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A Critical Comparison of Alternative Risk Priority Numbers in Failure Modes, Effects, and Criticality Analysis

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ABSTRACT Risk priority number (RPN) is a widely used approach, and it is a powerful means to assess the criticality of modes in a failure modes, effects, and criticality analysis (FMECA) worksheet. In the application of the traditional FMECA, the RPN is determined to rank the failure modes; however, the method has been criticized several times for having many drawbacks and weaknesses, such as the presence of gaps in the range of admissible values, the duplicates value provided by different combinations of the base factors, and the high sensitivity to small changes. This paper analyses and compares some alternative RPN formulation proposed in the literature to overcome these limits. This paper takes into account only the alternative RPN, which proposes a powerful solution without increasing the computational complexity and remaining coherent to the classical idea included in the international standard IEC 60812. In order to compare the advantages and disadvantages of these alternative RPNs, an FMECA was developed for a heating, ventilation, and air condition (HVAC) system in railway application. The critical analysis of the comparison can provide recommendations and suggestions regarding the choice of the alternative RPN based on the type of application. Finally, this paper takes into account the scales reduction of possible values related to the parameters (i.e., occurrence, severity, and detection), which influence the assessment of the RPN. This approach allows the designers to mitigate the drawbacks related to the full scale and provide an easier and faster assessment of the scores to evaluate the criticality analysis and prioritization.

INDEX TERMS FMECA, railway engineering, reliability theory, risk priority number.

I. INTRODUCTION

Failure modes and effects analysis (FMEA) is one of the most powerful methods used for risk assessment and maintenance management [1].

FMEA has been used to identify the critical risk events and predict a system failure to avoid or reduce the potential failure modes and their effect on operations. FMECA is composed of two separates analyses, the Failure Mode and Effects Analysis (FMEA) and the Criticality Analysis (CA) [2]. FMEA includes a list of possible device failure modes, failure causes, local and final effects that refers to the impact of each failure on the system element and the whole system respectively, and the alternative recommended corrective actions to avoid each failure. On the other hand, Criticality Analysis plans and focuses the maintenance activities according to a set of priorities by giving failures with the highest risk the highest priority. More details on FMECA process and application are given in references [3]–[6]. FMECA is one of the most used techniques for failure analysis in particular during design stage of new systems.

This method is an inductive analysis method that starts from the lowest level (single component) and continues analyzing the upper hierarchical level. In order to achieve a priority ranking of the identified failure modes and effect the second analysis (Criticality Analysis) is performed. This ranking is obtained using a quantitative index, Risk Priority Number (RPN), given by the multiplication of the Occurrence (O), Severity (S) and Detection (D) of a failure [1]–[4], [7]:

$$RPN = O \cdot S \cdot D \tag{1}$$

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where [1]:

- Occurrence (O) is the probability that a failure mode will happen, therefore it is strongly linked to the failure rate of the equipment.
- Severity (S) defines the strength of failure impact on the system, it's related to the effects of the failure modes.
- Detection (D) indicates the possibility of diagnose the failure mode before its effects are manifested on the system.

The range of the RPN values depends on the measurement scales for the three parameters. As suggested by IEC-60812 [4], parameters O, S and D are generally measured on a 10-point scale wherein greater O and S numbers stand for increasing values of the frequency of occurrence and of the severity respectively, whereas D is ranked in a reversers order, namely the higher the detection value, the lower the detection probability of the failure mode, producing overall RPN values ranging from 1 to 1000.

II. DRAWBACKS OF CLASSICAL RPN

The classical RPN formula is very simple and intuitive, but its use for the criticality analysis of the system/process failure modes has highlighted many drawbacks [4], [8]–[19]:

- Gaps in the Range: The RPN values are not continuous but have only a few unique values. If a 10 values scale is used, 88% of the range is empty; the largest number is 1000, but 900 is the second largest followed by 810, 800, 729, and 720.
- Duplicate RPNs: Different values of the parameters may generate identical RPN values. For example, the RPN numbers 60, 72, and 120 can be formed from 24 different combinations of S, O, and D. However, the hidden risk implications of the three events may be very vastly different because of the different severities of the failure modes.
- High Sensitivity to Small Changes: Multiplying the numbers comprising the RPN is intended to magnify the effects of high-risk factors. For above mention example, if O and D are both 8, then a 1- point difference in severity rating results in a 64 quantitative grade difference in the RPN. It is very evident RPN value varying sensitivity to small changes.
- Inadequate Scale of RPN, in fact the relative importance among O, S and D is not taken into consideration. The three factors are assumed to have the same importance. This may not be the case when applying to a practical FMECA. For example, the RPN1 with 3, 4, and 5 as S, O, and D, respectively, gives the value of 60, whereas the RPN2 with 3, 5, and 5 gives 75. In fact, in RPN2 the failure mode has the twice the occurrence, but the RPN value is not doubled. This explains that the RPN values cannot be compared linearly.
- O, S, D are defined in very subjective way, in fact the three factors are difficult to precisely determine. Much information in FMECA can be expressed in a linguistic way such as moderate, remote or very high. Anyway, people who express these judgments should presumably be experts in the field where FMECA is performed, and these experts represent the most reliable source of information. In spite of that, expert' knowledge is often uncertain and incomplete so that FMECA analysis is to performed by the support of methods able to properly manage such uncertainty of input data@perio
- Dispersion of RPNs: All the possible RPN values are scattered among the full range,in fact there is a high concentration of multiple value in the left side of the scale and a low concentration in the right side.

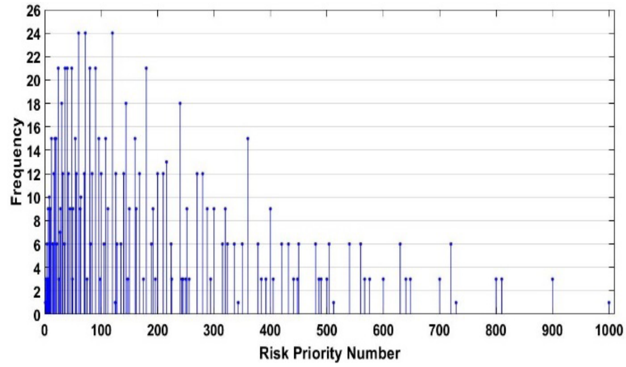

FIGURE 1. Histogram of all the possible values of risk priority number.

Fig. 1 shows the numbers formed by the RPN and the relative problems expressed below. The "holes" in the scale between the numbers, in fact greater part of the numbers are concentrated in the left side of the scale representing by low values of RPN, then another problem shown by the figure is the multiplicity of some values, for example there are 24 different combination for obtaining a specific RPN values.

III. ALTERNATIVE RISK PRIORITY NUMBERS

Several papers propose different approaches to overcome the limits associated to RPN, described below. Table 1 summarizes the main proposed approaches for each of the individual problem, the first column contains the drawbacks and the second one contains the main methods suggested in literature to solve them.

The following subparagraphs explain in detail the methods proposed in literature to overcome the RPN issue included in table 1.

A. SUM

Braband and Griebel [15] and Braband [16] proposes an alternative equation for the RPN assessment, using the sum of the three metrics, called IRPN - Improved Risk Priority Number. The international standard IEC 60812-2018 [4] includes the alternative RPN method proposed by Braband and Griebel [15] and Braband [16] (called ARPN - Alternative Risk Priority Number - instead of IRPN) as a modified version of the commonly used RPN with the aim of providing a more consistent assessment of criticality when parameters can be quantified on a logarithmic scale.

TABLE 1. Possible approaches to solve common RPN issues.

Issues	Possible approach
Holes	- Sum O, S and D;
Duplicate RPNs	- Introduction of corrective factors; - Using exponentiation or exponential function; - Scale reduction; - Fuzzy theory;
High sensitivity	- Sum O, S and D;
Importance O, S, D	- Introduction of corrective factors; - Different formulation of RPN; - Fuzzy theory;
Subjectivity O, S, D	- Fuzzy theory
Dispersion	- Logarithmic equation; - Sum O, S and D; - Scale compression;

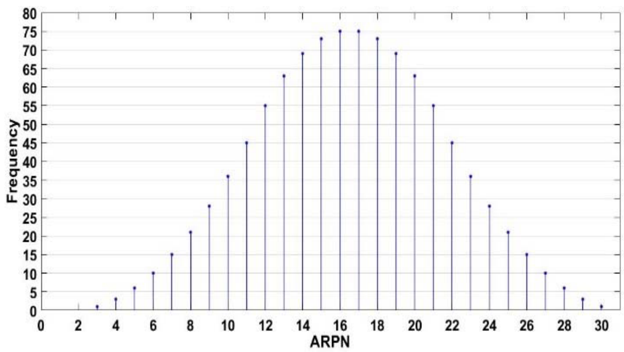

FIGURE 2. Histogram of all the possible values of ARPN (or IRPN).

Equation 2 shows how to assess the Alternative Risk Priority Number [4], [15], [16]:

$$ARPN = IRPN = O + S + D \quad (2)$$

Considering a [1; 10] range of integer values for the three parameters O, S and D, Fig. 2 shows the numbers formed by the IRPN and the relative repetition frequency. The IRPN is a powerful solution for most the problems explained above because it results in a continuous scale delating the value dispersion, as shown in Fig. 2. In fact, IRPN assumes all the integer values in the interval from 3 to 30, therefore the IRPN scale has no gaps. Moreover, it solves the sensitivity problem because small variations in one ranking have the same effects on the IRPN, independently of the values of the other factors. Despite these advantages, the problem of the duplicate IRPNs is highly accentuated, with the maximum repetition frequency of 75, three times bigger than the classical RPN. This problem is clearly evident considering that the percentage number of unique value is only 2.8% comparing to the 12% of the classical RPN.

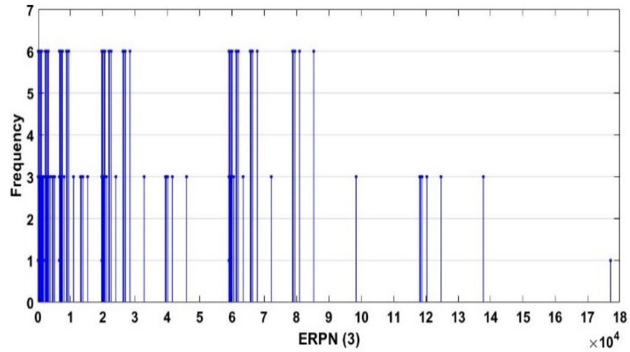

FIGURE 3. Histogram of all the possible values of ERPN(3).

B. EXPONENTIAL

Chang *et al.* [12] proposed an exponential RPN (ERPN) as eq. 3. In this method, the number of unique values for risk evaluation of failures has been increased, reducing the number of duplicates RPNs (Fig. 3).

$$ERPN\ (x) = x^{W_S \cdot S} + x^{W_O \cdot O} + x^{W_D \cdot D} \quad (3)$$

where x is a positive integer, and $x \geq 2$; O, S and D are integer rating range between 1 and 10; W_S, W_O, W_D are weights for severity, occurrence and detection respectively. Chang proved that the optimal choice is $x = 3$, leading to 220 different unique values.

Akbarzade Khorshidi *et al.* [20] modified the equation, as the product of occurrence and detection stand as probability, and severity plays a role as value in power as (4).

$$URPN\ (z) = (O \cdot D) \cdot z^S \quad (4)$$

where z is a real number, and $z \geq 1$. According to Khorshidi, the choice that leads to the maximum number of unique values is $z = e$ (Fig. 4).

Both ERPN and URPN solve very well the problem of duplicate RPNs and of different importance between O, S and D; but they amplify the problems of the "holes" and of the dispersion because the maximum possible values are respectively 2 and 3 order of magnitude larger than the classical RPN.

C. CORRECTIVE FACTORS

Several papers [21]–[26] propose different RPN formulations introducing innovative coefficients and parameters in order to overcome the duplicate issue and the same importance of O, S and D problem. The introduction of new parameters and/or corrective factors consists in equations harder to compute than the multiplication in the old RPN concept.

These additional terms are usually difficult to evaluate, therefore the benefits obtained with this kind of alternative RPNs are not enough to justify this increase of the analytical computation.

TABLE 2. Comparison between different alternative risk priority numbers.

Function	Range factors	Mean	Median	Most frequency	Number of unique values	% unique values	Min	Max
RPN	[1; 10]	166	105	24	120	12%	1	1,000
IRPN	[1; 10]	16.5	16.5	75	28	2.8%	3	30
ERPN(3)	[1; 10]	26,572	13,203	6	220	22%	9	177,147
URPN(e)	[1; 10]	105,402	4,877.5	4	420	42%	*e*	2,202,646.6
LRPN	[1; 10]	1.9679	2.0212	24	120	12%	0	3

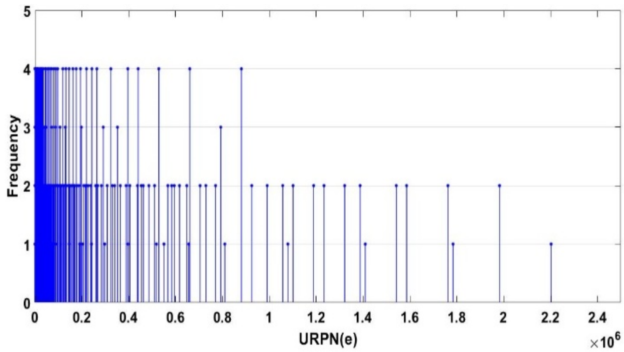

FIGURE 4. Histogram of all the possible values of URPN(e).

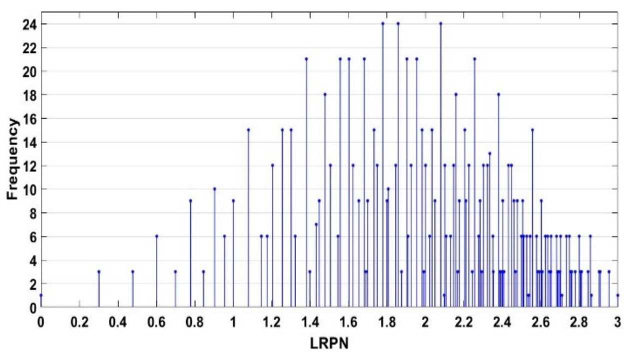

FIGURE 5. Histogram of all the possible values of LRPN(e).

D. LOGARITHM

The application of logarithm in the classical RPN equation compress the scale of possible RPN to a 0-3 range (if base-10 is used), as shown in Fig 5.

$$LRPN = \log(O \cdot S \cdot D) \tag{5}$$

The logarithmic RPN reduces the dispersion and the "holes" in the scale, but it has no effects on duplicates issue and on the importance of the three factors. For these reasons it is not an optimal method and in literature there is not any documentation that applies this equation on real system.

E. COMPARISON

The associated statistics of different alternative Risk Priority Numbers (e.g. mean, median, minimum value and maximum value) were evaluated and included in table 2. The table also includes the maximum repetition frequency of a single risk value (called "Most frequency"), the number of different unique values and the percentage of unique values, considering that the possible different combinations of three factors expressed in 10-scale is 10^3.

The IRPN proposed by Braband and Griebel [15] and Braband [16] is characterized by a very compressed range from 3 to 30, with mean value and median coincident with the midpoint of the range. These parameters highlight that this method can easily overcome the "holes" and the dispersion issues. At the same time, the duplicate problem is amplified, as it is clearly identified considering that the percentage number of unique values is only 2.8% comparing to the 12% of the classical RPN. Indeed, it is characterized by the highest "most frequency", representing the main problem related to this approach.

Quite the opposite, ERPN and URPN solve very well the duplicates drawback with the maximum repetition frequencies of 6 and 4 respectively, and the related percentages of unique values of 22% and 42% respectively. In spite of these advantages, both these methods have a limited use because of the range of possible values that is extremely broadened. Indeed, the mean value and the median of ERPN and URPN are shifted toward high numbers, producing results very difficult to interpret.

The logarithmic RPN is characterized by a very compressed and dense scale with the same number of unique values of the classical RPN. The worst issue of this method is the shape of the distribution, that is moved toward the highest values of the range (i.e. on the right side of the plot), as it is possible to see in figure 5. The statistical demonstration of this sentence is provided by the LRPN median, that is the only value in the column higher than the midpoint of the range. In this case, the shape of the distribution and the high median value make the definition of the RPN threshold very challenging, because lots of RPN are concentrated in the final section of the range.

Finally, table 2 highlights that all the alternative approaches proposed above have advantages and disadvantages, and no one can solve at the same time all the RPN drawbacks without introducing other limitations. Therefore, in many real cases,

TABLE 3. Comparison between different alternative risk priority numbers using a 1 to 5 scale.

Function	Range factors	Mean	Median	Most frequency	Number of unique values	% unique values	Min	Max
RPN	[1; 5]	27	20	9	30	24%	1	125
IRPN	[1; 5]	9	9	19	13	10.4%	3	15
ERPN(3)	[1; 5]	217.8	189	6	35	28%	9	729
URPN(e)	[1; 5]	419.77	147.78	3	70	56%	*e*	3.710,33
LRPN	[1; 5]	1.78	1.86	9	30	24%	0	3

the classical RPN is still suitable, and the choice of alternative method depend on the analytical cost that a company can support.

IV. SCALE ADJUSTMENT

Many papers [27]–[31] suggest to reduce the number of O, S and D levels because in many applications it is difficult to evaluate the parameters in ten different levels. According to these works, the choice of only 5 levels is optimal in several manufacturing fields. The standard IEC 60812 – 2006 [32] proposed a ten levels approach and a reference guide to how assess these values. The 2018 new version of the standard [4] revises the reference guide table and it lets the designers free to assign the O, S and D values personalizing the own tables.

For instance, the assessment of the occurrence rank is strictly related to the item failure rate and usually the failure rates of the components that make up a generic system varying in few orders of magnitude. Therefore, the use of a 5 or less different occurrence values is recommended in order to cover the failure rates range in an optimal way.

The consequences of a failure mode influence the severity assessment. In many applications it is not possible to define ten different levels of failure consequences, therefore the severity ranks are merged in sublevels with two or three individual level together. The same considerations are valid also for the detection range because usually the diagnostic information is not completely available during the design phase. For these reasons, a 5 or less levels evaluation is optimal also for severity and detection.

Table 3 compares the application of a scale adjustment on the classical RPN and on the alternative Risk Priority Numbers proposed above. Obviously, the identification of just 5 different values mitigates the duplicate issue, as it is possible to see comparing the percentages of unique values in table 2 and table 3. Two examples of the application of a 1-5 scale of the O, S and D parameters for classical RPN and for IRPN are illustrated respectively in Fig. 6 and Fig. 7.

ERPN and URPN using 1 to 5 scale are both the best solutions in term of duplicate issues, but the range of possible values has little significance even in this case, as it is possible to see in Fig. 8 in case of the URPN(e) approaches is applied

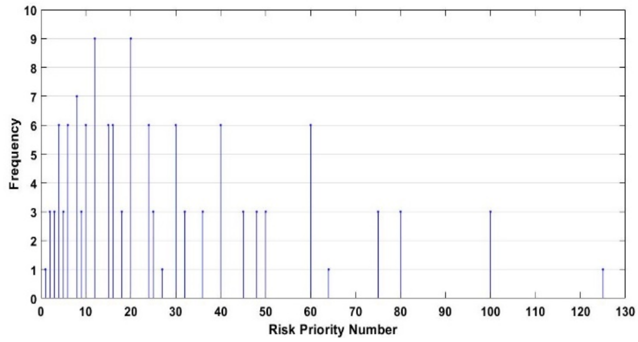

FIGURE 6. Histogram of all the possible values of RPN using a 1-5 scale of the O, S and D parameter.

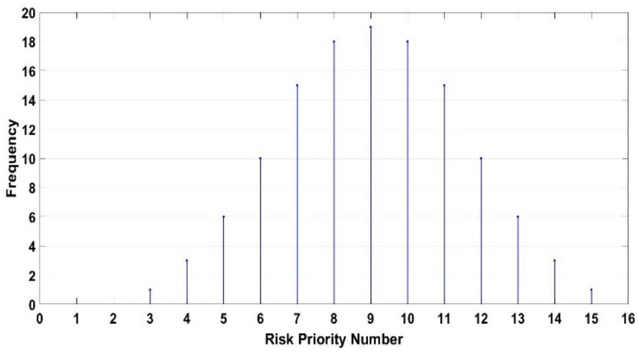

FIGURE 7. Histogram of all the possible values of IRPN using a 1-5 scale of the O, S and D parameter.

using a reduced scale. In general, all the proposed approaches maintain each related drawback, but the adjustment of the scale using only five different values allow to mitigate these limits, making every technique more suitable for industrial and manufacturing applications.

V. FUZZY AND MULTI-CRITERIA APPROACHES

To overcome the above drawbacks, fuzzy logic has been widely applied in Failure Modes, Effects and Criticality Analysis [33]. Vast majority of fuzzy FMECA approaches employs fuzzy *if–then* rules for prioritization of failure modes [34]–[37]. This requires a vast amount of expert knowledge and expertise.

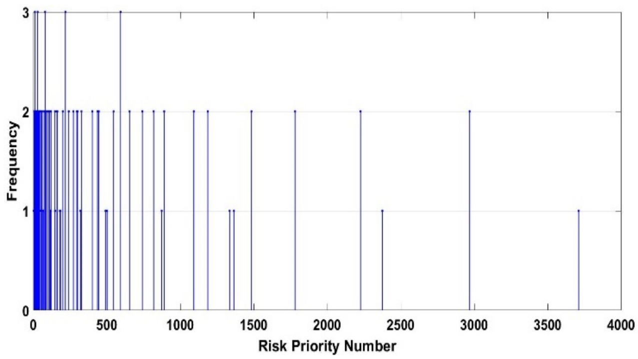

FIGURE 8. Histogram of all the possible values of URPN(e) using a 1-5 scale of the O, S and D parameter.

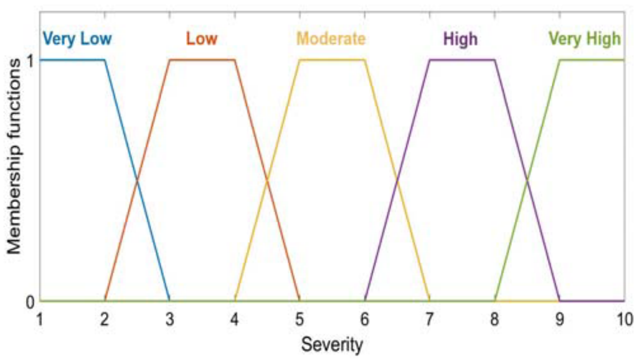

FIGURE 9. Example of membership functions for severity assessment.

The idea is to represent O, S, and D using linguistic variables and rank them using fuzzy numbers (e.g., triangular or trapezoidal fuzzy numbers) instead of crisp numbers [38], [39]. To do that, the first step is to define membership functions for the three risk factors O, S, and D as shown in figure 9, that is an example of fuzzy assessment for severity S index.

Once membership functions are defined, each risk factor can be represented by linguistic variables. After that, expert judgment can be collected regarding the three risk factors in the form of linguistic terms. These linguistic terms are integrated in the fuzzy rule base to produce linguistic term representing the RPN [40]–[42]. In particular, a complete *if–then* rule base may consist of hundreds of rules, where ''If'' refers to an antecedent that is compared to the inputs, and ''Then'' refers to a consequent, which is the result/output [43]–[45]. It is absolutely not realistic to ask an expert to make hundreds of judgments. Moreover, this approach has a very high level of subjectivity during the rule definition phase, that is a contradiction because the fuzzy theory is generally used to mitigate the subjectivity of O, S and D definition.

Instead of using fuzzy *if–then* rules, some papers propose to combine fuzzy and other approaches to prioritize failure modes in FMECA [46]–[50].

Most works in literature also propose the support of Multi-criteria decision methods (MCDM) to carry out FMECA [51]–[53]. Braglia [54] proposes the Analytic Hierarchy Process (AHP) to pairwise compare the potential causes of failure by assuming as criteria O, S and D together with the expected cost due to failures. Braglia *et al.* [55] develop a fuzzy criticality assessment model that present a risk function where *if-then* fuzzy rules are automatically generated. To take into account the uncertainty that often occurs in the evaluation of O, S, and D, the authors propose the fuzzy-technique for order preference by similarity to ideal solution (FTOPSIS) [56]. A combined FTOPSIS and fuzzy-AHP approach to FMECA is proposed by Kutlu and Ekmekçioğlu [57]. The fuzzy-AHP method is applied to weight the risk factors that are successively used within the FTOPSIS approach to obtain the final closeness coefficients on the basis of which failure modes are prioritized. Carpitella *et al.* [51] proposes a decision support tool, based on FTOPSIS and AHP, to perform a reliability analysis with relation to a subsystem, in which the process of eliciting judgments from experts did not contemplate a consensus obtained from a modeling of the differing decision-making power of each expert.

These modern techniques solve many RPN problems (see Table 1) using different analytical models, but usually introduce a complexity and a computational cost that may not be suitable for many companies. In particular, Fuzzy and Multi-Criteria approaches are extremely effective and powerful solutions, especially to solve the subjectivity problem and the relative importance of O, S and D. Despite of these advantages, this paper aim is to analyze the alternative methods that save the nature of the classical formula expressed by the standard IEC60812 considering only a simple combination of O, S and D without introducing other mathematical theory. Therefore, the following paragraphs compare the alternative RPNs, proposed in section III, on a real case.

VI. RISK ASSESSMENT FOR HVAC IN RAILWAY SYSTEMS

Heating, ventilation, and air conditioning (HVAC) is the technology of indoor and vehicular environmental comfort.

The objectives of HVAC systems are to provide an acceptable level of occupancy comfort and process function, to maintain good indoor air quality, and to keep system costs and energy requirements to a minimum [58]–[61]. With hundreds of commuters often crowded onto train carriages during peak hours, passenger comfort is a major concern for operators around the world. While train carriages can mitigate some of the misery of overcrowding with good design and punctual service, an efficient heating, ventilation and air conditioning system (HVAC) is the best way of regulating temperature and air quality on crowded trains [62]–[64].

The HVAC systems used in railway application are composed by several different components, the main ones are included in the diagram in figure 10.

This study focuses on the failure modes, effects and criticality analysis of some of the most critical components that make up the HVAC: compressor, evaporator blower and air flow detector.

TABLE 4. Failure modes and effects analysis for HVAC in railway application.

Component	Failure modes	Causes of failure	Local effects	Global effects	Effects on train
Compressor	FM1 - Motor does not start on demand	- Motor seize up. - Internal failure. - Blocked compressor. - Damage winding.	Loss of pumping capacity.	Loss of cooling function.	Loss of cooling capacity in the cabin.
	FM2 – Incorrect signal from thermostat	- Overheating of compressor. - Thermostat dirty.	Loss of protection	Possible damage of compressor.	Possible loss of cooling capacity in case of compressor damage.
	FM3 – Pump gas leakage	- Mechanical failure. - Fretting compressor.	Loss of refrigerant pumping.	Loss of cooling function.	Loss of cooling capacity in the cabin.
	FM4 – Sticking internal valve	- Internal failure. - Valve dirty.	The refrigerant gas doesn't increase the pressure.	Loss of cooling function.	Loss of cooling capacity in the cabin.
	FM5 - Internal overload motor protection	- Motor is short circuit. - Electric overload. - Compressor motor protection failure.	Loss of pumping capacity. Short circuit of compressor.	Loss of cooling function.	Loss of cooling capacity in the cabin.
Evaporator Blower	FM6 – Incorrect signal from thermostat	-Vibrations over specification. -Aging.	Motor does not work.	There is no ventilation and low pressure switch will cut off.	Loss of ventilation / cooling / heating capacity in the cab
	FM7 – Fails to run	- Internal failure. - Coil in short-circuit. -Lifetime of the motor (aging).	Motor does not work.	There is no ventilation in the evaporator coil and the pressure will increase.	Loss of ventilation / cooling / heating capacity in the cab
	FM8 -Mechanical crack	- Lack of oil. - Internal failure. - Bearings deteriorated. -Lifetime of the motor (aging).	Motor does not work.	There is no ventilation in the evaporator coil and the pressure will increase.	Loss of ventilation / cooling / heating capacity in the cab
Air Flow Detector	FM9 – The air pressure switch does not detect air flow when there is	-Internal failure.	-The heating coil is stopped during heating mode. -The compressor is stopped during cooling mode.	Loss of heating or cooling function, depending on the operating mode.	Loss of heating / Loss of cooling capacity in the cab
	FM10 - The air pressure switch detects air flow when there is no supply air	-Internal failure.	There is no detection of air flow.	Possible damage of the system. Possible overheating in the HVAC unit.	No effect

The compressor draws in the cold gases exiting the evaporator battery at low pressure and compresses them, so it comes out as gas at high pressure and overheated. The motor compressor is fitted with an electromagnetic valve to vary the capacity according to the demands of refrigeration load at any time.

Blowers are used to compress the water vapor for the purpose of raising its pressure and saturation temperature. This produces the desired heat transfer in the main heat exchanger for recycling the energy in the vapor, which greatly improves energy efficiency.

Air flow detector, due to the interaction with the streaming fluid, generates an electrically measurable signal for determination of the total flow of the fluid. The air flow sensor can alert to HVAC cooling system failures, or be used to ensure there is air flow through the cabins all times.

A. RISK ASSESSMENT USING 1 TO 10 SCALE

A real case of Heating, Ventilation and Air Conditioning system was analyzed using FMECA in order to test and validate the potentiality of the alternative RPNs proposed above. Table 4 includes all the items failure modes, the causes and the effects of each mode, the last one divided in ''Local effects'' (i.e. effects on compressor), ''Global effects'' (i.e. effects on the upper classification-level) and ''Effects on train'' (i.e. effects on the global system).

TABLE 5. Failure mode of HVAC in railway application ranked using classical and alternative risk priority numbers.

Failure Mode	O	S	D	RPN		IRPN		ERPN(3)		URPN(*e*)		LRPN	
				Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
FM1	8	6	7	336	3	21	2	9,477	4	22,592	5	2.527	3
FM2	3	5	4	60	10	12	10	351	10	1,780	9	1.778	10
FM3	6	6	7	252	6	19	6	3,645	7	16,944	6	2.401	6
FM4	5	6	5	150	7	16	8	1,215	8	10,085	7	2.176	7
FM5	4	6	5	120	9	15	9	1,053	9	8,068	8	2.079	9
FM6	8	8	4	256	5	20	5	13,203	3	95,390	3	2.408	5
FM7	9	8	6	432	1	23	1	26,973	1	160,971	1	2.636	1
FM8	8	8	5	320	4	21	2	13,365	2	119,238	2	2.505	4
FM9	7	7	7	343	2	21	2	6,561	5	53,735	4	2.535	2
FM10	7	3	7	147	8	17	7	4,401	6	984	10	2.167	8

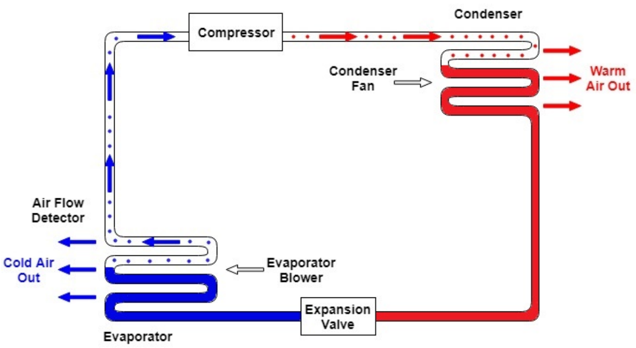

FIGURE 10. HVAC functional diagram.

The occurrence O, severity S and detection D of each mode were provided by three reliability experts in order to quantitatively consider the criticality of the components and included in table 5. According to the international standard [4] the O, S and D parameters can assume value in the 1-10 scale, the assessment follows the rules proposed in the standard. The occurrence values are assessed considering the failure rate of each failure mode (provided by the manufacturer), while the failure effects influence the severity values. The Detection is usually ranked in reverse order from the severity or occurrence numbers; the higher the detection number, the less likely the detection.

Table 5 is divided in six sections:

1) Occurrence, Severity and Detection assessment for each failure mode;
2) Classical RPN assessment (“value” column) and its decreasing ordering of the modes (“rank” column). The highest is the rank the highest is the criticality related to this failure mode;
3) IRPN assessment (“value” column) and its decreasing ordering of the modes (“rank” column);
4) ERPN assessment using base $x = 3$ and identical weights (set as 1) for the factors (“value” column) and its decreasing ordering of the modes (“rank” column),
5) URPN assessment using $z = e$ (“value” column) and its decreasing ordering of the modes (“rank” column);
6) LRPN assessment (“value” column) and its decreasing ordering of the modes (“rank” column);

The criticality assessment using the classical method leads to RPN values which vary in the first half of the admissible range (i.e. from 1 to 1000). The results are quite distant from each other: this lead to an easy prioritization of the mode from the highest RPN (most critical) to the lowest (least critical). A threshold value which distinguish the group of the most dangerous modes from the set of the least critical one could be identified comparing the data or by different mathematical approaches [14], [65], [66].

The IRPN scores vary in a limited range, leading to two main problems: item with the same values (e.g. Despite different O, S and D index FM1, FM8 and FM9 have the same IRPN = 21) and difficulty in the definition of a RPN threshold rate due to a very compressed scale of admissible results.

Both ERPN(3) and URPN(*e*) provide outcomes hardly comparable with the classical formulation because of the very wide admissible range. For the same reason the definition of a RPN threshold value is very critical: the gap between two high values is very large and the interpretation of the criticality related to these numbers is quite hard.

The LRPN is the only one that maintains the same prioritization ordering of the classical formulation. The results are irrational numbers compressed in a very small range.

For this reason, also in this case the definition of a threshold value is very critical.

Fig. 11 presents the results obtained from the analysis of table 5 highlighting how the different approaches provide different prioritization orders. The chart shows ten different groups composed by five bars with different colors where the groups stand for the analyzed failure mode, the colors represent the different techniques and the height of the bars identifies the criticality of the mode.

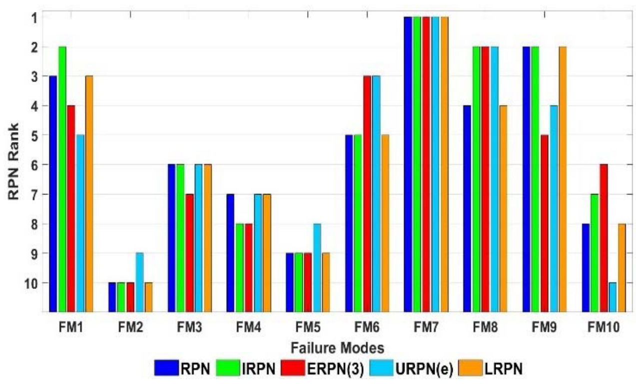

FIGURE 11. Bar plot of the classical and alternative RPNs ranking for each failure mode.

The height of a bar depends on the priority associated to that mode with the specified method: the higher the bar and more critical is the mode, therefore higher is the rank.

What is striking about Fig. 11 and table 5 is that the different approaches provide different ordering despite they consider the same O, S and D dataset. The most evident finding to emerge from the IRPN analysis is the duplicate issue, consequently the IRPN prioritization is meaningless because it is impossible to distinguish the more critical modes in presence of many identical values.

The ERPN amplifies the importance of higher values of O, S and D; for instance, FM8 moves from the fourth rank in the classical RPN prioritization to the second position in the ERPN rank, due to the very high value of O and S. In some circumstances, giving high priority to higher O, S and D values could be positive. The disadvantages are evident when only one value of O, S and D is close to 10: in this case the exponential formulation of the higher parameter is dominant making the other one negligible. The URPN amplifies the importance only of the severity, therefore if the severity is very high the mode will be definitely critical. For example, using this method FM6, FM7 and FM8 have the maximum priority because they are characterized by the highest severity of the system ($S = 8$).

In summary, these results show that the most reasonable prioritization order is the one provided by the classical Risk Priority Number.

B. RISK ASSESSMENT USING 1 TO 5 SCALE

The occurrence O, severity S and detection D were evaluated again considering a scale adjustment in order to test and validate the advantages and disadvantages of the 1 to 5 scale applied to the classical Risk Priority Number.

A new set-rule was defined for the assessment of the criticality indices of the failure mode included in table 4. The new O, S and D score are collected in table 6, while table 7 include a comparison between the results of the classical RPN assessment obtained using the standard scale and the reduced scale.

The differences between the two scales assessment are highlighted in Table 7. As the table shows, there is not a significant difference between the rank provided by the two approaches. There are only two small differences between the two data-set:

a The rank of the failure modes FM4 and FM10 are inverted: using the 1-10 scale FM4 and FM10 are the 7th and the 10th most critical modes respectively, instead the rank are swapped when the 1-5 scale are used.
b The failure modes FM1 and FM8 are characterized by the same RPN when the 1-5 scale are used: it results in two modes with the same rank.

TABLE 6. O, S and D assessment for the failure mode of HVAC in railway application using 1 to 5 scale.

Failure Mode	O	S	D
FM1	5	3	5
FM2	1	2	2
FM3	3	3	5
FM4	2	3	3
FM5	1	3	3
FM6	5	5	2
FM7	5	5	4
FM8	5	5	3
FM9	4	4	5
FM10	4	1	5

TABLE 7. Comparison of the ranks using 1 to 5 scale and 1 to 10 scale applied to classical risk priority number.

Failure Mode	1-10 scale RPN		1-5 scale RPN	
	Value	Rank	Value	Rank
FM1	336	3	75	3
FM2	60	10	4	10
FM3	252	6	45	6
FM4	150	7	18	8
FM5	120	9	9	9
FM6	256	5	50	5
FM7	432	1	100	1
FM8	320	4	75	3
FM9	343	2	80	2
FM10	147	8	20	7

The difference a) is negligible because affect two modes characterized by low Risk Priority Number. In fact, FM4 and FM10 are considered not critical mode, therefore the difference in the rank provided by the two approaches is not significant. Quite the opposite, the difference b) is very relevant because highlights that the scale reduction could involves in a duplicates problem.

This result is somewhat counterintuitive. The most surprising aspect of this difference is that the percentage of unique value using the 1-5 scale is doubled respect to use the 1-10 scale. Theoretically, reducing the scale, the number of duplicates decrease. Actually, the use of a small scale involves more duplicates in the O, S and D assessment, consequently the possibility of a duplicate in RPN evaluation increase.

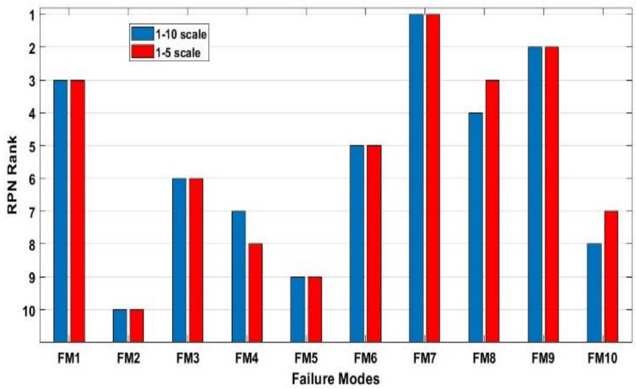

FIGURE 12. Bar plot of the RPN ranking using 1-10 scale and 1-5 scale for each failure mode.

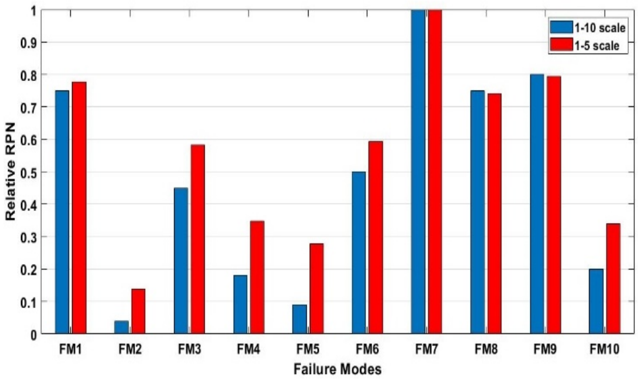

FIGURE 13. Bar plot of the relative Risk Priority Number obtained using the classical RPN approach and the 1-5 scale RPN.

The probability of a duplicate generated by the same combination of O, S, D increases using 1-5 scale while the probability of a duplicate generated by different combination of O, S, D decreases.

Taken together, these results suggest that there is a benefit in the use of a reduced scale in term of unique values, but it is very important to pay specific attention to the Occurrence, Severity and Detection assessment in order to cover the complete admissible range of the parameter and reduce the possibility of a duplicate in the Risk Priority Number.

The results obtained in table 7 are summarized in Fig. 12, using a bar plot illustrating ten different groups composed by two bars with different colors where the groups stand for the analyzed failure modes, the blue bar represents the 1-10 scale assessment and the red bar stands for the 1-5 scale evaluation. The higher the bar, higher is the rank associated to that mode (i.e more critical is the failure modes).

Fig. 13 shows another comparison of the Risk Priority Numbers obtained in the previous assessments, where the height of the bars stands for the relative RPN, expressed as the ratio between the Risk Priority Number of that mode divided by the maximum RPN of the analysis.

Considering the critical failure mode (i.e. the mode characterized by high relative RPN) no significant differences were found between the two approaches. Quite the opposite, analyzing the modes with low Risk Priority Number there was a significant difference between the two method. This means that, in proportion, the reduced scale affects more the assessment of the lower RPNs compared to the higher RPNs.

VII. CONCLUSION

The aim of the present research was to examine the different approaches presented in literature regarding the evaluation of alternative risk priority numbers. Several methods currently exist for the assessment of the criticality of modes during a FMECA. These alternative approaches try to compensate the multiple issues related to the classical RPN interpretation, such as: holes, duplicates, dispersion etc.

The paper focuses on the techniques which do not introduce additional corrective factors or do not completely distort the formulation of the RPN with the introduction of new analytical theory.

The analyzed approaches are: RPN, IRPN (consists of the sum of O, S, D), ERPN (based on the exponentiation of O, S, D), URPN (consists on the product of O, D and S as power) and LRPN (based on the logarithm of the product of O, S, D).

The advantages and disadvantages of each techniques are evaluated by using a chart of all the possible values obtained combining O, S, D according to each procedure. This study has identified that no one method succeeds to solve all the issues and the solution of one problem involves the worsening of the other drawbacks.

The previous methods are analyzed also considering a reduced O, S, D scale from 1 to 5. This reduction does not solve the problems but mitigates all of them, therefore it represents a trade-off through easiness of implementation, accuracy of results, flexibility to different application field, solution of the issues.

Moreover, the work presents an overview regarding fuzzy theory and multi-criteria approaches to solve some of the RPN issues. These models allow the designers to mitigate the subjectivity and the relative importance of the O, S and D factors. Industrial companies objective is to achieve the optimal result in the most time and cost effective way. Therefore, fuzzy and multi-criteria approaches are not always very suitable for industrial application even though they are a powerful solution to identify the optimal rank of the failure modes in term of criticality.

In order to test and validate these assumptions, a FMECA was developed for the critical components of a HVAC system used in railway applications. These results show that the RPN is the most trustworthy equation because it provides the most reasonable prioritization order of the failure modes.

The different approaches provide different orderings despite they consider the same O, S and D dataset: the IRPN includes many duplicates, the ERPN amplifies the importance of higher values of O, S and D and the URPN amplifies the importance only of the severity.

Anyway, all the methods agree with the most critical failure modes of the system: the electrical failure of the evaporator blower (FM7).

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