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The application of failure mode and effects analysis (FMEA) for the risk assessment of changes in the maintenance system of railway vehicles

Zastosowanie analizy przyczyn i skutków uszkodzeń (FMEA) do oceny ryzyka zmian w systemie utrzymania kolejowych środków transportu

Abstract

This paper presents the application of failure mode and effects analysis (FMEA) for the risk assessment of changes in the maintenance system of railway vehicles based on the example of the 6Dg type shunting locomotive. The application example is preceded with an introduction to the methodological basis of FMEA, which is specified in literature and standards. In order to ensure the comparability of the analysis results with vehicles of a similar type and to quantify the risk components (the probability of hazard occurrence, the consequences of the occurrence of a hazard and the possibilities of hazard detection) the classification which applies to shunting locomotives was used. Based on the conducted analysis, the possibility to make changes to the maintenance plan for 6Dg locomotives which would not be in breach of the acceptable safety level was demonstrated and preventive safety measures were determined.

Keywords: railway systems, maintenance systems, risk assessment, FMEA

Streszczenie

W pracy przedstawiono zastosowanie analizy przyczyn i skutków uszkodzeń (FMEA) do oceny ryzyka zmian w systemie utrzymania kolejowych środków transportu na przykładzie lokomotywy manewrowej typu 6Dg. Przykład aplikacyjny poprzedzono wprowadzeniem do podstaw metodycznych analiz FMEA, które są precyzowane w licznej literaturze i normach. W celu zapewnienia porównywalności wyników analizy z pojazdami podobnego typu do kwantyfikacji składowych ryzyka: prawdopodobieństwa wystąpienia zagrożenia, skutków zagrożenia i możliwości wykrycia zagrożenia, zastosowano klasyfikację odnoszącą się do lokomotyw manewrowych. Na podstawie przeprowadzonej analizy wykazano możliwość wprowadzenia zmian w planie utrzymania lokomotyw, jak również określono prewencyjne środki bezpieczeństwa.

Słowa kluczowe: systemy kolejowe, systemy utrzymania, ocena ryzyka, analiza FMEA

Abbreviations

ALARP – as low as reasonably practicable
CSM – common safety method
ETA – event tree analysis
FMEA – failure mode and effects analysis
FMECA – failure mode, effects and criticality analysis
FTA – fault tree analysis
HAZOP – hazard and operability study
MDBHF – mean distance between hazardous failures (km)
MSD – maintenance system documentation
MTBHF – mean time between hazardous failures (hr)
PHA – preliminary hazard analysis
RAMS – reliability, availability, maintainability, safety
RPN – risk priority number (-)
VSC – vehicle safety controls

Symbols

c – the size of losses caused by a hazardous event (-)
D – parameter of the potential of hazard identification (-)
H – frequency of hazardous failures (failure/hr or failure/km)
k – cause of hazard (-)
$r_1(z_k)$ – risk component corresponding to the criterion of the probability of hazard occurrence 'O' (-)
$r_2(z_k)$ – risk component corresponding to the criterion of the consequences of the occurrence of a hazard 'S' (-)
$r_3(z_k)$ – risk component corresponding to the criterion of the possibilities of hazard detection 'D' (-)
O – frequency of the occurrence of hazard (-)
S – scale of losses involved in the occurrence of hazard (-)

1. Introduction

The prevailing formal document for the assessment of safety in rail transport is Directive 2004/49/EC of the European Parliament and the Council of 29 April 2004 on safety on the Community's railways. The currently applicable version was amended by Directive 2008/110/EC of the European Parliament and the Council of 16 December 2008 and Commission Directive 2014/88/EU of 9 July 2014. The principles for the common safety method (CSM) concerning the risk analysis are described in Commission Implementing Regulation (EU) No. 402/2013 [2].

A detailed algorithm for the process of risk management is presented in the appendix to the aforementioned regulation entitled *Risk management process and independent assessment*. The procedure of risk qualification in the case of technical, operational or organisational changes in rail transport requires an analysis of the significance of the proposed changes. The procedure is not required to be applied where the proposed change does not have an effect on the safety of the railway system or if, after the application of the criteria specified in Article 4(2) of the appendix, it is certain that the risk involved therein falls within the permitted level. If there is no such certainty, the change should be subjected to the risk qualification procedure [13].

The aim of the risk qualification is to demonstrate the conformity of the change with the safety requirements. To begin, the system needs to be defined with regard to its scope, functions and interfaces, which is then followed by a risk analysis comprising the identification and classification of hazards and the choice and application of the risk acceptance principle. This forms the basis for performing risk analysis and identifying the relevant safety requirements or measures to be implemented as the ultimate effect of the risk qualification process.

If it is demonstrated during the identification and classification of the hazards that the risk concerning the changes under analysis is essentially permitted, then the process which has been commenced is stopped and the decision taken need only be substantiated and documented; if this is not the case, the process is continued. In accordance with the regulation, at least one of three risk acceptance methods needs to be chosen; these are as follows:

- application of the codes of practice,
- application of a reference system,
- explicit risk estimation.

The last principle requires the choice of specific safety criteria; these may be either qualitative or quantitative. The quantitative criteria are defined in the regulation and include estimated frequency of 'accidents and incidents resulting in harm caused by a hazard' and the estimated 'degree of severity of the harm'. Appendix E of the standard PKN-CLC/TR 50126--218 [9] presents a comparison of a dozen or so methods of estimating the explicit risk used in analysing railway systems, including rail vehicles; these methods are as follows:

- FMEA (failure mode and effects analysis);
- HAZOP (hazard and operability study);
- PHA (preliminary hazard analysis);
- FTA (fault tree analysis);
- ETA (event tree analysis);
- matrix method;
- index-based method (e.g. risk score), and others.

Depending on the acceptance principle which has been adopted, it should be decided at the risk assessment stage whether the risk that is analysed is permissible compared with the existing criteria. The standards for the assessment of safety in railway systems [3–5, 9–11] present general guidance which enables a reduction of the occurrence of hazards to the minimum acceptable level in accordance with the ALARP (as low as reasonably practicable) principle which is based on the division of risk into the following three areas:

1. upper limit where it is mandatory to take up measures to reduce the risk;
2. tolerable risk (so-called ALARP) area where appropriate remedial measures and risk control measures should be undertaken;
3. lower risk limit where the risk level is acceptable and further measures are not required.

The distinctions between acceptable, tolerable and non-acceptable risks are set by acts of law on railways (directives, regulations, standards, internal procedures of the safety management system of railway carriers) – these are blurred dividing lines which, in qualitative terms, relate to applicable requirements set for objects. If a vehicle meets these requirements, it is considered safe for humans and for the environment. This paper presents a method of estimating explicit risk through the application of FMEA (failure mode and effects analysis), which is amongst those methods most frequently applied by Polish railway carriers.

2. Methodological basis of failure mode and effects analysis

As stated in the introduction, FMEA is one of many methods of explicit risk estimation. The aim of FMEA is to assess the risk involved in the occurrence of hazards and undertake measures to control or eliminate it, primarily with regard to hazards relevant for the railway system. The FMEA method with reference to various technical systems and facilities is widely described in literature [1, 7, 8, 11, 12, 14–18] and standards, for example:

- MIL-STD-1629A Procedures for Performing a Failure Mode, Effects and Criticality Analysis;
- BSI BS 5760-5:1991 Reliability of systems, equipment and components – guide to failure modes, effects and criticality analysis (FMEA and FMECA), IMO MSC Resolution 36(63) Annex 4 – Procedures for Failure Mode and Effects Analysis;
- PN-EN 60812 Failure modes and effects analysis (FMEA and FMECA).

The procedure for performing FMEA for rail vehicles is presented in Fig. 1.

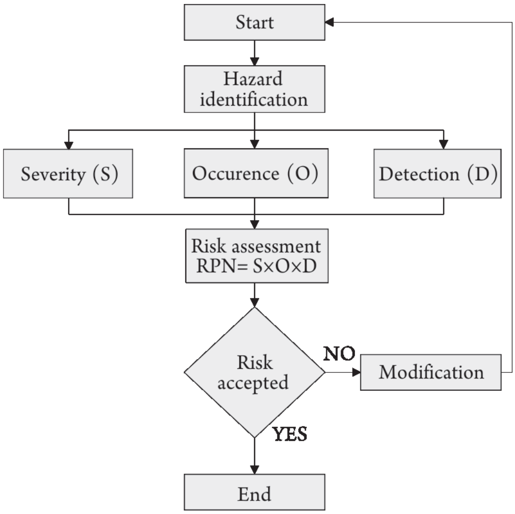

Fig. 1. Procedure for implementing FMEA for a rail vehicle

3. Application of the FMEA method for risk qualification

As an application example of FMEA for risk qualification, changes in the maintenance system of 6Dg diesel locomotives (Fig. 2) is presented. FMEA is required by the procedure *Identification of hazards and risk assessment of the Safety Management System* of the railway carrier operating the locomotives.

Fig. 2. View of 6Dg type diesel locomotive

4. Risk of hazard occurrence

FMEA is a quantitative method in which the risk of occurrence of any identified type of hazard is expressed using the RPN (risk priority number). According to the standard EN 60812:2018 *Failure modes and effects analysis (FMEA and FMECA)*, the RPN may be obtained using the following expression [6]:

$$\mathrm{RPN}(z_k) = \prod_{i=1}^{3} r_i(z_k) \Rightarrow \mathrm{RPN} = O_k \cdot S_k \cdot D_k \tag{1}$$

where:

- $r_1(z_k)$ – risk component corresponding to the criterion of the probability of hazard occurrence ‘O’,
- $r_2(z_k)$ – risk component corresponding to the criterion of the consequences of the occurrence of a hazard ‘S’,
- $r_3(z_k)$ – risk component corresponding to the criterion of the possibilities of hazard detection ‘D’,
- k – cause of hazard.

The above elements are assessed on a scale of 1 to 10 based on the classification criteria which were adopted. The risk assessment ratio RPN takes values from between 1 and 1000. Various techniques for categorising risk components are proposed in standards and literature. The number of categories, their scale and description should match the particular object of study in order to ensure the comparability with vehicles of a similar type operating in similar conditions. In the case of a 6Dg locomotive, the divisions which apply to shunting locomotives are used to quantify the frequency of the occurrence of hazard O (Table 1).

Table 1. Categories of the probability of hazard occurrence

Ratio 'O'	Frequency of occurrence of the hazard *H*		Qualitative classification	Description of the probability of occurrence
	[failure / hr operation]	[failure / km]		
1–2	$H \leq 10^{-6}$	$H \leq 10^{-7}$	unlikely	The probability of the occurrence of a hazard is marginal and will likely not occur.
3–4	$10^{-6} < H \leq 10^{-5}$	$10^{-7} < H \leq 10^{-6}$	rather unlikely	The probability of the occurrence of a hazard is low. The causes of the hazard are very rare.
5–6	$10^{-5} < H \leq 10^{-4}$	$10^{-6} < H \leq 10^{-5}$	occasional	The probability of hazard occurrence is medium. The causes of the hazard occur occasionally.
7–8	$10^{-4} < H \leq 10^{-3}$	$10^{-5} < H \leq 10^{-4}$	likely	The probability of hazard occurrence is high. The causes of the hazard occur frequently.
9–10	$H > 10^{-3}$	$H > 10^{-4}$	frequent	The probability of hazard occurrence is very high. It is nearly certain that the hazard will occur.

The scale of losses involved in the occurrence of hazard *S* was referred to human losses estimated by means of the equivalent fatalities and financial losses. The classifications of the consequences of the occurrence of a hazard are presented in Table 2.

Table 2. Categories of the consequences of the occurrence of a hazard

Ratio 'S'	Human losses (equivalent fatality)	Financial losses (euro)	Qualitative classification	Description of the effects of the occurrence of hazard
1	none	none	negligible	The effects of the hazard are irrelevant for the safety level.
2–3	one slightly injured person ($0 < c \leq 0.01$)	between 0 and 50,000	low	The effects of the hazard may be small and may only cause a minor reduction in the safety level (disruptions in railway transport, delays).
4–6	several slightly injured persons ($0.01 < c \leq 0.1$)	between 50,000 and 0.5 million	significant	The effects of the hazard may be quite considerable and cause a reduction in the safety level (incident, slightly injured persons).
7–8	many severely injured persons or one fatality ($0.1 < c \leq 1$)	between 0.5 million and 2 million	serious	The effects of the hazard may be serious and cause a considerable reduction in the safety level (railway accident, seriously injured persons, fatality).
9–10	many fatalities ($c > 1$)	more than 2 million	catastrophic	The effects of the hazard may be very serious and lead to a dramatic reduction in the safety level (serious railway accident, fatalities).

The parameter of the potential of identification of hazard *D* defines the possibility of diagnosing a potential hazard (Table 3). The inclusion of this characteristic makes FMEA different from other risk acceptance methods. The possibility of earlier hazard detection by advanced systems of on-board diagnostics or the application of advanced tools and methods of tests during checks or maintenance has a material effect on the ensuring of a high level of safety in the operation of the vehicle.

Table 3. Categories of the possibilities of hazard detection

Ratio 'D'	Qualitative classification	Description of hazard detection possibilities
1–2	very high	The probability of hazard detection is very high. Identification of the cause of the error is certain.
3–4	high	The probability of hazard detection is high. The control measures which are applied enable the identification of the cause of the error. Symptoms for the occurrence of the cause are noticeable.
5–6	average	There is an average probability of hazard detection. The control measures may enable the identification of the cause of the error. Symptoms may be established and identified which indicate the possibility of hazard occurrence.
7–8	low	There is a low probability of hazard detection. It is very likely that the control measures which are applied will not make it possible to identify the cause of the error. It is very difficult to identify the cause of the error.
9–10	very low	Minimal probability of hazard detection. It is practically impossible to identify the cause of the error.

In accordance with the guidelines for the procedure of the identification of hazards and the technical risk assessment applied by the carrier, the FMEA method identifies three risk levels on the basis of the so-called risk matrix (Table 4). Depending on the calculated RPN, an assessment is performed of which hazards involve the highest risk. Hazards with an RPN figure higher than 120 are relevant. The higher the RPN figure, the more relevant the hazard for the railway system. RPN figures above 150 relate to events which pose a direct threat to the safety of the railway system. Where the risk *R* is in class 3, process control measures should be undertaken to eliminate the hazard or limit its effects. Preventive, corrective measures should be addressed in the first instance to items with a high RPN figure.

Table 4. Risk levels applied in the FMEA according to the procedure applied by the carrier

Risk class	RPN	Risk level	Description
1	RPN ≤ 120	acceptable	Measures to eliminate the hazard are not required to be taken.
2	120 < RPN ≤ 150	tolerable (ALARP level)	Means and/or measures eliminating the hazard and reducing risk should be identified.
3	RPN > 150	unacceptable	This is a hazard which poses a direct threat to the railway system safety.

5. Risk estimation sheet

Table 5 presents the mean times to failure and mean times between hazardous failures for selected systems and elements of a 6Dg locomotive having an impact on the safety of railway transport.

Table 5. Mean time to failure and time between hazardous failures for selected systems and elements

No.	Description	MTBHF [hr]	MDBHF [km]
1.	**Running gear**	**27,506.3**	**178,200.0**
1.1.	failures and wear of the wheels' outer contour	27,506.3	178,200.0
2.	**Brake system (pneumatic and mechanical parts)**	**6,430.0**	**41,657.1**
2.1.	failures of the main or auxiliary compressor	18,337.5	118,800.0
2.2.	failures of the engine driving the main or auxiliary compressor of rail vehicle	165,037.5	1,069,200.0
2.3.	failures of pneumatic valves (inter alia, main or auxiliary valve of the driver, reducing valve, end valve, safety valve)	29,124.3	188,682.4
2.4.	failures of pneumatic conduits	41,259.4	267,300.0
2.5.	failures of the actuator in the brake system	247556.3	1,603,800.0
2.6.	failures of other elements in the pneumatic circuit	49,511.3	320,760.0
2.7.	failures of elements of the brake, e.g. levers, couplers, coupling pins, bushings, couplings, brake blocks	82,518.8	534,600.0
3.	**Train drive safety control engineering devices**	**8,841.3**	**57,278.6**
3.1.	failures of vehicle safety controls (VSC), metering device (speed meter, ammeter) or radiotelephone	8,841.3	57,278.6

Based on the above-calculated figures and the aforementioned assessment criteria, Table 6 presents a FMEA sheet with the results of the estimated risk for the identified hazards relevant for the safety of the railway transport of a 6Dg locomotive.

6. Analysis of the results and preventive safety measures

The analysis demonstrated that the highest frequencies of the occurrence of threats (parameter O) relate to failures of the vehicle movement safety controls. Detailed identification of the recorded occurrences showed that the measuring devices and the radiotelephone are the weakest elements in this structural group.

The highest figures of losses involved in the occurrence of a threat (parameter S) and the highest chances for detecting the threat (parameter D) were estimated for the threats which are not currently present and which link to the possibility of fatigue-related cracks in the structural nodes of the vehicle frame (support) and the bogie support. Analysis of the results demonstrated that the permitted risk level of RPN ≤ 120 was not exceeded for any of the hazards. The highest risk of hazard was noted for failures of the automated vehicle safety controls, checking apparatus or radiotelephone $\mathrm{RPN}_9 = 70$ ($O = 7$, $S = 5$, $D = 2$).

Table 6. Risk estimation sheet using the FMEA method for a 6Dg locomotive

No.	Hazard	Potential consequences	Existing inspection methods	O	S	D	RPN	Additional control methods
1	2	3	4	5	6	7	8	9
			Running gear					
1.	failure of or wear of the wheels' outer contour	increase in dynamic loads, exceeding the permitted wear, wheel thread failure, cracking of the rim, derailing of locomotive	check and parametric cards in the MSD of wheel sets and wear check cards of the rims of wheel sets manual for the checking and technical assessment of wheel sets of rail vehicles Ct-4	5	2	2	**20**	introduction within P3 level of flaw-detection tests of wheel sets
			Brake system (pneumatic and mechanical parts)					
2.	failure of the actuator in the brake system	slower response of the brake system, elongation of the braking path, incapacity to drive	check and parametric cards in the MSD of the brake and pneumatic system	3	3	1	**9**	not required
3.	failure of elements of the brake	failure of brake gear, jamming of the wheel set, heating of the wheel rim, incapacity to drive	check cards and protocols in the MSD of the brake – mechanical part manual for the operation and maintenance of brakes in railway rolling stock Cw1	5	3	3	**45**	not required
4.	failure of main or auxiliary compressor	no air in the brake system, vehicle immobilisation	check the technical condition in accordance with the compressor's technical requirements for the production and acceptance; check cards in the MSD of the compressor unit	6	2	1	**12**	not required
5.	failure of the engine driving the main or auxiliary compressor of rail vehicle	problem with controlling the vehicle's brake	check cards in the MSD of the pneumatic system	4	3	1	**12**	not required
1	2	3	4	5	6	7	8	9

6.	failure of pneumatic valves	unstable operating parameters of the pneumatic system, possibility of excessive pressure growth	check cards in the MSD pneumatic system	5	2	2	**20**	not required
7.	failure of pneumatic conduits	drop in air pressure, automatic vehicle braking, intensive work of the compressor	check cards in the MSD of the pneumatic system	5	2	3	**30**	not required
8.	failure of other elements in the pneumatic conduit	drop in air pressure, no possibility to switch the system down, incapacity to drive	check cards in the MSD of the pneumatic system	5	2	2	**20**	not required
Vehicle safety control devices								
9.	failure of the vehicle safety controls (VSC), metering device or radiotelephone	no signal and reception, disruptions in communications, vehicle's incapacity to drive, collision or derailing of the locomotive	check cards and protocols in the MSD of the metering systems, brake automation system, dead man's switch and Radio Stop	7	5	2	**70**	not required
	Vehicle support structure							
10.	corrosion wear of the bogie support or frame	decommissioning in the event of exceeding corrosion of 0.2 mm of the thickness of sheet metal of the support or 0.2 of the thickness of sheet metal of longerons, headstocks and transverse colon	check cards and protocols in the MSD of the bogie support and frame rail vehicle maintenance manual Ct-3	1	5	4	**20**	not required
11.	cracks in the support's nodes	damage of the construction structure, propagation of fatigue cracking in further operation	check and parametric cards in the support's MSD rail vehicle maintenance manual Ct-3	1	6	4	**24**	visual assessment of the condition of the nodes of the support at the P2 maintenance level and penetration tests at the P3 maintenance level
12.	cracks in the nodes of the bogie frame	damage of the construction structure, propagation of fatigue cracking in further operation	check and parametric cards in the MSD of the bogie frame rail vehicle maintenance manual Ct-3	1	6	4	**24**	visual assessment of the condition of the nodes of the bogie frame or penetration tests at the P3 maintenance level

In most cases, the risk level reaches RPN = 20 (Fig. 3, 4). A higher figure was found for:

- failures of brake elements $RPN_3 = 45$ ($O = 5$, $S = 3$, $D = 3$);
- failures of pneumatic conduits $RPN_7 = 30$ ($O = 5$, $S = 2$, $D = 3$);
- cracks in the nodes of the bogie support and frame RPN_{11}, $RPN_{12} = 24$ ($O = 1$, $S = 6$, $D = 4$).

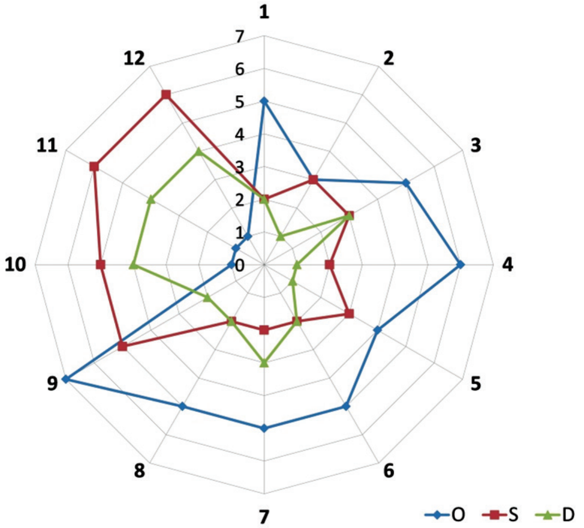

Fig. 3. Presentation of FMEA results – *O*, *S*, *D* parameters

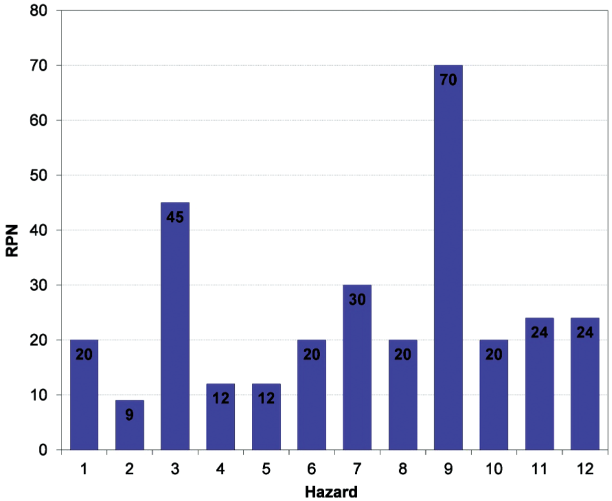

Fig. 4. Presentation of FMEA results – RPN figures for the particular hazards

Based on the conducted analysis, the possibility to make changes to the maintenance plan for 6Dg locomotives which would not be in breach of the acceptable safety level was shown. Nonetheless, changes to the locomotive maintenance plan require particular attention during the performance of operation and repair work with regard to the assemblies and subassemblies which have a major effect on the safety of railway transport. These assemblies and subassemblies are:

- wheel sets,
- brake system,
- bogie support and frame.

Due to the considerable age of the locomotives' support structure, special attention should be placed on visual inspection and the checking of the structural nodes of the body's support and bogie frame. The following preventive safety measures were proposed:

- introduction, at the P2/1 maintenance level, of visual check activities on the structural nodes of the vehicle frame and bogie frame;
- at the P3 level, conducting of simplified flaw-detection tests of the wheel sets;
- performance of penetration tests of the structural nodes on the bogie support and frame during repairs at the P4 maintenance level;
- in the IT system supporting the management of the carrier's transporting potential, the possibility of ongoing monitoring of the technical condition of the locomotives should be taken into account.

7. Conclusion

FMEA is one of the many explicit risk estimation methods mentioned in Commission Implementing Regulation (EU) No. 402/2013. It establishes a systematic approach requiring knowledge of all types of failure that are either registered during operation or are anticipated. This paper has presented an example of its application based on changes in the maintenance system of the 6Dg type locomotive. Changes in the maintenance plan require maintenance system documentation to be updated for the operations and processes allocated to particular maintenance levels. The changes were the subject of an analysis of the applicable maintenance system documentation.

In accordance with Commission Regulation (EU) No. 1078/2012 of 16 November 2012 on a common safety method for monitoring, the effectiveness of the taken control measures or preventive measures should be monitored and supervised and their effects should be verified. The regulation obliges railway undertakings and entities in charge of maintenance to ensure the exchange of relevant safety information identified in the monitoring process. After the specified time of operation of the control measures, the process should be evaluated and the new RPN risk indicator should be calculated. Preventive actions proposed during hazard identification and risk assessment by the FMEA method should be used as the input data to the safety improvement program.

The next stage of works related to the change of the maintenance strategy of the analysed locomotive should be the assessment of the effectiveness of the proposed changes using the life cycle costs (LCC) analysis. It can be particularly useful to compare the maintenance costs in the full maintenance plan of the locomotive and compare the unit maintenance costs before and after the proposed changes.

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