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A METHOD FOR ASSESSING THE CRITICALITY OF FAILURES OF RAILWAY VEHICLE COMPONENTS USING THE FMECA METHOD

Summary. Assessing the risk of hazards in the operation of rail vehicles is an important part of verifying their reliability and safety. This paper presents an example of the application of the Failure Mode and Effects Analysis included in dedicated railway standards, extended to the Failure Mode, Effects and Criticality Analysis with additional criticality factors. This extension allows for the assessment of the risk of failures of assemblies, subassemblies, and components of rail vehicles. Compared to the Failure Mode and Effects Analysis method, the Failure Mode, Effects and Criticality Analysis method introduces the indicators, such as: failure mode criticality, criticality of component, criticality of subassembly, and the criticality of assembly. It enables the more precise identification of critical components, subassemblies, and assemblies of the rail vehicles. This precision is crucial for planning preventive actions and maintenance strategies. The new method can be used to validate the results of classical Failure Mode and Effects Analysis using the indicator of failure mode criticality, which relies on the actual failure frequency function obtained from the reliability model of individual failure modes. This would increase the accuracy of the analysis and allow for a better representation of the system's actual behavior. The extended Failure Mode, Effects and Criticality Analysis method enables a more comprehensive criticality analysis, considering not only the value of criticality indicators but also their quantities in the reliability hierarchical structure of the analyzed wagons.

1. INTRODUCTION

Failure Mode and Effects Analysis (FMEA) is used in the risk assessment of railway systems. Its most notable advantage is that it can be implemented even at the design stage of a system. When failures are prioritized, FMEA becomes Failure Mode, Effects and Criticality Analysis (FMECA), which can take into account different criticality factors. In addition, the application of the FMEA method is not limited to reliability applications; it also involves safety and maintenance. The results of such an analysis can be a decision criterion for making changes in the maintenance systems of rail vehicles [5, 18]. An important issue in the safety assurance process of railway systems is the failure analysis done at the design stage. The effectiveness of this analysis affects the appropriate preventive actions during operation. One of the methods allowing for the early safety assessment is the FMEA method, which is demonstrated in the paper [19]. Because the FMEA method has numerous limitations, scientific works contain numerous proposals aimed at improving the effectiveness of this method. This also applies to the rail industry, where FMEA is used for risk management. An example is paper [7], which presents

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the application of cumulative prospect theory and elements of fuzzy logic to prioritize the risk of rail vehicles.

The use of the FMEA method involves estimating a threshold risk value which allows the classification of risk as acceptable or unacceptable. This classification is usually subjective, which is a significant disadvantage of the FMEA method. The work of Catelani et al. introduces the idea of the two different subsets that remove this subjectivity issue [2].

The FMEA method can be combined with other methods to detect potential failures systematically. Chi et al. indicated this method for the systematic detection of potential automotive component failures when developing a classification scheme of the defective component and failure type. In turn, Zhu et al. used the FMEA and fuzzy-set-based approach to analyze the maintenance strategy of urban rail transit vehicles. The combination of fuzzy logic and the FMEA approach has also been used to provide risk assessments of railway infrastructure projects (Macura et al.) [3, 13, 21].

In the studies of LaFleur et al., the FMEA method was used to identify failures in liquefied natural gas/diesel hybrid locomotives in combination with the Hazard and Operability Study (HAZOP) method. To properly identify the failure impact and prioritize failure modes, Rahimdel and Ghodrati used the analytical hierarchy process (AHP) together with the FMEA [12, 16].

The literature presents many models for predicting hazards and accidents in rail transport and level crossings. Many of them contain common factors that affect the accuracy of the analysis. They include the quality and accuracy of the input data. However, the research carried out as part of work [1] shows the implemented safety procedures and the risk assessment measures used to assess the risk of hazards differ depending on the area of their application.

Assessments of the reliability and safety of railway systems based on the failure rate show that maintenance management and spare parts configuration also play an important role. Railway vehicle control systems affect traffic flexibility. Some of the failure rate-based models can achieve an accuracy rate of over 99% [9].

Achieving target reliability requires consideration of multiple correlation failures as well as uncertainty which is called reliability allocation. In addition, reliability issues are closely related to safety assurance. Regarding rail vehicles, the lack of the required level of safety may lead to derailments. Reliability measures can often represented by the operational parameters of the analyzed object. Numerical simulations can be used and compared with the results obtained from experimental tests to determine the operational reliability of rail vehicles against derailment [10, 11].

The reliability of the analyzed object may affect the deterioration of the operating parameters of other objects. An example is the study on the impact of the reliability of a railway wheelset on track deterioration [20]. A similar issue concerns the disruption and efficiency of rail freight operations. Delays can be caused by many factors. The authors of the work [17] analyzed the causes of accidents on Polish railway lines in 2019 and determined the probability of their occurrence, as well as the probability of delays due to various emergency situations. In the work [15], a comparative analysis of the Markov models and simplistic Fault Tree analysis was performed to verify the safety integrity level of the power supply systems in the railway industry.

The present work describes an approach for assessing the failure modes and effects of failures of rail vehicles using the extended FMECA method based on the additional criticality factors, such as Failure Mode Criticality (FMC), criticality of component (CC), criticality of subassembly (CS), and criticality of assembly (CA). It is worth mentioning that the use of the FMC indicator is based on the real failure rate function obtained from the reliability model of individual failure types. Therefore, the method presented in this paper can be used as the validation tool of the previously performed FMECA analysis based on the RPN indicator. The analyzed vehicle is a normal construction high sides open wagon – type E, operated on Polish railway lines. Real failure data was used to develop reliability models and determine critical assemblies, subassemblies, and components within the breakdown structure of the wagon. The obtained results were compared with the risk priority number index gained from the analysis during the wagon design phase.

2. OBJECT OF THE ANALYSIS

2.1. Technical description of the analyzed wagon

The analyzed vehicle is a normal construction high sides open wagon – type E, operated on Polish railway lines. Real failure data was used to develop reliability models and determine critical assemblies, subassemblies, and components within the breakdown structure of the wagon were determined. The obtained results were compared with the risk priority number index, obtained from the analysis of the results from a high sides open wagon during the wagon design phase.

The subject of the research is the population of the four most numerous structural types of normal construction high sides open wagons with a quotient of several thousand pieces. High sides open wagon railway wagons have a very wide range of applications. They can be used to transport various materials, such as any loose or crushed materials insensitive to weather conditions, scrap, logs, wood, metallurgical products, precast concrete, and piece loads. In Poland, high sides open wagons are called coal wagons. This may affect the incorrect interpretation of the purpose of these vehicles as dedicated only to the transport of coal. The Technical Specifications for Interoperability (TSI) for Operation and Traffic Management (OPE) [4], include also the name given to wagons with the letter symbol of category "E", according to the International Union of Railways (UIC) classification. The view and basic technical data of the selected type of category "E" wagon are presented in Fig. 1a.

a)

b)

Purpose of use	Transport of bulk materials (coal, ore, aggregate)
Weight	20/22 t
Maximum speed	120 km/h
Maximum axle load	196 kN
Track gauge	1.435 mm
Loading length	12.792/12.800 mm
Loading width	2.760/2.762/2.788 mm
Loading height	2.000/2.025/2.040 mm
Loading surface	35.3/36.0 m^2
Usable volume	71.5/72.0 m^3

Fig. 1. The analyzed object – a normal construction high sides open wagon

Table 1 contains a breakdown structure of the analyzed wagon, generated by the authors. This structure includes a three-level decomposition of the wagon and the assigned types of failures to each of the listed components. The applied decomposition of the wagon made it possible to easily locate the failure and to perform the criticality analysis of components, subassemblies, and assemblies. The listed types of failures were registered between successive repairs occurring every six years of operation.

Table 1

Breakdown structure of the analyzed wagon

Complete vehicle	**Assembly Level I**	**Subassembly Level II**	**Component Level III**	**Failure mode**
High sides open wagon – type E	1. Running gear	1.1 Wheelset	1.1.1 Wheel	1.1.1.1 Tire loosened or offset to the wheel
				1.1.1.2 Tire broken or with peripheral cracks
				1.1.1.3 Illegible control characters
				1.1.1.4 Tire-clip loose, cracked, broken or missing
				1.1.1.5 Exceeded tire thickness limit
				1.1.1.6 Wheel center broken, cracked, or with a defect removed by welding

Complete vehicle	**Assembly Level I**	**Subassembly Level II**	**Component Level III**	**Failure mode**
				1.1.1.7 Wheel thermally overloaded by the brake
				1.1.1.8 Minimum thickness of wheel rim or control groove invisible
				1.1.1.9 Wheel with the ovalization symptoms
				1.1.1.10 Wheel center broken, cracked, or with a defect removed by welding
				1.1.1.11 Flat spots
				1.1.1.12 Material growths
				1.1.1.13 Holes, tears, spalling, or dents on the running surface
				1.1.1.14 Cavities
				1.1.1.15 Cracks and notches
				1.1.1.16 Front surface painted or dirty
				1.1.1.17 Exceeded limits of external profile features including rolling or loss on the edge surface
				1.1.1.18 A wheel that is offset from the axle hub or has other signs of derailment
				1.1.1.19 Wheelset damaged outside the national network – serious but unspecified damage
			1.1.2 Axle of wheelset	1.1.2.1 Axle cracked or bent, axle defect repaired by welding
				1.1.2.2 Axle with sharp edges or abrasions on the surface
		1.2 Bearing subsystem	1.2.1 Bearing body	1.2.1.1 Bearing housing leaking, cracked, or deformed
			1.2.2 Roller bearing of axle	1.2.2.1 Overheated bearing - damaged rings, cage, or rolling components
		1.3 Wheelset guide	1.3.1 A guide device	1.3.1.1 Guides (forks) bent, broken, or loosely attached
			1.3.2 Guides on the bearing's body	1.3.2.1 Guides on the bearing's body do not ensure the safe driving of the wheelset
			1.3.3 Sliders	1.3.3.1 Fork slides - cracked welds, fallen or omitted
		1.4 Suspension	1.4.1 Helical springs	1.4.1.1 Outer spring broken
				1.4.1.2 Inner spring moved or broken
				1.4.1.3 Friction parts of friction absorber lubricate
				1.4.1.4 Pins and damping links deformed, broken, or missing
				1.4.1.5 Bearing housing vertical movement limiter deformed, screw loosened or omitted
		1.5 Frame of the boogie	1.5.1 Structural components and joints of railway boogie	1.5.1.1 Structural part broken or visibly deformed
				1.5.1.2 Screw joints loosened or cracked
			1.5.2 Railway boogie – under-frame connection	1.5.2.1 Screws of boogie pivot cracked or broken
				1.5.2.2 Boogie pivot and turning seat including lubrication system damaged
				1.5.2.3 Side friction blocks of the body support – springs cracked or not present

2.2. Life data source of the wagons

Maintaining the documentation related to the maintenance process of railway vehicles lies with the relevant responsible entity (called ECM – entity in charge of maintenance). According to the Article 8 of the Regulation of the Polish Minister of Infrastructure and Construction of 28 July 2017, the term of ECM relates mainly to railway carrier, infrastructure manager, or administrator. In paragraph 9 of the regulation, the specification of activities related to the maintenance of railway vehicles is mentioned. Paragraph 15, on the other hand, specifies that each entity that participates in the process of maintaining a railway vehicle should have records of information related to the implementation of the maintenance process of railway vehicles. In particular, such records were:

- maintenance records,
- failure records,
- data on the operation and maintenance of railway vehicles and their components, necessary for planning their maintenance, according to the principles set out in the maintenance plan.

The method used for operational documentation usually depends on the internal regulations of the specific entity responsible for maintenance and the type of railway vehicle. Statistical analysis of operational data is one of the tools used to assess the reliability of rail means of transport. Data for tests carried out to assess the reliability and safety of railway vehicle transport are obtained from operational information collected continuously during the operational process. Properly recorded and processed, this data can form the basis for statistical assessment of relevant states and events. The methodology of data collection depends on the method used to observe the operation and maintenance process. In the analyzed case, data from the observation of the operation and maintenance process were collected on electronic media in a specially adapted IT system. Operational tests were carried out for six years, which made it possible to observe the course of operation of:

- date of failure occurrence,
- date of commencement of corrective maintenance activities,
- date of completion of corrective maintenance activities,
- failed assembly, subassembly, and component in accordance with the adopted three-level system decomposition while taking into account the assumptions of the General Contract of Use for Wagons (GCU),
- service time characteristics, the materials and spare parts used, and the utilized repair technologies.

The analytical part of this paper was carried out based on the assumption that the failure of the wagon occurs when at least one of the measurable or unmeasurable features of a high sides open wagon no longer meets the requirements for proper operation included in technical documentation or the internal instructions of the wagon. At the beginning of the observation period, the moment of completion of renewal was assumed and carried out in accordance with the maintenance cycle as part of preventive maintenance restoring the state of the wagon corresponding to the new one. The basic assumption was that the signs of such renewal are fulfilled by periodic repair. The research was conducted according to the plan [n, R, t], in which n wagons were tested, failed wagons were subject to maintenance activities carried out as part of corrective maintenance, and the test ended after time t. During the experiment, only some vehicles were damaged, the observation time was strictly fixed, and the number of failed rail wagons was a random variable. Reliability analysis of the wagons taking into the above-mentioned scenario requires the application of the right censored data.

3. METHODS AND ASSUMPTIONS

3.1. Maximum Likelihood Estimation

Assume that $(x_1, x_2, \dots, x_n)$ is a set of n independent observations with a probability density function $f(x_i;\ \theta_1, \theta_2, \dots, \theta_k)$, where $(\theta_1, \theta_2, \dots, \theta_k)$ is a set of unknown distribution parameters. The right censored data also includes the items that did not fail during the observation period (suspensions). The likelihood function is expressed as follows [6]:

$$L(\theta_1, \theta_2, \ldots . \theta_k | T_1, T_2, \ldots . T_R; S_1, S_2, \ldots . S_M) = \\ = \prod_{i=1}^{R} f(T_i; \theta_1, \theta_2, \ldots, \theta_k) \cdot \prod_{j=1}^{M} [1 - F(S_j; \theta_1, \ldots, \theta_k)] \quad (1)$$

where:

$T_1, T_2, \ldots, T_R$ are the values at which the failures were recorded,

$S_1, S_2, \ldots, S_M$ are the values at which the suspensions were recorded.

If we assume that the probability density function of a three-parameter Weibull distribution is given by

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \cdot e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \quad (2)$$

where:

β is the shape parameter;

η is the scale parameter;

γ is location parameter,

then the logarithmic likelihood function for a three-parameter Weibull distribution can be expressed as

$$\ln(L) = \Lambda = \sum_{i=1}^{F_e} N_i \ln\left[\frac{\beta}{\eta}\left(\frac{T_i-\gamma}{\eta}\right)^{\beta-1} \cdot e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}\right] - \sum_{i=1}^{S} N_i' \left(\frac{T_i'-\gamma}{\eta}\right)^{\beta} \quad (3)$$

where:

F_e is the number of failed items,

N_i is the time to failure value in the i^{th} time-to-failure data group,

T_i is the time of the i^{th} group of time-to-failure data,

S is the number of suspended items,

N_i' is the number of suspensions in the i^{th} suspension data group,

T_i' is the time of the i^{th} suspension data group.

Unknown parameters of the Weibull distribution (β, η, γ) can be obtained by maximizing the Λ function. This is the most common approach since the logarithmic function is monotonically increasing and its maximization is more appropriate than the maximization of the likelihood function. Maximization may be done using the following equation:

$$\frac{\partial \Lambda}{\partial \theta_j} = 0; \mathrm{j} = 1,2, \ldots, \mathrm{k} \quad (4)$$

In the case of the three-parameter Weibull distribution, we obtain:

$$\frac{\partial \Lambda}{\partial \beta} = \frac{1}{\beta}\sum_{i=1}^{F_e} N_i + \sum_{i=1}^{F_e} N_i \ln\left(\frac{T_i-\gamma}{\eta}\right) - \sum_{i=1}^{F_e} N_i \left(\frac{T_i-\gamma}{\eta}\right)^{\beta} - \ln\left(\frac{T_i-\gamma}{\eta}\right) - \sum_{i=1}^{S} N_i' \left(\frac{T_i'-\gamma}{\eta}\right)^{\beta} \ln\left(\frac{T_i'-\gamma}{\eta}\right) = 0$$

$$\frac{\partial \Lambda}{\partial \beta} = \frac{-\beta}{\eta}\sum_{i=1}^{F_e} N_i + \frac{\beta}{\eta}\sum_{i=1}^{F_e} N_i \left(\frac{T_i-\gamma}{\eta}\right)^{\beta} + \sum_{i=1}^{S} N_i' \left(\frac{T_i'-\gamma}{\eta}\right)^{\beta} \left(\frac{\beta}{\eta}\right) = 0$$

$$\frac{\partial \Lambda}{\partial \gamma} = (1-\beta)\sum_{i=1}^{F_e} \left(\frac{N_i}{T_i-\gamma}\right) + \sum_{i=1}^{F_e} N_i \left(\frac{T_i-\gamma}{\eta}\right)^{\beta} \left(\frac{\beta}{T_i-\gamma}\right) + \sum_{i=1}^{S} N_i' \left(\frac{T_i'-\gamma}{\eta}\right)^{\beta} \left(\frac{\beta}{T_i'-\gamma}\right) = 0$$

A graphical representation of the MLE method is presented in Fig. 2.

3.2. Goodness of fit analysis based on the Chi-square test

A Chi-square test was applied to confirm that the three-parameter Weibull distribution is a relevant model to cover the failure behavior of the selected railway wagons' components. The results of the Chi-square test match accuracy analysis is the probability that the critical value $\chi^2_{critical}$ is smaller than the calculated χ^2 value. The assumption of the Chi-square test is based on the idea that the smaller the χ^2 value, the greater the fit of the assumed probability distribution to the empirical data. For the analyzed railway wagon components, the results of the Chi-square test showed a high accuracy of the fit, as shown in Table 2.

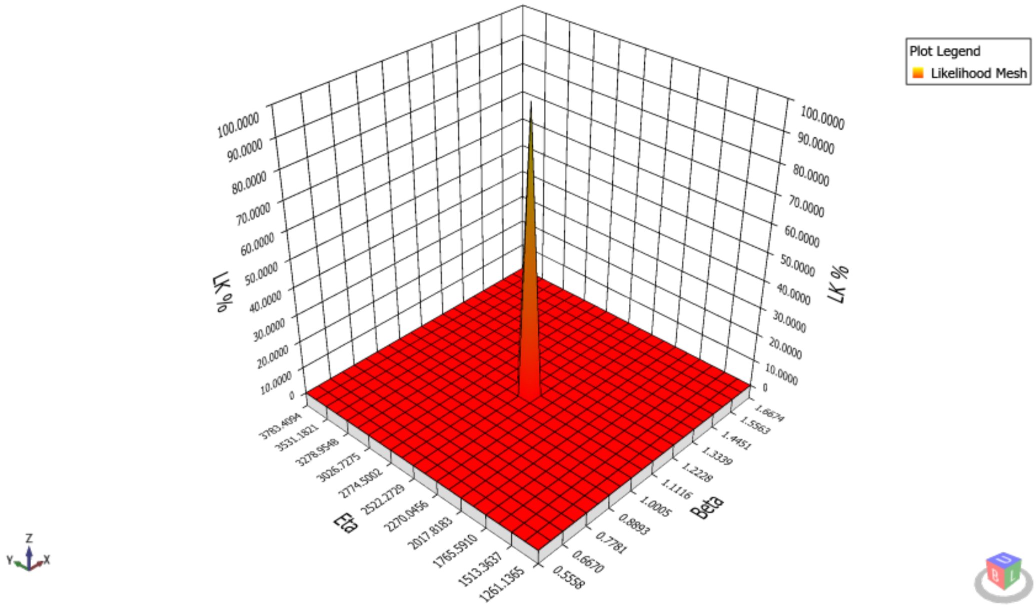

Fig. 2. Exemplary MLE plot obtained for the reliability model of railway wheel

Table 2

Results of Chi-squared goodness-of-fit test

Component of the wagon	Chi-squared goodness of fit $\chi^2_{critical} < \chi^2$	Weibull distribution		
		β	η	γ
Wheel	0.000	1.112	2.522E+03 h	6.940 h
Axle	0.008	0.559	1.274E+07 h	25.750 h
Axle bearing	0.000	1.412	5.367E+04 h	-30.860 h
Structural components and joints of railway boogie	0.000	0.941	6.489E+04 h	41.595 h
Railway boogie – frame connection	0.000	1.364	3.239E+03 h	11.963 h
Lever set	0.000	1.196	1.772E+03 h	7.930 h
Structural components of the frame	0.000	1.834	2.519E+03 h	12.175 h

The graphical results of the goodness of fit analysis for the analyzed components of the railway wagons are presented in Fig. 3.

3.3. Criticality indicators

Extending the qualitative FMECA approach to the quantitative approach requires the introduction of the criticality factors for the assemblies, subassemblies, components, and the identified failure mode.

The following formula may be used to calculate the criticality of the assembly p consisting of s subassemblies:

$$\mathrm{CA}_p = \textstyle\sum_{c=1}^{s} \mathrm{CS}_s, \tag{5}$$

where:

CS_s is the criticality of the subassembly s, defined as:

$$\mathrm{CS}_s = \textstyle\sum_{i=1}^{c} \mathrm{CC}_\mathrm{i} \tag{6}$$

where:

CC_i is the criticality of the component i, defined as:

$$\mathrm{CC_i} \sum_{j=1}^{m} \mathrm{FMC}_{ij} \tag{7}$$

where: FMC_{ij} is the criticality failure mode j for the component i, as follows:

$$\mathrm{FMC}_{ij} = \mathrm{CU}_{i(t)} \cdot \mathrm{RU}_{ij} \cdot \mathrm{PL}_{ij} \tag{8}$$

where:

$\mathrm{CU}_{i(t)}$ is the unreliability of the component at the time t.

RU_{ij} is the ratio of the unreliability of failure mode j.

PL_{ij} is the probability class of the failure mode j.

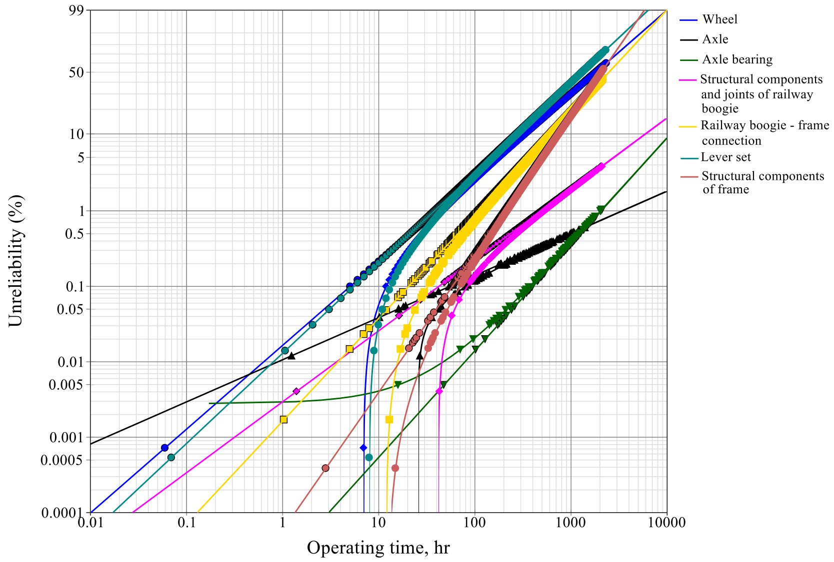

Fig. 3. Probability plots for the analyzed components of the railway wagon

In the case of the applied three-parameter Weibull distribution for the components of a railway wagon, $\mathrm{CU}_{i(t)}$ can be obtained as follows:

$$\mathrm{CU}_{i(t)} = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \tag{9}$$

The probability of failure for a given component consists of m different failure modes with the appropriate weights. Therefore, the sum of these weights is always equal to 1:

$$\sum_{i=1}^{m} \mathrm{RU_{i(t)}} = 1 \tag{10}$$

A fundamental issue for the criticality analysis is to assign the relevant failure probability class. PL_{ij} for each of the failure mode j as mentioned in the MIL-STD 1629A. The development of these classes depends on the analysts' judgment. Based on the experience of the authors and the specificity of the object used, the classes are proposed in Table 3 [14]:

Table 3

Failure probability class

Failure effect	**PL (probability of loss)**
Actual loss	1.00
Probable loss	0.10 ÷1.00
Possible loss	0 ÷0.10
No effect	0

3.4. FMEA assumptions

The purpose of the FMEA analysis is to identify and assess potential types of failures that have the greatest impact on operational reliability and safety and then mitigate them by taking recommended preventive actions. The assessment of the risk of failure occurrence in the classic FMECA method is based on the use of the risk priority number (RPN) indicator. For any type of failure, the following relationship can be written:

$$\mathrm{RPN}_i = S_i O_i D_i \tag{11}$$

Severity (S_i) indicates the degree of impact of a given type of failure on reliability, safety, and costs associated with the occurrence of that failure. This factor refers to the impact of damage on the object of analysis, people in the immediate vicinity, and the environment associated (Table 4).

Table 4

Severity rating scale

Severity, S		Rank
The effects of failure are not relevant to the level of safety. No Cost.		1
The effects of failure may be minor and lead to only a slight reduction in the level of safety (e.g., disruption of traffic) or/and costs:	Up to 10,000 EUR	2
	Up to 50,000 EUR	3
The effects of failure can be quite significant and lead to a reduction in the level of safety (e.g., incident, injury) and/or costs:	Up to 100,000 EUR	4
	Up to 250,000 EUR	5
	Up to 500,000 EUR	6
The consequences of failure can be serious and lead to a significant reduction in safety (e.g., train accident, serious injuries) and/or costs:	Up to 750,000 EUR	7
	Up to 1,000,000 EUR	8
The consequences of failure can be very serious and lead to a drastic reduction in safety (e.g., serious train accidents, fatalities) and/or costs:	Up to 2,000,000 EUR	9
	More than 2,000,000 EUR	10

the occurrence (O_i) value indicates the frequency with which a given type of failure occurs. Frequency values may be based on actual data on similar components from previous operations, or they may be based on the guidelines of MIL-STD-1629A or IEC 60812 standards (Table 5).

Table 5

Occurrence rating scale

Occurrence, O	Occurrence [failure/ vehicle-kilometer]		Rank
The probability of failure is negligible (practically non-existent).	4.00E-07	2,500,000	1
The likelihood of failure is low. The causes of the hazard are very rare.	5.71E-07	1,750,000	2
	8.00E-07	1,250,000	3
The probability of failure is medium. The causes of the hazard occur sporadically, from time to time.	1.18E-06	850,000	4
	1.67E-06	600,000	5
	2.86E-06	350,000	6
The probability of failure is high. The causes of the hazard are rare.	8.00E-06	125,000	7
	1.33E-05	75,000	8
The probability of failure is very high. It is almost certain that a given hazard will occur.	2.00E-05	50,000	9
	4.00E-05	25,000	10

The detection rate (D_i) is the probability that a given type of failure will be detected before the failure occurrence. Location of defects can be made during various inspections, using various methods, from simple visual detection to the need to use specialized control equipment. Detection may also require partial or complete disassembly of the component to which the given type of failure applies (Table 6).

The classification of the presented S_i, O_i, D_i factors and their adopted scales (presented in Tables 4-6) was done based on the MIL-STD-1629A or IEC 60812 standards guidelines [8, 13].

Table 6

Detection rating scale

Detection, D	Rank
The probability of being detected is very high. Disclosure of the cause of the failure is certain.	1
	2
The probability of being detected is high. The control measures in place make it possible to reveal the cause of the failure. The symptoms of the occurrence of the cause are noticeable.	3
	4
The average probability of detecting failure. The control measures in place may reveal the cause of the failure. Symptoms that indicate a possible hazard can be identified and determined.	5
	6
Low probability of failure detection. It is very likely that the control measures in place will not reveal the cause of the failure. It is very difficult to determine the cause of the failure.	7
	8
Negligible probability of failure detection. It is virtually impossible to determine the cause of the failure.	9
	10

4. RESULTS AND ANALYSIS

Table 7 shows a part of the FMECA sheet for the considered type of wagon. It contains information about the types of failure, components, subassemblies, and assemblies collected during the operation period of six years.

Table 7

Part of the FMECA sheet

Component	Failure code	%	O	D	S	RPN	Failure rate [1/h]	CU	RU	PL	FMC	CC	CS	CA
1.1.1	1.1.1.1	0.5%	1	2	10	20	5.41E-07	0.3248	0.1010	0.80	0.0263	0.1346	0.1399	0.9367
	1.1.1.2	0.0%	1	3	10	30	3.68E-09		0.0007	1.00	0.0002			
	1.1.1.3	2.1%	5	2	8	80	2.45E-06		0.4570	0.10	0.0148			
	1.1.1.4	0.0%	1	3	10	30	1.80E-08		0.0034	1.00	0.0011			
	1.1.1.5	0.0%	1	3	10	30	1.64E-09		0.0003	0.80	0.0001			
	1.1.1.6	0.0%	1	4	10	40	2.46E-09		0.0005	1.00	0.0001			
	1.1.1.7	0.0%	1	3	8	24	5.07E-08		0.0095	0.40	0.0012			
	1.1.1.8	0.0%	1	2	8	16	1.19E-08		0.0022	0.70	0.0005			
	1.1.1.9	0.0%	1	2	8	16	9.82E-09		0.0018	0.80	0.0005			
	1.1.1.10	0.0%	1	4	10	40	2.46E-09		0.0005	1.00	0.0001			
	1.1.1.11	0.4%	1	4	7	28	4.49E-07		0.0839	0.60	0.0164			
	1.1.1.12	0.5%	2	4	7	56	5.91E-07		0.1103	0.60	0.0215			
	1.1.1.13	0.1%	1	4	7	28	1.33E-07		0.0248	0.60	0.0048			
	1.1.1.14	0.0%	1	3	7	21	1.64E-09		0.0003	0.60	0.0001			
	1.1.1.15	0.0%	1	4	8	32	1.23E-09		0.0002	0.90	0.0001			
	1.1.1.16	0.0%	1	4	3	12	2.05E-09		0.0004	0.00	0.0000			
	1.1.1.17	0.9%	3	4	8	96	1.06E-06		0.1971	0.70	0.0448			
	1.1.1.18	0.0%	1	8	10	80	2.05E-08		0.0038	1.00	0.0012			
	1.1.1.19	0.0%	1	8	10	80	1.23E-08		0.0023	1.00	0.0007			
1.1.2	1.1.2.1	0.0%	1	4	10	40	1.15E-08	0.0052	0.2523	1.00	0.0013	0.0052		
	1.1.2.2	0.0%	1	4	10	40	3.40E-08		0.7477	1.00	0.0039			
1.2.1	1.2.1.1	0.3%	1	4	9	36	3.07E-07	0.0351	0.8313	1.00	0.0292	0.0292	0.0299	
1.2.2	1.2.2.1	0.1%	1	4	9	36	6.22E-08	0.0043	0.1687	1.00	0.0007	0.0007		
1.3.1	1.3.1.1	0.0%	1	2	7	14	1.27E-08	0.0017	1.0000	1.00	0.0017	0.0017	0.2866	
1.3.2	1.3.2.1	0.0%	1	2	7	14	2.50E-08	0.0027	1.0000	1.00	0.0027	0.0027		
1.3.3	1.3.3.1	5.4%	6	4	6	144	6.33E-06	0.2822	1.0000	1.00	0.2822	0.2822		
1.4.1	1.4.1.1	0.1%	1	4	8	32	9.62E-08	0.2612	0.0204	1.00	0.0053	0.2588	0.2588	
	1.4.1.2	0.2%	1	4	8	32	2.44E-07		0.0517	1.00	0.0135			
	1.4.1.3	0.1%	1	2	6	12	1.08E-07		0.0229	0.60	0.0036			
	1.4.1.4	2.8%	6	2	6	72	3.25E-06		0.6876	1.00	0.1796			
	1.4.1.5	0.9%	3	2	7	42	1.03E-06		0.2175	1.00	0.0568			
1.5.1	1.5.1.1	0.0%	1	6	9	54	4.50E-09	0.0205	0.0311	1.00	0.0006	0.0205	0.2215	
	1.5.1.2	0.1%	1	6	8	48	1.40E-07		0.9689	1.00	0.0198			
1.5.2	1.5.2.1	0.4%	1	5	9	45	4.34E-07	0.2011	0.1028	1.00	0.0207	0.2011		
	1.5.2.2	1.3%	4	5	9	180	1.47E-06		0.3492	1.00	0.0702			
	1.5.2.3	2.0%	5	4	7	140	2.31E-06		0.5480	1.00	0.1102			

Figs. 4 and 5 contain the RPN and FMC values for the particular failure modes. The calculations allowing to obtain the RPN and FMC were performed based on Equations (11) and (8), respectively.

Fig. 4. Histogram for RPN values for the failure modes.

Fig. 5. Histogram for FMC values for the failure modes

Both the RPN indicator and the FMC indicator are used to identify critical failure modes due to the operational reliability of the wagons. Nevertheless, a comparison of the RPN and FMC charts reveals some differences between the values of the risk indicator and the values of the criticality indicator for the given types of failure modes. The five failure modes reaching the highest values of the RPN indicator are:

- 1.5.2.2 Boogie pivot and turning seat (including lubrication system): RPN = 180,
- 1.3.3.1 Fork slides - cracked welds, fallen, or omitted: RPN = 144,
- 1.5.2.3 Side friction blocks of the body support – springs cracked or not present: RPN = 140,
- 2.2.3.1 Air brake is unusable: RPN = 120,
- 4.1.1.1 Designations and inscriptions illegible, incomplete, or omitted: RPN = 100.

On the other hand, taking into account the FMC indicator, the following types of failures are of the greatest importance for the reliability of the considered wagons:

- 1.3.3.1 Fork slides – cracked welds, fallen or omitted: FMC = 2.82E-01/h
- 4.2.2.1 Leaky, riddled, or bent doors: FMC = 2.11E-01/h,
- 2.1.1.3 Empty/loaded, braking force, brake on/off device, or release rod work improperly: FMC = 1.81E-01/h,
- 1.4.1.4 Pins and damping links deformed, broken, or missing: FMC = 1.80E-01/h,
- 6.1.1.1 Steps, ladders, or handles are worn, cracked, or unusable. Lack of steps: FMC = 1.56E-01/h.

The differences between the RPN and FMC indices result from the fact that they are calculated during different life cycle stages of the wagon. The RPN indicator results from the assumptions made at the wagon design stage and is an expected indicator. In turn, the FMC indicator reflects failure behavior during the real operation. This is because one of the components of the FMC indicator is the distribution function, based on the probabilistic model, and this model is developed based on real operational data.

Figs. 6-8 show the criticality values on the level of components, subassemblies, and assemblies.

During the criticality analysis of the component indicator (CC_i), it can be noticed that the most critical component is 2.1.1 (levers, tie rods, bushings, and other components of the lever system). The identified types of failure of this component contributed 6.8% of all failures identified among the analyzed wagons.

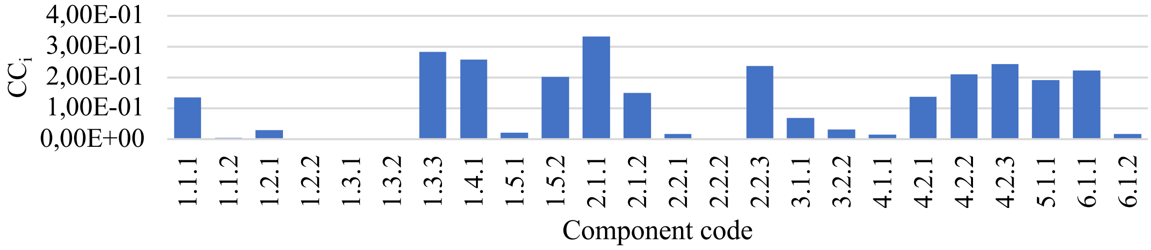

Fig. 6. Histogram of the criticality of component, CC_i

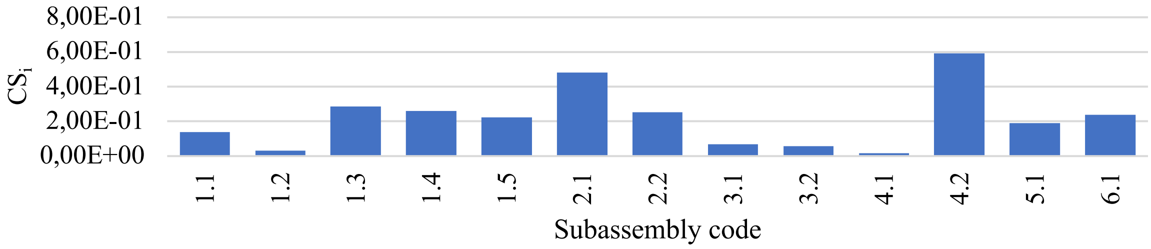

Fig. 7. Histogram of the criticality of subassembly, CS_i

The criticality analysis at the subassembly level clarifies that the most important subassembly is 4.2 (body, floor). For this subassembly, three components have been identified, which contribute to the total value of the C_S=5.93E-01/h. This is an effect of the strong impact of the component with the greatest global impact on criticality, which is: 2.1.1 (levers, tie rods, bushings, and other components of the lever system).

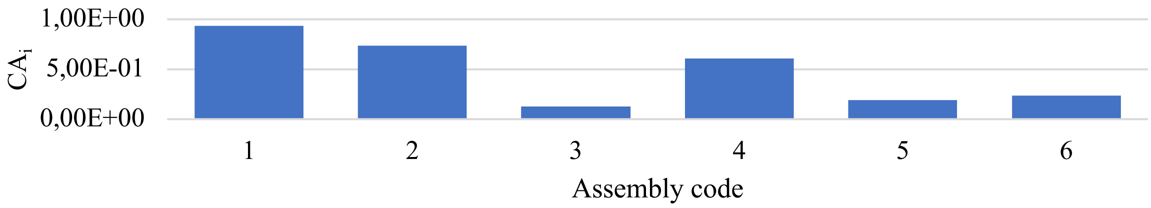

Fig. 8. Histogram of the criticality of assembly, CA

As the highest level in the hierarchical structure of the analyzed wagons is approached, a critical assembly emerges. It is a running system. Even though neither the subassembly nor the components of this assembly were marked as critical, it did not turn out to be the most important. This is due to the way CA_i is calculated. Not only do the values of CS_i, CC_i, and FMC_i have a significant impact, but so do their quantities. The interaction of the quantity and value of the CA_i components led to the result shown in Fig. 8.

5. CONCLUSIONS

The classic FMEA analysis, the results of which are based solely on the RPN indicator, reveals difficulties in considering the relationship between the various types of failures (each of them is treated as independent). In addition, the use of the RPN indicator eliminates the possibility of obtaining smoothness of its scale. Moreover, the obtained results are ambiguous, given that different combinations of S, O, and D values yield the same RPN values. This hinders the implementation of the key task in the FMECA method, which is the identification of critical components, subassemblies, or assemblies.

The approach to the FMECA method used in the present work extends the typical method by adding criticality indicators, such as FMC, CC, CS, and CA, making it devoid of the disadvantages of the RPN indicator. It is worth mentioning that the use of the FMC indicator is based on the real failure rate function obtained from the reliability model of individual failure types. Therefore, the method presented in this paper can be used as the validation tool of the previously performed FMECA analysis based on the RPN indicator.

The proposed method is also universally applicable and can be used for other failure modes, components, subassemblies, and assemblies of the means of transport.

Nevertheless, a limitation of the proposed method may be the need to have real operating data considered when building reliability models. In this case, reference should be made to existing facilities with similar operating parameters, if possible. The analysis also requires time-consuming calculations due to the applied areas of mathematics in the field of probability theory and statistical analysis.

The proposed approach can be developed in the future to include other criticality indicators, and it could be the basis for developing the reliability growth plan and optimizing the maintenance strategy.

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