehicle) and damage to or malfunction of the on-board part of ERTMS (European Rail Traffic Management System)	1	0.00877193
8	11	damage or poor technical condition of a car (including running over a structural part of the car)	6	0.052631579
9	12	failure or malfunction of signalling equipment	1	0.00877193
10	13	running over a railway vehicle or other obstacle (e.g. brake skid, luggage trolleys, postal cart, etc.)	26	0.228070175
11	15	premature termination of the route or release and shifting of the railway point under the railway vehicle	1	0.00877193
12	17	improper loading, unloading, irregularities in securing the cargo or other irregularities in cargo operations	10	0.087719298
13	21	collision of railway vehicle with road vehicle (other road construction equipment, agricultural machinery) on a level crossing not equipped with a crossing system (cat. D)	12	0.105263158
14	23	collision of railway vehicle with road vehicle (other road construction equipment, agricultural machinery) outside level crossings in stations and routes or on the communication and access track to the siding	3	0.026315789
15	34	collision of a railway vehicle with persons when crossing the tracks at level crossings or crossings at stations or on the routes	1	0.00877193
16	35	events with persons related to the movement of a railway vehicle (jumping, falling from a train, railway vehicle, strong approach or sudden braking of a railway vehicle)	1	0.00877193

Source: own study based on: [41], [52].

4.2. Mapping of accident categories to risk areas

Based on the causes of railway accidents in the railway transportation system in 2019, the publicly available statistics list the risks *(F)* assigned to the following areas:

- employees (F_p)
- rolling stock (F_t),
- surface, subgrade, tunnels and civil engineering structures (F_n),
- level crossings and level track crossings (F_k),
- unauthorised persons on railway premises (F_l),
- other (F_o).

Table 4. Mapping of accident categories to risk areas

Kind of risk (*F*)												
	Railway lines						Railway sidings					
Risk areas	F_p	F_t	F_n	F_k	F_l	F_o	F_p	F_t	F_n	F_k	F_l	F_o
Category	03, 04, 06, 15, 17,35	08, 10, 11, 13, 24	09	18, 19, 20, 21, 23, 31, 32, 33, 34	18	00, 41	03, 04, 07, 15, 17.35	08, 10,11, 13,	09	21, 23, 34	-	00, 12

Source: own study

A broader set of risks comprehensively addressing adverse events in the railway transport system is presented in the risk register contained in [41].

4.3. Analysis and evaluation of the cost of delays associated with the risk of adverse events

rail freight transport delays are also affected by passenger and work-related incidents. The Office for Railway Transport has provided the cost of the parameter of one minute's delay for a freight train, which amounts to EUR 44.74 [44]. Table 5 shows the minute ranges of delay together with the delay costs assigned to them (based on the arithmetic mean of the interval).

Taking into account the probability of occurrence of railway accidents presented in Table 2 and Table 3 and the costs of delays of freight trains, the level of risk for each accident category was assessed taking into account the costs of delays:

Table 5. Delay costs

Minute range	1-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99
Arithmetic mean of the range (EURO)	223.700	648.729	1096.128	1543.527	1990.926	2438.325	2885.725	3333.124	3780.523	4227.922

Source: own study based on [44]

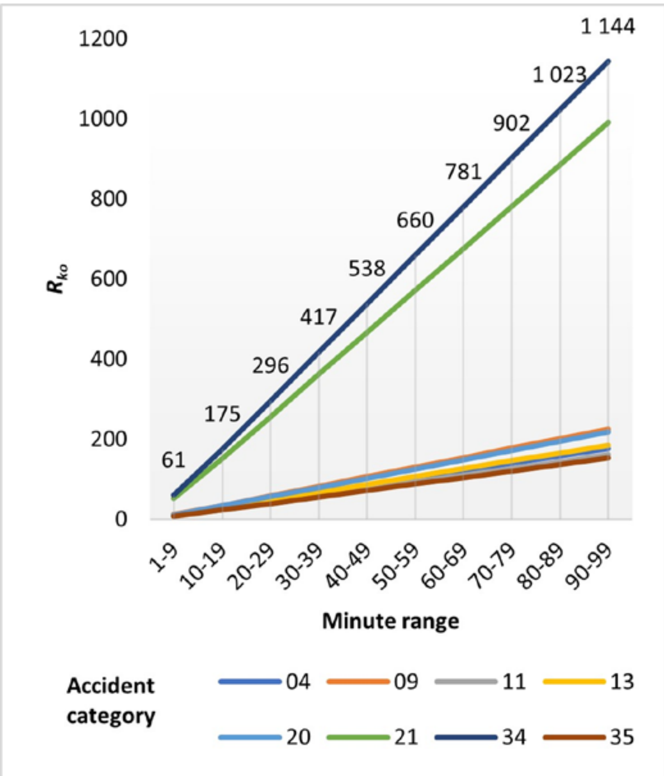

Fig. 5. Risk related to the cost of delays of freight trains on railway lines in Poland (P>0.03) in a given minute range
Source: own study

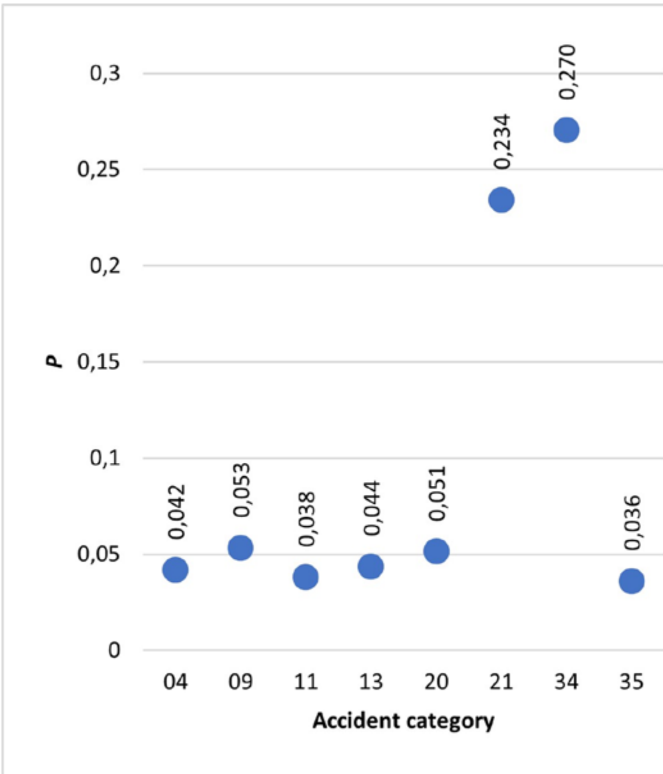

Fig. 6. Probability of occurrence of a given accident category on railway lines in Poland in 2019 (P> 0.03)
Source: own study

Table 6. Risk assessment of delay costs for the railway system in 2019 based on events occurring on railway lines

Accident category	1-9 min	10-19 min	20-29 min	30-39 min	40-49 min	50-59 min	60-69 min	70-79 min	80-89 min	90-99 min
00	4.260944	12.35674	20.87863	29.40052	37.92241	46.44429	54.96618	63.48807	72.00996	80.53185
03	5.539228	16.06376	27.14222	38.22067	49.29913	60.37758	71.45604	82.53449	93.61295	104.6914
04	9.374078	27.18483	45.93298	64.68114	83.42929	102.1774	120.9256	139.6738	158.4219	177.1701
06	0.426094	1.235674	2.087863	2.940052	3.792241	4.644429	5.496618	6.348807	7.200996	8.053185
08	1.278283	3.707022	6.263588	8.820155	11.37672	13.93329	16.48986	19.04642	21.60299	24.15956
09	11.93064	34.59887	58.46016	82.32145	106.1827	130.044	153.9053	177.7666	201.6279	225.4892
10	2.130472	6.178369	10.43931	14.70026	18.9612	23.22215	27.48309	31.74404	36.00498	40.26593
11	8.521889	24.71348	41.75726	58.80103	75.84481	92.88859	109.9324	126.9761	144.0199	161.0637
13	9.800172	28.4205	48.02084	67.62119	87.22153	106.8219	126.4222	146.0226	165.6229	185.2233
15	5.539228	16.06376	27.14222	38.22067	49.29913	60.37758	71.45604	82.53449	93.61295	104.6914
17	2.982661	8.649717	14.61504	20.58036	26.54568	32.51101	38.47633	44.44165	50.40697	56.3723
18	3.408756	9.885391	16.7029	23.52041	30.33792	37.15544	43.97295	50.79046	57.60797	64.42548
19	5.965322	17.29943	29.23008	41.16072	53.09137	65.02201	76.95266	88.8833	100.8139	112.7446
20	11.50455	33.3632	56.3723	79.3814	102.3905	125.3996	148.4087	171.4178	194.4269	217.436
21	52.40962	151.9879	256.8071	361.6264	466.4456	571.2648	676.0841	780.9033	885.7225	990.5418
23	2.982661	8.649717	14.61504	20.58036	26.54568	32.51101	38.47633	44.44165	50.40697	56.3723
24	0.426094	1.235674	2.087863	2.940052	3.792241	4.644429	5.496618	6.348807	7.200996	8.053185
30	3.83485	11.12107	18.79077	26.46047	34.13017	41.79987	49.46957	57.13927	64.80897	72.47867
31	5.113133	14.82809	25.05435	35.28062	45.50689	55.73315	65.95942	76.18569	86.41195	96.63822
32	2.130472	6.178369	10.43931	14.70026	18.9612	23.22215	27.48309	31.74404	36.00498	40.26593
33	4.260944	12.35674	20.87863	29.40052	37.92241	46.44429	54.96618	63.48807	72.00996	80.53185
34	60.50541	175.4657	296.4765	417.4873	538.4982	659.509	780.5198	901.5306	1022.541	1143.552
35	8.095795	23.4778	39.66939	55.86098	72.05257	88.24416	104.4357	120.6273	136.8189	153.0105
41	1.278283	3.707022	6.263588	8.820155	11.37672	13.93329	16.48986	19.04642	21.60299	24.15956

Source: own study

$$R_{ko}=\bar{x}_{<a,b>}\times P_{kat} \tag{2}$$

where:

R_{ko} - the level of risk associated with the cost of delays of a freight train,

$\bar{x}_{<a,b>}$ - average costs of delay for the minute range (a,b),

P_{kat} - the probability of the cause of the selected category, affecting train delay in 2019.

The presented approach allows to estimate the potential risk level for different delay ranges. In order to perform a detailed analysis of the cost matrix, it would be necessary to determine the probability density function for the time of delay as a result of an accident caused by a given cause. Table 6 provides an assessment of the risk associated with the cost of train delays in 2019 as a result of incidents occurring on railway lines. The colour scale in Table 6 reflects the level of risk, with green being acceptable and red indicating the need for intervention e.g. by the rail operator or the terminal operator or transhipment centre operator. Based on the expert assessment and the estimation of the expected value of delays for an event of a given category, it is possible to identify the main areas requiring improvement actions. The risk associated with delay costs and the probability of an accident of a given category are shown in Figures 5 and 6.

As can be seen from the data presented, the highest level of risk associated with the cost of delays on railway lines was identified in category 34, i.e. collision of a railway vehicle with persons when crossing the tracks at level crossings or crossings at stations or on the routes. In 2019, probability of occurrence on railway lines that exceed a factor of 0.03 occurred for categories:

- 04 – failure of a railway vehicle to stop before a "stop" signal or in a place where it should stop, or starting a railway vehicle without required authorisation,
- 09 – damage or poor maintenance of the surface, bridge or overpass, including also improper execution of works, e.g. improper unloading of materials, surface, leaving materials and equipment (including road machines) on the track or within the clearance of the railway vehicle, or running the railway vehicle over elements of the structure,
- 11 – damage or poor technical condition of a car (including running over a structural part of the car)
- 13 – collision of a railway vehicle with a railway vehicle or another obstacle (e.g. brake skid, luggage trolleys, postal cart, etc.)

Table 7. Risk assessment of delay costs in 2019 based on events occurring on railway sidings

Accident category	1-9 min	10-19 min	20-29 min	30-39 min	40-49 min	50-59 min	60-69 min	70-79 min	80-89 min	90-99 min
00	5.88683119	17.07181	28.84547	40.61914	52.3928	64.16646	75.94012	87.71378	99.48745	111.2611
03	33.3587101	96.74026	163.4577	230.1751	296.8925	363.6099	430.3274	497.0448	563.7622	630.4796
04	11.7736624	34.14362	57.69095	81.23827	104.7856	128.3329	151.8802	175.4276	198.9749	222.5222
07	1.96227706	5.690603	9.615158	13.53971	17.46427	21.38882	25.31337	29.23793	33.16248	37.08704
08	1.96227706	5.690603	9.615158	13.53971	17.46427	21.38882	25.31337	29.23793	33.16248	37.08704
09	47.0946495	136.5745	230.7638	324.9531	419.1424	513.3317	607.521	701.7103	795.8996	890.0889
10	1.96227706	5.690603	9.615158	13.53971	17.46427	21.38882	25.31337	29.23793	33.16248	37.08704
11	11.7736624	34.14362	57.69095	81.23827	104.7856	128.3329	151.8802	175.4276	198.9749	222.5222
12	1.96227706	5.690603	9.615158	13.53971	17.46427	21.38882	25.31337	29.23793	33.16248	37.08704
13	51.0192036	147.9557	249.9941	352.0325	454.0709	556.1093	658.1477	760.1861	862.2245	964.2629
15	1.96227706	5.690603	9.615158	13.53971	17.46427	21.38882	25.31337	29.23793	33.16248	37.08704
17	19.6227706	56.90603	96.15158	135.3971	174.6427	213.8882	253.1337	292.3793	331.6248	370.8704
21	23.5473247	68.28724	115.3819	162.4765	209.5712	256.6658	303.7605	350.8551	397.9498	445.0444
23	5.88683119	17.07181	28.84547	40.61914	52.3928	64.16646	75.94012	87.71378	99.48745	111.2611
34	1.96227706	5.690603	9.615158	13.53971	17.46427	21.38882	25.31337	29.23793	33.16248	37.08704
35	1.96227706	5.690603	9.615158	13.53971	17.46427	21.38882	25.31337	29.23793	33.16248	37.08704

Source: own study

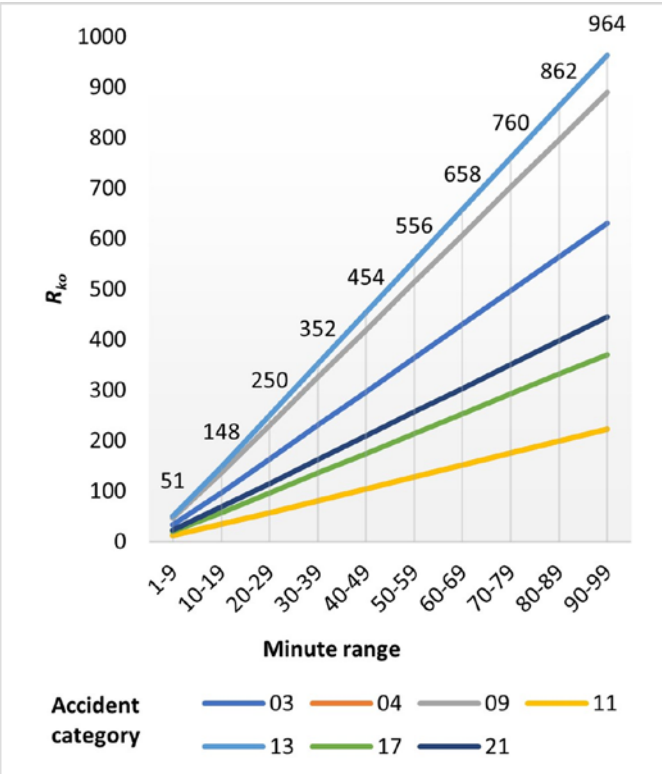

Fig. 7. Risk related to the cost of delays of freight trains on railway sidings in Poland (P>0.03) in a given minute range
Source: own study

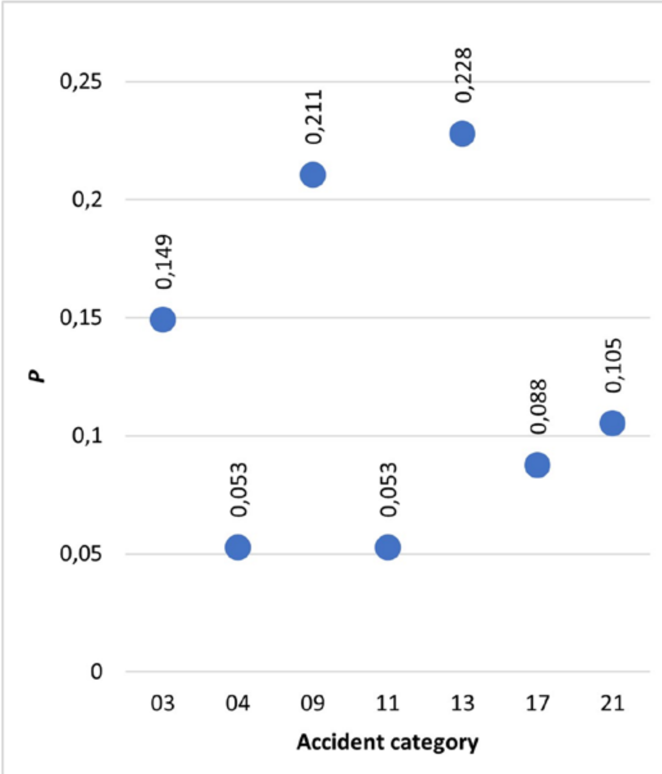

Fig. 8. Probability of accidents of a given accident category on railway sidings in 2019 (P> 0.03)
Source: own study.

- 20 – collision of railway vehicle with road vehicle (other road construction equipment, agricultural machinery) on a level crossing equipped with automatic crossing system with traffic lights and without grade-crossing gate (cat. C),
- 21 – collision of railway vehicle with road vehicle (other road construction equipment, agricultural machinery) on a level crossing not equipped with a crossing system (cat. D),
- 34 – collision of a railway vehicle with persons when crossing the tracks at level crossings or crossings at stations or on the routes,
- 35 – events with persons related to the movement of a railway vehicle (jumping, falling from a train, railway vehicle, strong approach or sudden braking of a railway vehicle).

Table 8. Summary of serious accidents, other accidents and incidents involving freight trains

No.	Year	Accident category	Date	Venue	Carrier	Restrictions on train traffic	Injurie Injuries and fatalities s and fatalities
1	2014	B10	31.08.2014	On route at km 12.629 of railway line No. 100 Kraków Prokocim – Kraków Płaszów	PKP CARGO S.A.	Delays of freight trains – 9, total number of minutes of delay – 1109	None
2	2016	B13	02.12.2016	On the route Myszków – Zawiercie, at track no. 2, at km. 263.830 of railway line no. 1 Warszawa Zachodnia – Katowice	PKP CARGO S.A., “EURONAFT Trzebinia” Sp. z o.o.	Delays of passenger trains – 201, total number of minutes of delay – 8082; delays of freight trains – 62, total number of minutes of delay – 15,304	None
3	2017	C52	16.05.2017	At Podstolice station, in station track no 2, at km 262.500 of railway line no. 3 Warszawa Zachodnia – Kunowice	PKP CARGO S.A.	Delays of passenger trains – 18, total number of minutes of delay – 1226; delays of freight trains – 18, total number of minutes of delay – 1,701	None
4	2017	A04	30.08.2017	At Smętowo station, at station track no. 2, at km 457.485 of railway line no. 131 Chorzów Batory – Tczew	STK S.A. Wrocław, PKP INTERCITY S.A.	Delayed passenger trains – 34, total number of minutes of delay –1193; delayed freight trains – 31, total number of minutes of delay – 4508	10 people seriously injured, 18 people injured
5	2017	B37	10.11.2017	On Nysa – Nowy Swietów route, in line track no. 2, at km 129.650 of railway line no. 137 Katowice – Legnica	“Cargo Przewozy Towarowe Transport Sp. z o. o., Sp. k.	Delayed freight trains – 1, total number of minutes of delay – 735	None
6	2017	B13	24.11.2017	On the Warlubie – Laskowice Pomorskie route, track no. 2, at km 424.208, railway line no. 131 Chorzów Batory – Tczew	POL MIEDŹ TRANS Sp. z o.o., LOTOS Kolej Sp. z o. o.	Delayed passenger trains – 8, total number of minutes of delay – 66; delayed freight trains – 3, total number of minutes of delay – 166	None
7	2018	B11	10.05.2018	At Wronki station, track no. 1, at km 50.474 of railway line no. 351 Poznań Główny - Szczecin Główny	CTL Logistics Sp. z o. o.	Delayed passenger trains – 253, total number of minutes of delay –8810; delayed freight trains – 24, total number of minutes of delay – 3540	None
8	2019	B11	17.03.2019	On Taczanów – Pleszew route, at track no. 1, km 107.985 of railway line no. 272 Kluczbork – Poznań Główny	Przedsiębiorstwo Obrotu Surowcami Wtórnymi DEPOL Sp. z o.o.	Delayed passenger trains – 308, total number of minutes of delay – 1797; delayed freight trains – 167, total number of minutes of delay – 16733	None
9	2019	B13	19.05.2019	At Rybnik Towarowy station, on track no. 308 of railway line no. 140 Katowice Ligota – Nędza	PKP CARGO S.A.	bd	None
10	2019	B11	08.08.2019	On Tarnów Opolski – Opole Groszowice route, at track no. 1, at km 87.973 of railway line no. 132 Bytom – Wrocław Główny	PKP CARGO S.A.	Delayed passenger trains – 419, total number of minutes of delay – 3469; delayed freight trains – 34, total number of minutes of delay – 1857	None

Similar analyses were conducted for adverse events occurring at railway sidings. Table 7 provides an assessment of the risk associated with the cost of train delays in 2019 as a result of incidents occurring on railway sidings. Figures 7 and 8 show the risk associated with delay costs and the probability of the accident category.

The highest level of risk associated with the cost of delays on railway sidings was identified in category 13, i.e., collision of a railway vehicle with a railway vehicle or other obstacle (e.g. brake skid, luggage trolleys, postal cart, etc.), which was identified in category 13. In 2019, the probability of occurrence on railway sidings that exceeds a factor of 0.03 occurred for the following categories:

- 03 – dispatching, accepting or driving of a railway vehicle on an incorrectly planned, unsecured route or incorrect operation of traffic control devices,
- 04 – failure of a railway vehicle to stop before a “stop” signal or in a place where it should stop, or starting a railway vehicle without required authorisation,
- 09 – damage or poor maintenance of the surface, bridge or overpass, including also improper execution of works, e.g. improper unloading of materials, surface, leaving materials and equipment (including road machines) on the track or within the clearance of the railway vehicle, or running the railway vehicle over elements of the structure,
- 11 – damage or poor technical condition of a car (including running over a structural part of the car)
- 13 – collision of a railway vehicle with a railway vehicle or another obstacle (e.g. brake skid, luggage trolleys, postal cart, etc.)
- 17 – improper loading, unloading, irregularities in securing the cargo or other irregularities in cargo operations
- 21 – collision of railway vehicle with road vehicle (other road construction equipment, agricultural machinery) on a level crossing not equipped with a crossing system (cat. D).

Reports covering freight, passenger and work traffic are only submitted to ERA for selected major accidents, other accidents and incidents. Detailed reports in this regard can be found on the website of the State Commission for the Investigation of Railway Accidents [30]. They provide knowledge about the most serious events in the railway transport system in Poland in freight transport.

The authors of this article analysed 31 reports of the State Commission for Investigation of Railway Accidents (from the report No. PKBWK/01/2015 to the report No. PKBWK/10/2020). All events during the study period involving freight trains are shown in Table 8.

Rail freight delays expressed in the number of freight trains involved and the total number of minutes of delay associated with ERA-reported accidents are shown in Figure 9.

In 2019, the total number of delays for freight trains taking into account adverse events involving passenger and freight trains was

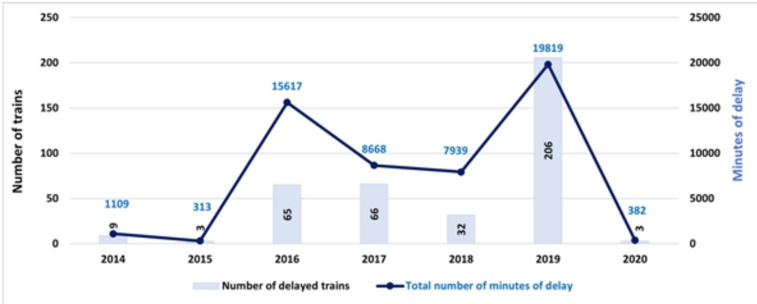

Fig. 9. Delays to freight trains as a consequence of adverse events in the railway system
Source: own study based on reports of the State Commission for Investigation of Railway Accidents (report no. PKBWK/01/2015 – report no. PKBWK/10/2020) [30]

19,819 minutes (the analysis does not take into account delays of cancelled and diverted freight trains). Data from the Office for Railway Transport show that 333,795 domestic freight trains were launched in 2019 [42]. On average in 2019, there will be approximately 16 minutes of delay per freight train running as a result of adverse events reported to ERA.

5. Conclusions

The risk analysis for the operation of rail freight transport operations has shown that undesirable situations on the railway network occur as a result of various events. For the smooth running of the train traffic, work on risk assessment should be carried out continuously.

As the market of rail freight transport includes among others: managers of railway lines, railway transport operators, operators of railway service infrastructure facilities, for proper estimation of the risk of occurrence of adverse events it is necessary to have a reliable database divided into areas and categories of adverse events.

Delays in train traffic are the consequence of adverse events. It is therefore substantiated to carry out extensive risk assessment analyses on rail freight transport, including assessment of the risks associated with train delays. In 2019, the total number of delays for freight trains taking into account adverse events involving passenger trains and freight trains was 19,819 minutes, while the average delay per freight train running was about 16 minutes.

Based on the collected data on the occurrence of adverse events on railway lines and sidings of PKP, the authors proposed some approach to estimate the potential level of risk for different ranges of delays. According to the authors of the article, for a detailed analysis of the cost matrix, it will be necessary, in future research, to determine the probability density function for the delay time as a result of the accident caused by a given cause.

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