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A new method for risk assessment in industrial processes

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Abstract: Safety is one of the most important issues in modern industrial plants and industrial activities. The Safety Engineering role is to ensure acceptable safety levels of production systems, not only to respect local laws and regulations, but also to improve production efficiency and to reduce manufacturing costs. For these reasons the choice of a proper model for risk assessment is crucial. In this context, the present research aims to propose a new method, called Total Efficient Risk Priority Number (TERPN), able to classify risks and identify corrective actions in order to obtain the highest risk reduction with the lowest cost. The main scope is to suggest a simple, but suitable model for ranking risks in a company, to reach the maximum effectiveness of prevention and protection strategies. The TERPN method is an integration of the popular Failure Mode Effect and Criticality Analysis (FMECA) with other important factors in risk assessment.

Keywords: risk priority number, safety, FMECA, cost, prevention, protection

1. INTRODUCTION

The most critical aspect related to safety at work is the identification, assessment, and reduction of risks (Fera et al. 2010) The engineering field has always emphasized safety, and it is common in safety management to use the concept of risk and risk assessments. However, as outlined by Aven (2016), from a scientific perspective, research related to risk management is a relatively recent development, i.e., in the last 30-40 years. Risk can be defined as the probability of suffering harm (injury, disease, death) from a hazard that directly or indirectly contributes to occupational risk. Several traditional risk management tools have been proposed and are used extensively. But, it is important to note that, originally, the practice of risk assessment was driven by regulatory authorities to fulfill legislative mandates (Whittaker, M.H., 2015). Currently, this approach is changing because companies have both an administrative duty and a social duty to conduct risk assessments of their activities. Complex industrial facilities, especially, should be assessed frequently using analytical assessment methods (Garbolino, et al., 2016). Another weakness is related to the Risk Priority Number (RPN) (Carmignani, 2009). According to the consideration of previous approaches, in our opinion it is necessary to develop a new, integrated approach to improve the FMECA technique. Our aim was to implement an FMECA project in terms of cost in order to define the priority for the selection of the corrective action. To solve this problem, the multi-criteria decision making approach has been proposed in the literature. Among multiple-criteria decision-making methods (MCDM), the Analytic Hierarchy Process (AHP), introduced by Saaty 1980, is a well-known and common method that is used for its simplicity. The AHP helps to manage the "uncertainty" that is a key concept in risk conceptualization and risk assessments. The scope is to identify, through the AHP, the most critical and essential contributors to risk management. For example, Liu *et al.* (2015) combined the FMEA with MCDM methods; in their research, the scale effects of the AHP were analyzed, and an index scale method was selected in order to improve the FMECA scale. Also, Chen and Wu (2013) modified the FMEA by applying the AHP method. Bevilacqua and Braglia (2000) [used the AHP to select the maintenance strategy for an Italian oil refinery. Lin *et al.* (2014) presented feasibility research for improving the traditional FMECA method with the AHP. Zhang *et al.* (2013) proposed an approach to evaluate the risk-of-failure mode by the encouragement-variable-weighted analytic hierarchy process (EVW-AHP). Trucco *et al.* (2012) proposed a standardized FMECA and the risk factors monitoring method. In their research, the AHP technique was used to calibrate the Severity Scale. Zammori and Gabbrielli (2012) integrated FMECA and the AHP approach so that the criticality assessment could take into account the possible interactions among the principal causes of failure. Starting from our previous work, the aim of this research was to propose a methodological approach simpler but equally efficient for ranking risks in a company, in order to reach the maximum effectiveness of prevention and protection strategies. The proposed model is based on FMECA, and it includes other factors (cost, effectiveness, prevention, etc). Definitively, the main scope of this work was to present an integrated approach, which we called **Total Efficient Risk Priority Number (TERPN).**

The proposed method will be simply to apply, such as the Farmer and FMECA methods, but effective (risk reduction) and efficient (safety costs reduction) as the AHP method.

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2. RISK ASSESSMENT METHODS

The risk is always defined as a function of probability of occurrence and magnitude (severity of damage) related to the single danger (Equation 1):

$$R = f(O, S) \quad (1)$$

- R: the risk level;
- O: probability of occurrence of a damage event;
- S: magnitude of the event.

All risk assessment methods follow the same, even if they differ by purpose, completeness and use,. The procedure involves the systematic identification of all dangers related to the activity under investigation and the linked risk factors, estimating the risk for each identified hazard and defining priorities for corrective action. The risk assessment methods can be classified as follows:

- ***Quantitative methods***: based on quantitative analysis of the risk R = f (O, S). The "f" function can take on a complex shape as it can take into account many parameters related to the risk.

- ***Qualitative methods***: based on subjective analysis of compliance with current regulations (HAZOP Analysis).

- ***Semi-quantitative methods***: based on a quantitative analysis, where the risk R = f (O, S), with simplified approach. Available data are recorded during the investigation and the comparison parameters are prescribed by technical standards, always dependent on the probability of occurrence and the magnitude for resulting damage (Farmer Method, AISS Method and FMECA).

- ***Multi-criteria methods***: allow to consider several factors simultaneously through a hierarchical structure. They allow a synthetic view of risk perception, while maintaining a quantitative nature and not reducing analysis factors (SIRA method).

2.1 Hazop Analysis

HAZOP is a procedure to identify any risks or functional problems in an industrial plant. The HAZOP is based on the creation of a multidisciplinary group that seeks to identify hazards and operating problems. Basically, this methodology identifies the initial events of the "worst case".The advantages of HAZOP Analysis are:

- High level of completeness;
- Effectiveness both in the management and design phase.

The disadvantages of HAZOP Analysis are:

- Need for a team with great knowledge in plant engineering field;
- Gaps in the identification of human errors.

2.2 Farmer method

The first studies in Europe on safety in industrial plants were carried by Professor Farmer. He linked the frequency of a damaging event resulting from a risk with its possible consequences. Thus a quantitative risk assessment was provided by defining a 'probability' scale and a 'Magnitude' one by identifying a risk level R (equation 2)

$$R = O \times S \quad (2)$$

Where:
O = frequency of occurrence of the risk event;
S = amount of damage (to persons and property) caused by the risk event.
It is a semi-quantitative method, potentially affected by a lack of objectivity and by the difficulty of comparing different risk effects.
The advantages of Farmer's method are:

- simple mathematical model;
- easy evaluation of O and S indexes;
- easy application.

The disadvantages of Farmer's method are:

- risks with low O value and high S value may be underestimated;
- subjective evaluation;
- small number of indexes (only O and S) for risk assessment.

2.3 Association Internationale de la Sècuritè Sociale (AISS) Method

The model provides a quantitative risk evaluation carried out by assigning numerical values to the factors: machinery, environment and operator.
In the first phase the overall risk of the workplace is assessed by applying the equation 3:

$$Rg = Ma \times Env \quad (3)$$

where:
Ma: risk related to machine
Env: impact of the work environment
The risk related to the machine (Ma) is evaluated by the product of four factors (equation 4):

$$Ma = Pd \times Ex \times Pr \times Ev \quad (4)$$

where:
Pd: Dangerous events (range 1 – 10)
Ex: Frequency and exposure duration during operation (range 1 – 10)
Pr: Probability of occurrence of a dangerous event linked to the "material" (range 0.5 - 1.5)
Ev: Probability of avoiding or limiting injury range 0,5 - 1
The risk related to the environment (Env) is evaluated by the sum of three other factors (equation 4):

$$Env = Qa + Qb + Qc \quad (5)$$

where:
Qa: Location (range 0,5 – 1);
Qb: Work environment (range 0,5 a 1);
Qc: Probability of occurrence of a dangerous event linked to the "machine".

The advantages of AISS method are:

- accurate mathematical model;
- identification and evaluation of a large number of factors for risk assessment;
- easy application.

The advantages of AISS method are:

- Subjective evaluation

2.4 The Failure Mode, Effects, and Criticality Analysis (FMECA)

The FMECA method originally was developed by the U.S. military. The reference was 'Military MIL-P-1629,' entitled "*Procedures for the Analysis of Failure Modes, Effects, and Criticality,*" dated November 9, 1949. This method was used for evaluating failures to determine the reliability of equipment and systems. The failures were classified according to their impact on personnel and the success of missions for the security of equipment. This methodology is very important because the performance and competitiveness of manufacturing companies is dependent on the reliability and availability of their production facilities. Accumulated information about design and process failures recorded through FMECA provides very valuable guidance for future product and process design. As a result, equipment down time, quality problems, slower production rate, safety hazards, and environmental pollution are the obvious outcomes. These outcomes have the potential for negative impacts on operating cost, profitability, customers' satisfaction, productivity, and other important performance requirements (Di Bona et al.,2021).

The RPN method is preferred mostly by the manufacturing industries, such as automotive companies, domestic appliance firms, and tire companies. The RPN criticality calculation uses linguistic terms to rank the probability of occurrence (O), the severity (S) of the consequences, and the probability of detection (D) on a numerical scale from 1 to 10. Well-known "conversion" tables report the typical basis for the linguistic judgment scales used to estimate the three quantities that are used to calculate the RPN value in the following manner (Equation 6):

$$RPN = \text{Risk Priority Number} = S \times O \times D \quad (6)$$

The RPN attributes a weight to each failure mode under consideration. This parameter makes it possible to classify failures in order of importance. This is often fulfilled by calculating the Risk Priority Number (RPN), which is the basis for risk ranking/prioritization and helps managers to make decisions. This is an extensively-used expression in industrial practices.

For risk management, the technique has some advantages, i.e.,:

- Easy to understand and to use because of its simplicity
- Well documented
- Appropriate for training
- Systemic and systematic for rapid decision taking

Unfortunately, from a technical perspective and in the interpretation of results, the technique has some disadvantages in practice. The product of the RPN factors produces some holes in the scale;

- The RPN numbers are duplicated. In other words, different combinations of ranking factors produce the same RPN and only 120 out of the 1000 numbers generated are unique;
- There is a high sensitivity to small change in factors' values caused by the effect of the multiplication of the RPN factors.

2.5 The Analytic Hierarchy Process: Safety Improve Risk Assessment (SIRA) Method

A decision making problem consists of n alternatives $A_1, \ldots, A_n$ and m criteria $C_1, \ldots, C_m$. The AHP procedure defines the relative importance of each criterion. For this purpose, pairs of criteria are compared to determine and measure which of them is more important. The result c (ij) of the comparison, known as the dominant factor, represents an estimate a the criterion i compared to j (i, j = 1,.. .m). The numerical values of the pairwise comparisons are measured using the Saaty semantic scale (Di Bona et al.,2021). The result of the pairwise comparisons, that provide the relative importance between the elements, is a matrix structure such as that below.

Through the calculation of the eigenvalues and eigenvectors, the absolute priority weights (vector w) are determined. Each element of the vector w represents the degree of influence of the single element. Following the hierarchy, the risk R can be placed at the top, while the evaluation criteria will be placed in two layers below, according to the example (Fig. 1).

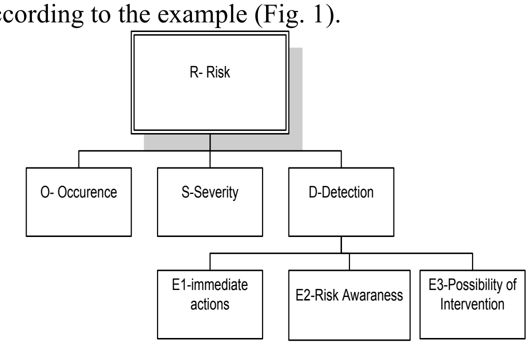

Figure 1: AHP model for risk assessment

According to the model, the equation to calculate R is (equation 7):

$$R = w_d \times D + w_f \times F + w_e \times E \quad (7)$$

where w_d, w_e, w_f are the weights relating to D, E and F. The same calculation is done for each lower level of the model. The ranking list of dangers is obtained, by multiplying the weights assigned to each level of risk for their weights of the hazard function and adding to each other the obtained results. Through this procedure a synthetic risk index is obtained for each source of danger and for each type of hazard. This index is used to compare the various parameters and thus to make choices of action based on the set priorities.

The advantages of SIRA method are:

- Integration between objective and subjective factors;
- Risk assessment based on a hierarchical level;
- Assessment through distributions of point values.

The disadvantages Method SIRA are:

- Strong link between result and hierarchical structure;
- difficulties of application.

3. TOTAL EFFICIENT RISK PRIORITY NUMBER (TERPN): THE METHODOLOGY

One of the most critical aspects of the FMECA methodology, which also is greatly contested by the authors, is that this kind of analysis fails to take into consideration extremely remarkable factors, such as the economic aspect of the failure modes. Indeed, the RPN index is not actually correlated to a risk estimable in economic terms, so it does not succeed in appraising the convenience of the corrective actions in a right way. Another aspect is the focus of the analysis, which is concentrated on equipment security rather than operators' safety. In fact, the reduction of safety problems is an end point of the analysis (corrective actions for more critical failures) and not a starting point. This paper presents a new risk analysis methodology for complex systems. It provides support to improve occupational safety and health in the simplest way possible, taking less time and less human and financial resources.

The purpose of this research is to develop a methodology for risk analysis and risk assessment with the following features:

- Easy to apply;
- A significant number of factors for risk assessment;
- Accuracy in the risk assessment.

The proposed method is a valid support for SMEs, where the application of complex methods would be difficult and expensive. The new model aims to obtain accurate results as the complex methods (SIRA) through a simple mathematical structure (Farmer and FMECA Methods) and through a proper number of factors (Method AISS). Therefore starting from FMECA Method, an integration with other factors based on effectiveness and cost of corrective actions was developed, in order to value a new RPN, called ERPN, Efficient Risk Priority Number. The main steps of the ERPN Methodology as follows:

Step 1. Identification of risk areas of analysis concerning:

- Tasks
- Machines
- Products

Step 2. Identification of the risks present in the above areas of analysis:

- Risks related to the safety of workers
- Risks related to the health of workers
- Risks related to management organizational aspects
- Risks related to product quality

Step 3. FMECA Analysis and evaluation of Probability (P), Severity (S), and Detection (D) for each area of analysis, where:

- $1 \leq O_{tasks} \leq 10$, $1 \leq S_{tasks} \leq 10$, $1 \leq D_{tasks} \leq 10$
- $1 \leq O_{machines} \leq 10$, $1 \leq S_{machines} \leq 10$, $1 \leq D_{machines} \leq 10$
- $1 \leq O_{products} \leq 10$, $1 \leq S_{products} \leq 10$, $1 \leq D_{products} \leq 10$

Subsequently, we evaluate the RPN Index for the areas of analysis:

- $RPN_i = O_i \times S_i \times D_i$; i=1….n
- $RPN_j = O_j \times S_j \times D_j$; j=1….m
- $RPN_k = O_k \times S_k \times D_k$; k=1….h

Step 4. Evaluation of the ERPN Index for each area of analysis:

Therefore the new procedure suggests an integration of RPN Index with other factors (Equation 9) and the definition of a new index called ERPN - Efficient Risk Priority Number:

$$ERPN = \frac{S \times O \times D \times P \times E}{C} = \frac{RPN \times P \times E}{C} \tag{8}$$

where

- S: Severity
- O: Occurrence
- D: Detection
- P: Prevention
- E: Effectiveness
- C: Cost

Prevention Factor (P)

First of all, according to the Cost-Effectiveness curve, in order to improve safety, we need to give a greater weight to prevention interventions, even if protection is also important to reach effectiveness maximization. So we have to put our attention on risks characterized by more opportunities of prevention. The possible scale of "P" value (from 1 to 10, like for the other factors of RPN) is showed in the following table. (Table 1).

Table 1: Scale of values for P index.

Opportunity	Criterion	"P" Value
Very Low	*No prevention action is possible*	1
Low	*Few preventions actions are possible*	2.5
Medium	*Some prevention action are possible*	5
High	*Many prevention actions are possible*	7.5
Very high	*A lot of prevention actions are possible*	10

Effectiveness Factor (E)

The second factor is the effectiveness of safety strategies (e.g. % of reduction of accidents), thanks to the implementation of preventive and/or protection actions. In order to value this factor the following check list is proposed (Table 4). We have to assign a value 1 or 0 respectively if the answer is Yes or No to each of the ten listed questions (again "E" value scale from 1 to 10).

Table 2: Check list for identifying the effectiveness of prevention/protection strategies

Questions	**Yes/No***	**Comment**
1. Has the risk been clearly understood?		
2. Do the prevention/protection strategies consider all the available information on the risk?		
3. Do the prevention/protection strategies meet the organization's criteria?		
4. Are the prevention/protection strategies in accordance with the organization's policies and procedures?		
5. Do prevention/protection strategies take into account the need to protect life, property and the environment?		
6. Are the prevention/protection strategies easy to implement within a required time frame?		
7. Is the associated administration of the prevention/protection strategies achievable?		
8. Is the person in charge easily identified?		
9. Have other risks that may be created by the prevention/protection strategies been considered?		
10. Are the prevention/protection strategies easily understood?		
TOTAL "E" Value		

** The supervisor has to complete the checklist for each risk identified with the below values:*
Yes = 1; No = 0

Cost Factor (C)

The last but not the least factor considered is the cost of corrective actions. In this case, the idea is to assign the "C" value considering the intervention cost for the specific risk, expressed in terms of % of the total annual budget fixed by the company for safety strategies. The factor in (9) appears in the denominator, because of its opposite effect. Therefore the scale is showed in Table 3.

Table 3: Scale of values for C Index

% of Annual Budget for Safety	**"C" Value**
1-10%	1
11-20%	2
21-30%	3
31-40%	4
41-50%	5
51-60%	6
61-70%	7
71-80%	8
81-90%	9
91-100%	10

Step 5. Evaluation of the TERPN Index for each area of analysis:

- $TERPN_{tasks} = \sum_{i=1}^{n} ERPN_i$
- $TERPN_{machines} = \sum_{j=1}^{m} ERPN_j$
- $TERPN_{products} = \sum_{k=1}^{h} ERPN_k$

Step 6. Evaluation of the Global TRPN Index (equation) for the whole company:

$$TERPN_{global} = TERPN_{tasks} + TERPN_{machines} + TERPN_{products} \quad (9)$$

Step 7. Based on the ranking ERPN values, the corrective actions for the company's risk reduction are identified; subsequently the new values of TERPN* are evaluated after the adoption of the chosen corrective actions $(TERPN^*_{tasks}, TERPN^*_{machines}, TERPN^*_{products})$. Then we have:

$$TERPN^*_{global} = TERPN^*_{tasks} + TERPN^*_{machines} + TERPN^*_{products}$$

Total Cost of Intervention

$$C^*_{global} = (C^*_{tasks} + C^*_{machines} + C^*_{products}) \leq SafetyBudget$$

$$IRPN^*_{global} = \frac{TERPN_{global} - TERPN^*_{global}}{TERPN_{global}} \%$$

4. DISCUSSION AND CONCLUSIONS

The risk analysis methodologies focus on the main hazard sources, in particular major values of RPN in the case of FMECA. But the actions on risks characterized by the highest RPN values, or in general probability and/or severity, does not always allow: 1) the greatest reduction of accidents; 2) significant impact on productivity, image and cost of insurance for businesses. Even if the law does not specify which procedure must be followed in carrying out the risk assessment, the choice of a particular method is fundamental, in order to drive the subsequent right actions of prevention and protection. RPN uses descriptive terms to rank the probability of the occurrence (O) of the failure, the severity (S) of the consequences and effects, and a probability of failure detection (D). All three factors are then multiplied to give RPN = S x O x D, result ranging from 1 (low priority) to 1,000 (high priority). The methodology in the present work suggests an integration of FMECA factors with new ones, linked to effectiveness and cost aspects. The idea is to put the analyst's attention not on those risks characterized by the highest values of RPN, but on the real possibilities of risk reduction.

The major advantages of the proposed approach are:

- The possibility of considering different factors jointly and not in parallel;
- A very simple mathematical formulation based on a simple multiplication of the factors' scores, that encourages its adoption by the analyst;
- The necessity of considering the correlation existing among criteria, in particular effectiveness of prevention and protection actions linked with the corresponding costs.

The main result achieved is the realization of a method to select the best mix of failures to be repaired with respect to the budget made available by the firm.

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