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TECHNICAL PAPER

Using fuzzy logic to reduce risk uncertainty in failure modes and effects analysis

Jéssica de Aguiar[1] · Regis Kovacs Scalice[2] · Danielle Bond[1]

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Abstract

Failure modes and effects analysis (FMEA) is used in product design as a systematic analysis tool that aims to identify and evaluate potential failure modes, their causes and effects. However, vital information for FMEA, such as consumer needs and expert opinions, is often uncertain or vague in the product design phase. On the other hand, fuzzy logic is a technique that has been used to overcome the absence of concrete data and generate robust results to drive decisions from uncertainties. In this sense, this paper proposes a methodology that combines the concepts of fuzzy logic and product FMEA. In the proposed approach, the parameters severity, occurrence and detectability are evaluated in a fuzzy inference system. Its applicability was investigated with the help of an illustrative case study. Fuzzy FMEA was carried out to prioritize risks on one module of a Jerusalem artichoke processing equipment. The results provide an alternate ranking to that obtained by the traditional method. The conclusion is that the proposed methodology enables experts to combine occurrence probability, severity and failure modes detectability in a more flexible and realistic manner by using their judgement and experience.

Keywords Failure modes and effects analysis (FMEA) · Fuzzy logic · Product design

1 Introduction

Due to strong competition in the global market, there is a growing demand for high-quality and low-cost products. In addition, because of the market's dynamism, corporations must respond to customer expectations within a short development time. Therefore, more effective product development strategies should gain prominence [1]. Companies should focus on quality, cost and reliability in their product development process. Product quality and reliability are critical to the final product's functional performance. To meet the reliability requirements, the failure modes and effects analysis (FMEA) is a tool used during the product development phase [2].

In some works [3], the term FMECA, which stands for failure mode, effects and criticality analysis, is commonly found. The main difference between FMEA and FMECA lies in the fact that the former is more closely related to the qualitative aspect, being widely used in project evaluation, while the latter includes a criticality analysis. Criticality analysis is a quantitative method to classify the modes and effects of critical failures, considering their probability of occurrence. For practical purposes, we consider FMEA and FMECA as the same procedure, since the use of FMEA is commonly associated with the criticality risk assessment.

FMEA is an analytical method that lists all potential sources of failure, and then assigns a weighted score called risk priority number (RPN). The RPN is the result of the multiplication of three failure parameters: severity (S), occurrence (O) and detectability (D). FMEA is used to ensure that all design failure modes have been considered and evaluated to be reduced and even eliminated, thus ensuring product's quality and reliability [4].

Technical Editor: Dr. Fernando Antonio Forcellini.

✉ Regis Kovacs Scalice
regis.scalice@ufsc.br

Jéssica de Aguiar
jessicadeaguiar@gmail.com

Danielle Bond
danielle.bond@udesc.br

[1] Universidade do Estado de Santa Catarina – UDESC, Rua Paulo Malschitzki, 200 Zona Industrial Norte, Joinville, SC CEP 89219-710, Brazil

[2] Universidade Federal de Santa Catarina, R. Dona Francisca, 8300 - Bloco U, Joinville, SC CEP 89219-600, Brazil

Despite the wide use of the traditional FMEA, such technique has been extensively criticized in the literature, mainly for the use of RPN. Different combinations of S, O and D may produce the same value of RPN, but their hidden risk implications may be totally different. Another disadvantage of the RPN ranking method is that it neglects the relative importance between S, O and D. The three factors are assumed to have the same importance, but in real applications their importance is relative [5].

To fill the gaps presented by the FMEA application, the literature show studies on the development of techniques that aim to complement it through innovative concepts, such as fuzzy rule-based system, grey theory, cost-based model and linear programming [5].

Regarding the fuzzy rule-based system, the fuzzy logic, originally introduced by Zadeh [6], makes it possible to perform information processing much like human reasoning, in which approximate and uncertain information is used to make decisions. The fuzzy logic was developed to mathematically represent uncertainty and imprecision and provide a formal tool to deal with the intrinsic inaccuracy of many problems [7].

A systematic literature review ("Appendix A" section) identified 61 articles relating FMEA and FMECA to fuzzy logic, 47 of which in the last 10 years, evidencing the topic's increasing relevance. Among those, only 13 mentioned the Mamdani inference system, a central element of our proposal, and only 5 [8–13] were related to FMEA. From that bibliographic portfolio, we analyzed the work that directly addressed the use of the Mamdani inference system to determine the number of risk priorities in FMEA, in order to compare the perceived opportunity of research to that observed in the literature. Each of those five articles proposes Mamdani inference models associated with the FMEA for applications in different areas such as civil construction, nuclear engineering systems, production systems and product design. To model each FMEA tool with fuzzy logic, the authors need to develop different elements that compute the fuzzy inference system, such as linguistic terms, pertinence functions and base rules. However, our work stands out from previous ones due to a combination of adopted linguistic terms and the pertinence function for the input and outputs, the developed base rules and the use of the Mamdani inference system.

The literature review shows that the union of the traditional FMEA with the fuzzy logic has been able to overcome the problems presented by the traditional tool. Thus, in this work, a methodology is proposed that integrates the concepts of product FMEA and fuzzy logic.

This paper is organized as follows: initially, it briefly contextualizes the two main topics in this study, FMEA and fuzzy logic, followed by a literature review on fuzzy logic applications in FMEA. Next, the stages of the proposed risk evaluation methodology are presented and an example is provided to illustrate the potential applications of the proposed fuzzy FMEA. Finally, conclusions, limitations and opportunities for further research are presented.

2 Literature review

2.1 Failure modes and effects analysis (FMEA)

The failure modes effects analysis (FMEA) is one of the most adopted techniques of failure analysis. FMEA is an analytical technique to systematically identify and document possible failures, in order to classify them according to their severity and thus describe actions to eliminate or reduce their occurrence. Such methodology can be applied to help identify potential failures in products, systems, processes or services, providing subsidies to guide decisions aiming to increase reliability [14].

Product FMEA is a tool used to analyze projects before they become products. The focus is on failure modes caused by deficiencies from the project's specifications. Its purpose is to avoid product or process failures resulting from the design. This type of FMEA can also be called development or design FMEA [14].

Product FMEA is used by the team responsible for product design to ensure that potential failure modes, as well as their causes and effects, have been considered. During its application, the final products, systems, subsystems and components can be evaluated. In other words, product FMEA is a summary of a team's thoughts about the behavior of a product, system, subsystem or component through an analysis of items that could fail based on experience and past problems. That systematic approach evaluates, formalizes and documents the specialists' line of thinking during a project's development [15].

According to Teoh and Case [2], due to the lack of information in the early stages of design (such as in conceptual design), the FMEA is generally developed during the detailed design phase. At such stage of the development cycle, the product's detailed description, the prototype's construction process specification and materials used take place. That project stage differs from the previous ones due to the corrections implemented, which are based on the project evaluation and a greater perception of the product's functionality. However, at such stage, design changes produce high costs, which end up reducing the tool's efficiency, sometimes being applied only to comply with contractual requirements from customers.

On the other hand, when the FMEA is applied in the conceptual design stage, in addition to the difficulty in obtaining accurate information, it is difficult for the traditional FMEA to cope with frequent design changes. With that in mind, some researchers [16, 17] have proposed different tools to make the FMEA more useful in the conceptual design phase, such as the application of some form of graphical diagrams or object representations for both functional and structural models. The advantage of using the graphical or object-based approach is that less detail is required to create the structural model.

The process of traditional FMEA is well established in the literature, including in several books [4, 18, 19], and focuses on determining the risk priority number (RPN) based on the failure severity rating (S), the occurrence probability (O) and the detection difficulty (D) for each possible failure mode.

Although traditional FMEA has been proved to be one of the most used tools for failure analysis, the conventional RPN method has been extensively criticized in the literature for a variety of reasons. Some of FMEA's major shortcomings are: the relative importance of O, S and D is not taken into consideration; RPNs are not continuous, with many holes, interdependencies among various failure modes and effects are not taken into account, different combinations of O, S and D may produce exactly the same value of RPN, but their hidden risk implications may be totally distinct [20].

2.2 Fuzzy logic

Zadeh [6] developed his methodology based on the assumption that the treatment of complex systems through conventional approximations did not lead to efficient results, because mathematical languages are not able to express relations between inputs and outputs in inaccurate information environments. As a solution to that gap, the author developed a logic that uses the concept of a value's degree of relevance in a given set. That way, a more expressive and flexible mathematical language is generated, capable of characterizing and inferring imprecise relations, as is the case of human judgement.

The fundamental difference between the fuzzy and the classical logic is in the capacity to understand values. While classical logic is bivalent, that is, it only recognizes two values (true and false), fuzzy logic is multivalent (it recognizes innumerable values), ensuring that the truth is a matter of point of view, and different degrees of veracity are possible to exist in a numerical range [21]. In classical logic, the sets are well defined, that is, an element may or may not belong to a set, and if it does, it does to only one. In fuzzy logic, the same element may belong to more than one set, also called fuzzy sets. According to the fuzzy logic, an element belongs to a fuzzy set with a certain degree, and thus there is a membership function $\mu_A(x)$, which defines the degree of relevance of an element x in a fuzzy set A. The membership function takes any present value in a real and continuous range of 0–1. There are infinite values within that range that may represent degrees of membership [22].

2.3 Related work

In order to fill the gaps presented in the application of the traditional FMEA, the literature has shown studies in the development of methods that add the fuzzy logic to it [1, 16, 23, 24].

Peláez and Bowle [16] focused on difficulties in applying the FMEA due to the lack of consistent information during the product design phase. The authors developed a method to deal with the vague nature of information by performing simulations to model the behavior of the system, and then apply the FMEA. This simulation is performed using the fuzzy cognitive maps (FCM) method, which uses graphs to present cause–effect relationships. Hence, the graphs can represent the causal relationships necessary for the elaboration of the FMEA and provide a new strategy to predict the effects of failures in complex systems.

Another question raised by the authors [1, 24, 25] is related to the RPN's reliability as a decisive factor to guide the actions of the project. According to Chin et al. [1], in some situations, the evaluation of the traditional FMEA through the RPN makes it difficult to determine the level of influence of a given cause on the failures of a product. To circumvent that limitation, the authors decided to apply the fuzzy logic to quantify, by means of linguistic variables, the specialists' evaluation on the indices that compose the RPN and, then, calculate the risk.

Pillay and Wang [25] developed a method to subjectively assess risks, which eliminates the need for a function to define the severity, occurrence and detection indices, thus avoiding the use of the traditional RPN. To achieve that, they applied an FMEA based on fuzzy logic (approximate rationalization probabilistic logic) combined with the grey theory. This theory explores the system behavior using relationship analysis and construction models. It also deals with making decisions about incomplete information. In such way, the model developed by the authors generates an RPN through the formal integration of the information coming from specialists, who are able to classify the potential causes identified in the FMEA in terms of their importance.

Wang et al. [24] developed a fuzzy FMEA methodology to carry out risk prioritization without using constant specialists' opinion. To do so, the indices that make up the RPN risk were treated as fuzzy variables and evaluated using linguistic terms instead of a classic RPN, thus obtaining a fuzzy RPN or a fuzzy risk priority number (FRPN). The FRPN is the geometric mean of the risk indices' fuzzy weights and is used to determine the risks that should be highlighted when determining preventive methods. Therefore, this methodology can transform the specialists' qualitative opinion in quantitative information, facilitating the product's risk evaluation.

In addition to being studied to predict product failures, the combination of the FMEA with fuzzy logic can be used to ensure compliance with standards. Hu et al. [26] performs the integration of the FMEA and fuzzy analytical hierarchy process (FAHP) methods to perform component risk analysis against compliance with the directives of the European Restriction of Hazardous Substances (RoHS). The FAHP is applied to determine the weights of four factors necessary for the application of the FMEA: occurrence, detectability, severity and frequency. From those indices, the Green Components Risk Priority number (GC-RPN) is calculated, which points out the components that must undergo improvements to comply with the green product guidelines.

Different authors have used the Mamdani inference system to improve the FMEA technique [8–13]. Guimaraes and Celso Lapa [8] introduced a modeling technique based on a fuzzy inference system to FMEA, to address nuclear reliability engineering problems. Ben Romdhanea, Badreddineb and Sansa [9] used the concept of fuzzy logic along with FMEA and other quality tools to propose a new Six Sigma implementation model for small- and medium-sized companies. Savino et al. [10] modified the FMECA methodology through the application of the Mamdani inference system in which the criticality assessment is performed considering both the production performance and the safety of users/workers. To reduce or prevent occupational hazards in the construction industry, a diffuse risk assessment method was proposed by Liu and Tsai [11]. Xu et al. [13] presented a fuzzy logic-based method for FMEA that aims to facilitate the incorporation of interdependencies among several failure modes with uncertain and imprecise information for product defect analysis. Finally, from the review of related research work, it is possible to realize that the combination of those tools yields different methodologies capable of treating uncertain data in a similar way to how humans think, generating positive results in several areas of application.

3 Methodological aspects

3.1 Methodology

In this work, a methodology is proposed that integrates the concepts of product FMEA and fuzzy logic. The fuzzy logic proposed by Zadeh [6] was developed to mathematically represent uncertainty and vagueness and provide formalized tools for dealing with the imprecision intrinsic to many problems. In that sense, the FMEA associated with fuzzy logic can provide a more flexible and meaningful way to assess the risk associated with a product's component failure modes. Figure 1 shows an overall view of the proposed fuzzy FMEA assessment system, in which there are three major steps: fuzzification, inference and defuzzification.

In the proposed methodology, the parameters S, O and D, which are used in traditional FMEA, are fuzzified using membership functions to determine the degree of membership in each input class. The resulting fuzzy inputs are evaluated in fuzzy inference, which makes use of if-then rules and fuzzy operations to obtain a fuzzy set that represents all aggregated parameters. This fuzzy conclusion is then defuzzified to get the fuzzy RPN. Like in the evaluation of the traditional FMEA, higher values of fuzzy RPN represent greater risk, and lower values indicate lesser risks. The fuzzy linguistic assessment model was developed using the tool InFuzzy, an open-source software developed at Universidade de Santa Cruz do Sul (UNISC) [27].

The evaluation of the developed method was carried out through a comparison between the characteristics of the proposed methodology and the traditional FMEA tool. This method of analysis has been used by different authors [5, 25, 28] to validate their methodologies developed for similar purposes: to overcome the gaps in the application of traditional FMEA through the application of the fuzzy sets theory. Fuzzy risk assessment was carried out for prioritizing

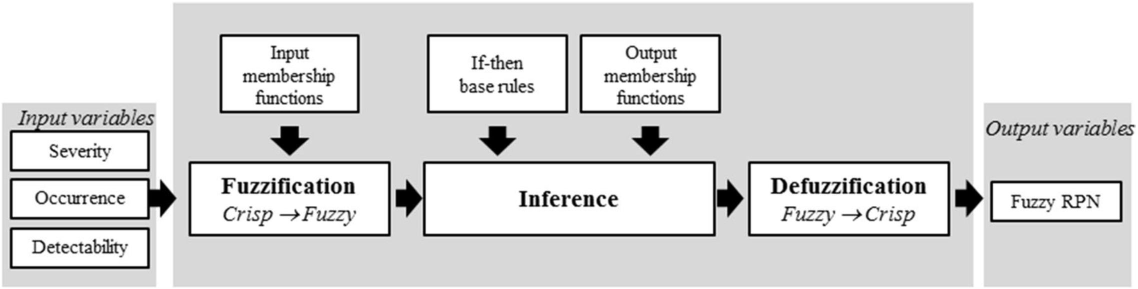


Fig. 1 Overall view of the proposed fuzzy FMEA assessment system

failure causes for one module of an equipment for Jerusalem artichoke processing.

The next topics will provide further details about the proposed method's development and application, which can be divided into three main steps: fuzzification, inference and defuzzification.

3.2 The proposed fuzzy FMEA method

3.2.1 Fuzzification of the input variables

Fuzzification refers to the processes of transforming crisp inputs (natural numbers) into a membership degree $\mu(x_i)$ contained in the interval between 0 and 1. The $\mu(x_i)$ expresses how well the input x_i belongs to each of the linguistic terms [22]. In the proposed methodology, the fuzzification process will transform the crisp inputs severity, occurrence and detectability into membership degrees of five terms defined as very low (VL), low (L), moderate (M), high (H) and very high (VH). These linguistic terms are already consolidated in the literature to represent the S, O and D indices used in different combinations of FMEA and fuzzy logic [29–31].

In this work, the same linguistic terms will be used to classify all FMEA indices (S, O and D). The linguistic terms will be represented by triangular fuzzy numbers, as described in Table 1 and Fig. 2. The fuzzy membership functions associated with each of the triangular fuzzy numbers were determined so they could be homogeneously distributed along the values belonging to the universe of discourse (between 1 and 10). That range was chosen as the same range used to describe the index of traditional FMEA.

3.2.2 Inference

After the inputs are fuzzified, they must be processed in a fuzzy inference system consisting of a rule base, an implication method and an aggregation method. A fuzzy rule is simply an "if-then" rule, which has two main parts, the antecedents and the consequences. The consequences are obtained through implication methods from the antecedents (fuzzy inputs). When the rules generate more than one consequence, then they are associated through an aggregation method [22]. Figure 3 gives an overall view of all parts of the inference process.

In the if-then rule base, "if" refers to an antecedent that is compared to the inputs, and "then" refers to a consequence, which is the result (output). Equation 1 represents a fuzzy rule R_I, where x is the input variable (antecedent), M_i is the linguistic term which refers to the input variables, y is the output variable (consequence) and N_i is the linguistic term which refers to the output variables [22].

$$R_I; \quad \text{if } x \text{ is } A_i \text{ then } y \text{ is } N_i \tag{1}$$

In this work, as previously stated, the input variables are the severity, occurrence and detectability, which may be attributed to the linguistic terms, as indicated in Table 1. The

Table 1 Linguistic terms and triangular fuzzy numbers for the input variables severity, occurrence and detectability

Linguistic terms	Triangular fuzzy numbers		
	Severity	Occurrence	Detectability
Very low (VL)	(1.00, 1.00, 3.25)	(1.00, 1.00, 3.25)	(1.00, 1.00, 3.25)
Low (L)	(1.00, 3.25, 5.50)	(1.00, 3.25, 5.50)	(1.00, 3.25, 5.50)
Moderate (M)	(3.25, 5.50, 7.75)	(3.25, 5.50, 7.75)	(3.25, 5.50, 7.75)
High (H)	(5.50, 7.75, 10.00)	(5.50, 7.75, 10.00)	(5.50, 7.75, 10.00)
Very high (VH)	(7.75, 10.00, 10.00)	(7.75, 10.00, 10.00)	(7.75, 10.00, 10.00)

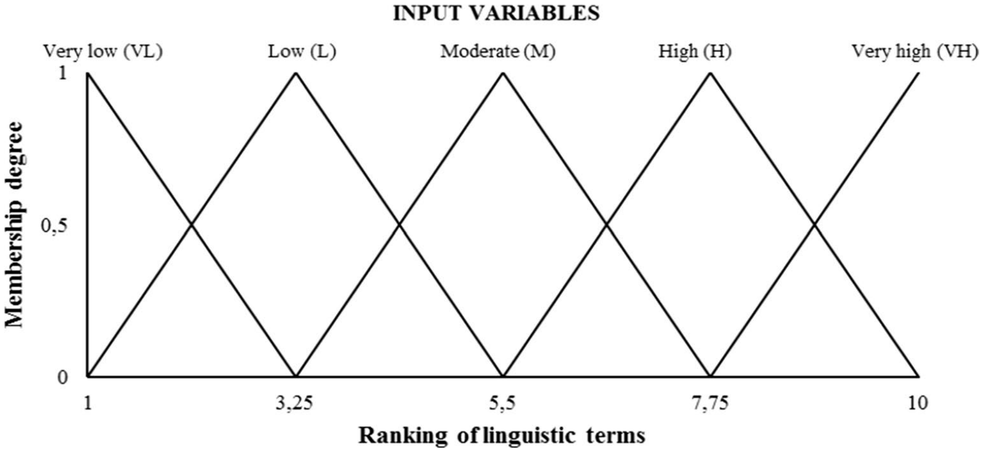


Fig. 2 Fuzzy membership functions of linguistic terms for input variables severity, occurrence and detectability

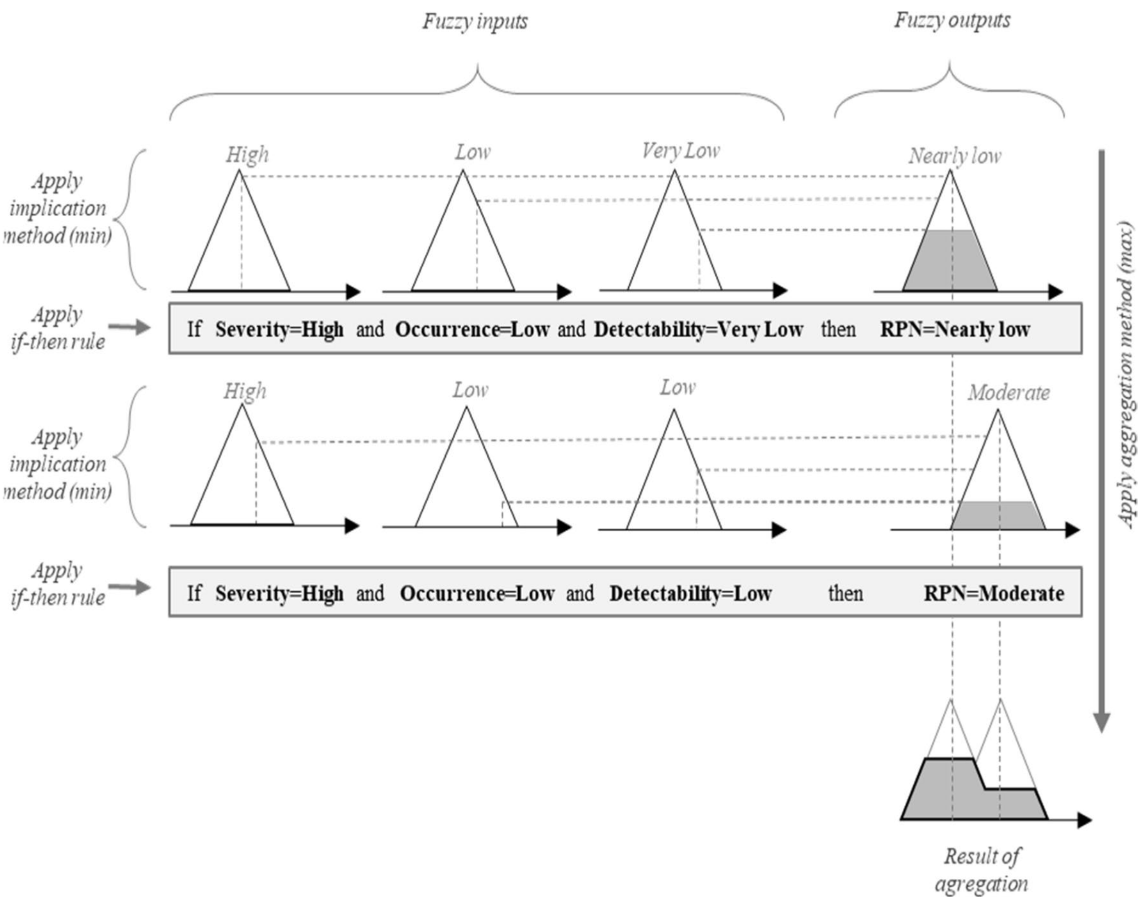


Fig. 3 Overall view of the fuzzy inference process (adapted from PEDRYCZ and GOMIDE [7])

Table 2 Linguistic terms and triangular fuzzy numbers for the output variable fuzzy RPN

Linguistic terms	Triangular fuzzy numbers
Very low (VL)	(1.00, 1.00, 167.5)
Low (L)	(1.00, 167.5, 334.0)
Nearly low (NL)	(167.5, 334.0, 500.5)
Moderate (M)	(334.0, 500.5, 667.0)
Nearly high (NH)	(500.5, 667.0, 833.5)
High (H)	(667.0, 833.5, 1000.0)
Very high (VH)	(833.5, 1000.0, 1000.0)

output variables will be named fuzzy RPN, which may be attributed to seven linguistic terms, as indicated in Table 2 and Fig. 4. The linguistic terms for the outputs will be represented by triangular fuzzy numbers as well. The fuzzy membership functions associated with each of the triangular fuzzy numbers were determined so they could be homogeneously distributed along the values belonging to the universe of discourse (between 1 and 1000). That range was chosen as the same range used to describe the RPN used in traditional FMEA.

In the context of the FMEA, the if-then rules represent the expert knowledge on the interaction between various failure modes and their effects and causes. All possible combinations of linguistic terms (125 possibilities) were evaluated by a team of experts, and the results are shown in Table 3.

Different fuzzy operators can be used to perform the implication and aggregation methods. According to the combination of those operators, different fuzzy inference systems are constructed, being the Mamdani and the Takagi–Sugeno models the most commonly used ones [32]. In this work, the Mamdani inference model was chosen because it is the most used technique in decision-making problems [33].

Briefly, Mamdani [34] proposes a fuzzy relation N between x and u (linguistic terms) to mathematically construct the rule base model. This method is based on the max–min inference composition rule. Its basic procedure is that, in each rule R_l, the conditional "If x is A_j and u is B_i, then y is N" is modeled by the minimum application. The $\bigwedge$ (minimum) operator is adopted for the logical concept "and". When the if-then rules generate more than one consequence N, they are associated with the maximum

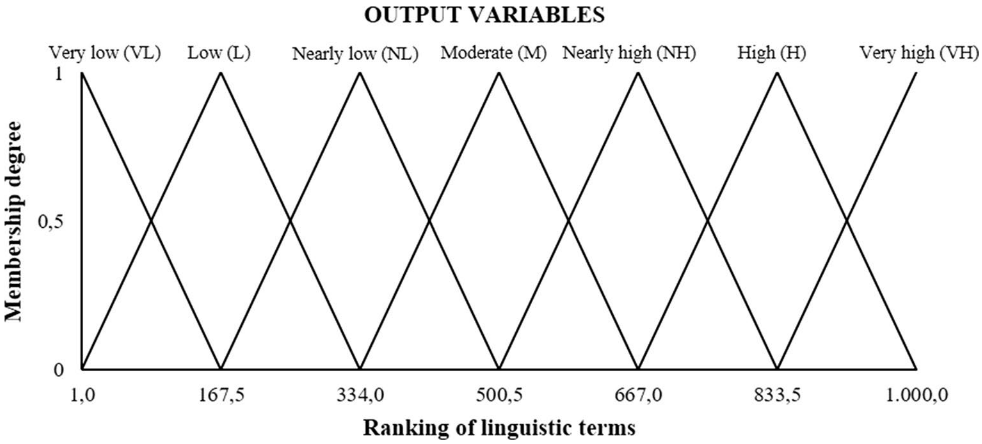


Fig. 4 Fuzzy membership functions of linguistic terms for input variable fuzzy RPN

application. Thus, the fuzzy relation N is the fuzzy subset of X × U, whose membership function is given by Eq. 2.

$$\mu_N(x,u) = \max_{1\le i\le r}\left[\mu_{A_i}(x) \wedge \mu_{B_i}(u)\right] \tag{2}$$

where r represents the number of rules that make up the rule base, and A_i and B_i are the fuzzy subsets of rule i.

3.2.3 Defuzzification

As seen in the previous topic, the output of the fuzzy inference system is a membership function. To transform such function into an easily interpreted value (natural number), a process called defuzzification is necessary. It creates a crisp ranking (the fuzzy RPN) from the fuzzy conclusion set to express the riskiness of the design, so that corrective actions and design revisions can be prioritized.

There are several defuzzification algorithms, such as the centroid, bisector, middle of maximum (the average of the maximum values of the output set), largest of maximum and smallest of maximum. In this work, the center of gravity algorithm, one of the widely used ones, is adopted, as it gives the average, weighted by degree of truth, of the support values at which all the membership functions that apply reach their maximum value. In this algorithm, the result is calculated using Eq. 3 [35].

$$Z = \frac{\sum_{i=1}^{K} \mu_i(x).x_i}{\sum_{i=1}^{N} \mu_i(x)} \tag{3}$$

where k is the number of quantized riskiness conclusions, x_i is the support value at which the i membership function reaches its maximum value (for trapezoidal membership functions, it is taken as the center of the maximal range), μ_i is the degree of truth of the ith membership function, and Z is the center of gravity conclusions.

4 Proposed application and evaluation

To demonstrate the application of the proposed approach for carrying out a system FMEA, a case study with a product under development is proposed. The product is an equipment aimed at familiar agriculture to mechanize the processing of Jerusalem artichoke, a root used as a food supplement and herbal medicine [36]. Due to the large number of equipment components, the failure mode analysis was chosen to be conducted in one of the main product modules, specifically the slice one. Figure 5 is the product's schematic indicating the modules that make up the equipment.

After the determination of the failure modes, their causes and effects, as well as the S, O and D indices, the fuzzy RPN was obtained using the previously described methodology. An example of the steps taken is presented in "Appendix B" section. In order to obtain the traditional RPN, a simple multiplication of the same indices (O, S, D) was performed. The results obtained for both methodologies are in the Table 4.

Comparing the results obtained through both methodologies, traditional and fuzzy FMEA, differences were perceivable. In this work, as well as in other authors' works [25, 28], the classification obtained for risk prioritization presented divergent values, i.e., the fuzzy RPN shows different values from the traditional RPN, as shown in Table 4.

Between the first eight risks described by the experts, both systems of analysis (traditional FMEA and fuzzy FMEA) show equal results, indicating a satisfactory assessment by the FMEA. However, between risks 9 and 10, there is inequality difference regarding the classifications from each method, which proves an inaccuracy of the traditional FMEA compared to the expectation of the specialists. In this sense, it is possible to see that, although risk 10 has different values for the indices (S = 6, O = 5; D = 10), it presents the same RPN as other risks, such as risks 5, 6, 7 and 8, that have indices (S = 10; O = 3; D = 10). That means that, in the traditional FMEA, the order of the factors will not

Table 3 Format of if-then rule base, where RPN is a function of severity (S), occurrence (O) and detectability (D)

	"If-then" rule base		
1	if (S = VL) and (O = VL) and (D = VL) then (RPN = VL)	64	if (S = M) and (O = M) and (D = L) then (RPN = M)
2	if (S = VL) and (O = VL) and (D = L) then (RPN = VL)	65	if (S = M) and (O = M) and (D = M) then (RPN = M)
3	if (S = VL) and (O = L) and (D = VL) then (RPN = VL)	66	if (S = M) and (O = H) and (D = L) then (RPN = M)
4	if (S = L) and (O = VL) and (D = VL) then (RPN = VL)	67	if (S = M) and (O = VH) and (D = VL) then (RPN = M)
5	if (S = VL) and (O = VL) and (D = M) then (RPN = L)	68	if (S = H) and (O = VL) and (D = H) then (RPN = M)
6	if (S = VL) and (O = VL) and (D = H) then (RPN = L)	69	if (S = H) and (O = VL) and (D = VH) then (RPN = M)
7	if (S = VL) and (O = VL) and (D = VH) then (RPN = L)	70	if (S = H) and (O = L) and (D = L) then (RPN = M)
8	if (S = VL) and (O = L) and (D = L) then (RPN = L)	71	if (S = H) and (O = L) and (D = M) then (RPN = M)
9	if (S = VL) and (O = L) and (D = M) then (RPN = L)	72	if (S = H) and (O = M) and (D = L) then (RPN = M)
10	if (S = VL) and (O = M) and (D = VL) then (RPN = L)	73	if (S = H) and (O = H) and (D = VL) then (RPN = M)
11	if (S = VL) and (O = M) and (D = L) then (RPN = L)	74	if (S = H) and (O = VH) and (D = VL) then (RPN = M)
12	if (S = VL) and (O = H) and (D = VL) then (RPN = L)	75	if (S = VH) and (O = VL) and (D = M) then (RPN = M)
13	if (S = VL) and (O = VH) and (D = VL) then (RPN = L)	76	if (S = VH) and (O = VL) and (D = H) then (RPN = M)
14	if (S = L) and (O = VL) and (D = L) then (RPN = L)	77	if (S = VH) and (O = VL) and (D = VH) then (RPN = M)
15	if (S = L) and (O = VL) and (D = M) then (RPN = L)	78	if (S = VH) and (O = L) and (D = L) then (RPN = M)
16	if (S = L) and (O = L) and (D = VL) then (RPN = L)	79	if (S = VH) and (O = M) and (D = VL) then (RPN = M)
17	if (S = L) and (O = M) and (D = VL) then (RPN = L)	80	if (S = VH) and (O = H) and (D = VL) then (RPN = M)
18	if (S = M) and (O = VL) and (D = VL) then (RPN = L)	81	if (S = VH) and (O = VH) and (D = VL) then (RPN = M)
19	if (S = M) and (O = VL) and (D = L) then (RPN = L)	82	if (S = L) and (O = M) and (D = VH) then (RPN = NH)
20	if (S = M) and (O = L) and (D = VL) then (RPN = L)	83	if (S = L) and (O = H) and (D = H) then (RPN = NH)
21	if (S = H) and (O = VL) and (D = VL) then (RPN = L)	84	if (S = L) and (O = H) and (D = VH) then (RPN = NH)
22	if (S = VH) and (O = VL) and (D = VL) then (RPN = L)	85	if (S = L) and (O = VH) and (D = M) then (RPN = NH)
23	if (S = VL) and (O = L) and (D = H) then (RPN = NL)	86	if (S = L) and (O = VH) and (D = H) then (RPN = NH)
24	if (S = VL) and (O = L) and (D = VH) then (RPN = NL)	87	if (S = M) and (O = L) and (D = VH) then (RPN = NH)
25	if (S = VL) and (O = M) and (D = M) then (RPN = NL)	88	if (S = M) and (O = M) and (D = H) then (RPN = NH)
26	if (S = VL) and (O = M) and (D = H) then (RPN = NL)	89	if (S = M) and (O = M) and (D = VH) then (RPN = NH)
27	if (S = VL) and (O = H) and (D = L) then (RPN = NL)	90	if (S = M) and (O = H) and (D = M) then (RPN = NH)
28	if (S = VL) and (O = H) and (D = M) then (RPN = NL)	91	if (S = M) and (O = H) and (D = H) then (RPN = NH)
29	if (S = VL) and (O = VH) and (D = L) then (RPN = NL)	92	if (S = M) and (O = VH) and (D = L) then (RPN = NH)
30	if (S = L) and (O = VL) and (D = H) then (RPN = NL)	93	if (S = M) and (O = VH) and (D = M) then (RPN = NH)
31	if (S = L) and (O = VL) and (D = VH) then (RPN = NL)	94	if (S = H) and (O = L) and (D = H) then (RPN = NH)
32	if (S = L) and (O = L) and (D = L) then (RPN = NL)	95	if (S = H) and (O = L) and (D = VH) then (RPN = NH)
33	if (S = L) and (O = L) and (D = M) then (RPN = NL)	96	if (S = H) and (O = M) and (D = M) then (RPN = NH)
34	if (S = L) and (O = M) and (D = L) then (RPN = NL)	97	if (S = H) and (O = M) and (D = H) then (RPN = NH)
35	if (S = L) and (O = H) and (D = VL) then (RPN = NL)	98	if (S = H) and (O = H) and (D = L) then (RPN = NH)
36	if (S = L) and (O = VH) and (D = VL) then (RPN = NL)	99	if (S = H) and (O = H) and (D = M) then (RPN = NH)
37	if (S = M) and (O = VL) and (D = M) then (RPN = NL)	100	if (S = H) and (O = VH) and (D = L) then (RPN = NH)
38	if (S = M) and (O = VL) and (D = H) then (RPN = NL)	101	if (S = VH) and (O = L) and (D = M) then (RPN = NH)
39	if (S = M) and (O = L) and (D = L) then (RPN = NL)	102	if (S = VH) and (O = L) and (D = H) then (RPN = NH)
40	if (S = M) and (O = M) and (D = VL) then (RPN = NL)	103	if (S = VH) and (O = M) and (D = L) then (RPN = NH)
41	if (S = M) and (O = H) and (D = VL) then (RPN = NL)	104	if (S = VH) and (O = M) and (D = M) then (RPN = NH)
42	if (S = H) and (O = VL) and (D = L) then (RPN = NL)	105	if (S = VH) and (O = H) and (D = L) then (RPN = NH)
43	if (S = H) and (O = VL) and (D = M) then (RPN = NL)	106	if (S = L) and (O = VH) and (D = VH) then (RPN = H)
44	if (S = H) and (O = L) and (D = VL) then (RPN = NL)	107	if (S = M) and (O = H) and (D = VH) then (RPN = H)
45	if (S = H) and (O = M) and (D = VL) then (RPN = NL)	108	if (S = M) and (O = VH) and (D = H) then (RPN = H)
46	if (S = VH) and (O = VL) and (D = L) then (RPN = NL)	109	if (S = M) and (O = VH) and (D = VH) then (RPN = H)
47	if (S = VH) and (O = L) and (D = VL) then (RPN = NL)	110	if (S = H) and (O = M) and (D = VH) then (RPN = H)
48	if (S = VL) and (O = M) and (D = VH) then (RPN = M)	111	if (S = H) and (O = H) and (D = H) then (RPN = H)
49	if (S = VL) and (O = H) and (D = H) then (RPN = M)	112	if (S = H) and (O = H) and (D = VH) then (RPN = H)
50	if (S = VL) and (O = H) and (D = VH) then (RPN = M)	113	if (S = H) and (O = VH) and (D = M) then (RPN = H)

Table 3 (continued)

	"If-then" rule base		
51	if (S = VL) and (O = VH) and (D = M) then (RPN = M)	114	if (S = H) and (O = VH) and (D = H) then (RPN = H)
52	if (S = VL) and (O = VH) and (D = H) then (RPN = M)	115	if (S = VH) and (O = L) and (D = VH) then (RPN = H)
53	if (S = VL) and (O = VH) and (D = VH) then (RPN = M)	116	if (S = VH) and (O = M) and (D = H) then (RPN = H)
54	if (S = L) and (O = L) and (D = H) then (RPN = M)	117	if (S = VH) and (O = M) and (D = VH) then (RPN = H)
55	if (S = L) and (O = L) and (D = VH) then (RPN = M)	118	if (S = VH) and (O = H) and (D = M) then (RPN = H)
56	if (S = L) and (O = M) and (D = M) then (RPN = M)	119	if (S = VH) and (O = H) and (D = H) then (RPN = H)
57	if (S = L) and (O = M) and (D = H) then (RPN = M)	120	if (S = VH) and (O = VH) and (D = L) then (RPN = H)
58	if (S = L) and (O = H) and (D = L) then (RPN = M)	121	if (S = VH) and (O = VH) and (D = M) then (RPN = H)
59	if (S = L) and (O = H) and (D = M) then (RPN = M)	122	if (S = H) and (O = VH) and (D = VH) then (RPN = VH)
60	if (S = L) and (O = VH) and (D = L) then (RPN = M)	123	if (S = VH) and (O = H) and (D = VH) then (RPN = VH)
61	if (S = M) and (O = VL) and (D = VH) then (RPN = M)	124	if (S = VH) and (O = VH) and (D = H) then (RPN = VH)
62	if (S = M) and (O = L) and (D = M) then (RPN = M)	125	if (S = VH) and (O = VH) and (D = VH) then (RPN = VH)
63	if (S = M) and (O = L) and (D = H) then (RPN = M)		

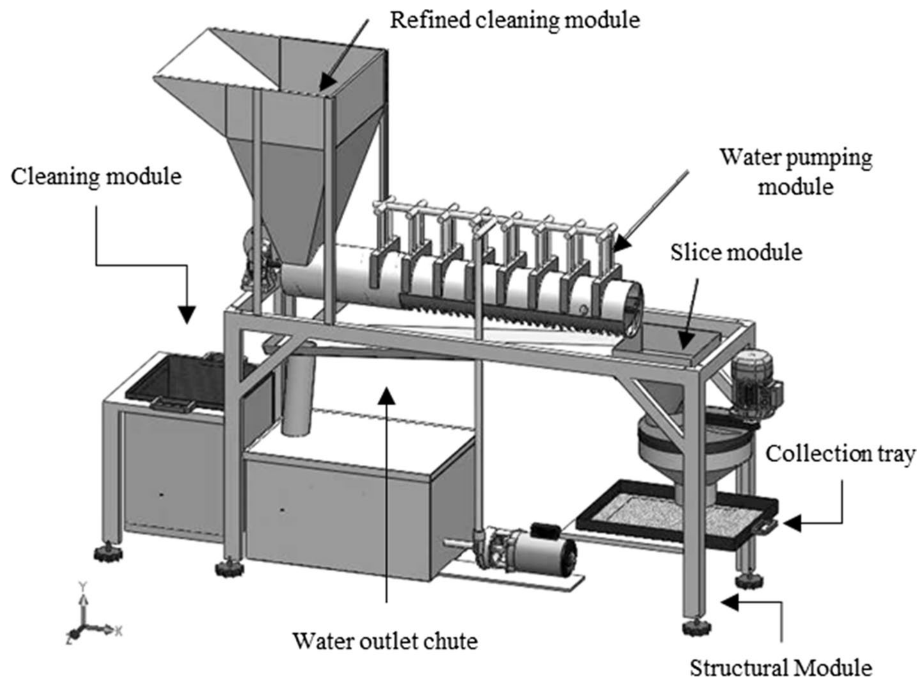


Fig. 5 Equipment for Jerusalem artichoke processing

change the results. Besides, it shows another weakness of the traditional FMEA, since it would mislead to equally prioritizing events with different parameters. On the other hand, the classification using logic could translate this difference and present a distinct fuzzy RPN index for each of the situations. The main cause of the differences is the nonlinear relationship between the variables, justified by the presence of a rule base and membership functions that the fuzzy logic provides. Through these, the experts can express their needs and get a response according to what they really prioritize.

5 Conclusions

Through the development of fuzzy FMEA, it was possible to obtain an organized method combining specialized knowledge and experience in an FMEA study. The relationship between the NPR and severity, occurrence and detectability parameters was no longer considered linear as in the conventional NPR (traditional FMEA) model.

The flexibility of assigning weights to factors can provide a specific means of identifying more critical failure modes, thus contributing to more effective prioritization. The combinations of input factors (S, O, D) were modeled through

Table 4 Comparison of results for traditional FMEA and fuzzy FMEA

Risk	Potential failure mode	Potential effect of failure	S	Potential cause of failure	O	Detection method	D	RPN	RPN fuzzy
1	Stopped system	Work accident	10	Clogging at the module input	5	Visual inspection	10	500	833.47
2	Stopped system	Work accident	10	Wrong assembly	5	Visual inspection	10	500	833.47
3	System operating with failures	Work accident	10	Clogging at the module input	5	Visual inspection	10	500	833.47
4	System operating with failures	Work accident	10	Wrong assembly	5	Visual inspection	10	500	833.47
5	Stopped system	Work accident	10	Blades not well attached	3	Visual inspection	10	300	775.04
6	Stopped system	Work accident	10	Deregulated pulleys	3	Visual inspection	10	300	775.04
7	System operating with failures	Work accident	10	Blades not well attached	3	Visual inspection	10	300	775.04
8	System operating with failures	Work accident	10	Deregulated pulleys	3	Visual inspection	10	300	775.04
9	Stopped system	Rhizome accumulated in the slicing process	6	Blades without sharpening	7	Visual inspection	10	420	773.01
10	Stopped system	Rhizome accumulated in the slicing process	6	Clogging at the module input	5	Visual inspection	10	300	710.82
11	System operating with failures	Rhizome without the required thickness	8	Blades not well attached	3	Visual inspection	10	240	666.99
12	Stopped system	Work accident	10	Inappropriately sized components	2	Visual inspection	10	200	654.59
13	System operating with failures	Work accident	10	Inappropriately sized components	2	Visual inspection	10	200	654.59
14	Stopped system	Rhizome accumulated in the slicing process	6	Deregulated pulleys	3	Visual inspection	10	180	641.79
15	System operating with failures	Rhizome without the required thickness	8	Inappropriately sized components	2	Visual inspection	10	160	603.48
16	Stopped system	Rhizome accumulated in the slicing process	6	Deregulated engine	2	Visual inspection	10	120	576.35

the rule base (if-then). That means that a fault only had a high NPR if it had a certain combination of factors S, O and D, which were described by the if-then rules with high consequence values. This helps to resolve situations in which the NPR did not reflect the true risk of failure.

As observed in our systematic literature review, some authors have already worked with the concept of associating the FMEA with the Mamdani inference system to overcome the gaps of the traditional FMEA, such as the tool's lack of flexibility and the traditional RPN's inability to reflect real situations. However, for each type of application, a specific modeling is required, reflecting in different linguistic terms, pertinence functions and base rules. With that in mind, our work was developed to fit the context of product development, more specifically the initial phases, such as in the conceptual design, where there is limited knowledge about the product, but changes are not yet very expensive.

One difficulty noticed on the proposed method is the computational power required to perform the inference. In this study, all possible combinations of input variables (O, S and D) are analyzed, generating a large number of if-then rules (125). So, for each evaluated risk, all 125 rules are analyzed, which, in the case of complex products, may require a relatively high computational power. One way of improvement is a study to reduce the number of rules by developing more universal ones, which can add a greater number of combinations at one time.

Therefore, the combination of fuzzy logic and FMEA may contribute to a more efficient resource allocation for corrective actions, since a fuzzy FMEA inference system returns better index results regarding the uncertainty of risk than the traditional FMEA approach.

Appendix A: systematic literature review

The search was performed on September 2018, using SCOPUS database with the following features:

- Search string: ((FMEA OR FEMECA OR "Failure Mode") AND "Fuzzy Logic"). The term "Failure Mode" was incorporated due to the absence of the acronyms in some papers on the adopted search fields.
- Search fields: Article Title, Abstract and Keywords.

Table 5 Results from the systematic literature review

#	Title	Year	Authors	Cited by
1	Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis	1995	Bowles J.B., Peláez C.E.	314
2	Risk evaluation in failure mode and effects analysis using fuzzy weighted geometric mean	2009	Wang Y.-M., Chin K.-S., Poon G.K.K., Yang J.-B.	259
3	Fuzzy assessment of FMEA for engine systems	2002	Xu K., Tang L.C., Xie M., Ho S.L., Zhu M.L.	234
4	Fuzzy TOPSIS Approach for Failure Mode, Effects and Criticality Analysis	2003	Braglia M., Frosolini M., Montanari R.	169
5	Fuzzy rule-based Bayesian reasoning approach for prioritization of failures in FMEA	2008	Yang Z., Bonsall S., Wang J.	146
6	Failure mode and effects analysis using fuzzy evidential reasoning approach and grey theory	2011	Liu H.-C., Liu L., Bian Q.-H., Lin Q.-L., Dong N., Xu P.-C.	126
7	Development of a fuzzy FMEA based product design system	2008	Chin K.-S., Chan A., Yang J.-B.	92
8	Risk management in the construction industry using combined fuzzy FMEA and fuzzy AHP	2010	Abdelgawad M., Fayek A.R.	91
9	Criticality assessment models for failure mode effects and criticality analysis using fuzzy logic	2011	Gargama H., Chaturvedi S.K.	81
10	On-line failure diagnosis for compression refrigeration plants	1995	Grimmelius H.T., Klein Woud J., Been G.	71
11	A fuzzy risk assessment approach for occupational hazards in the construction industry	2012	Liu H.-T., Tsai Y.-L.	68
12	Fuzzy FMEA applied to PWR chemical and volume control system	2004	Guimarães A.C.F., Lapa C.M.F.	61
13	Evaluating the risk of failure modes with extended MULTIMOORA method under fuzzy environment	2014	Liu H.-C., Fan X.-J., Li P., Chen Y.-Z.	48
14	Risk analysis using FMEA: Fuzzy similarity value and possibility theory based approach	2014	Mandal S., Maiti J.	47
15	Integrating lean principles and fuzzy bow-tie analysis for risk assessment in chemical industry	2014	Aqlan F., Mustafa Ali E.	36
16	Risk assessment model of mining equipment failure based on fuzzy logic	2014	Petrović D.V., Tanasijević M., Milić V., Lilić N., Stojadinović S., Svrkota I.	30
17	Integrated system for maintenance and safety management through FMECA principles and fuzzy inference engine	2011	Savino M.M., Brun A., Riccio C.	26
18	A framework for capturing and analyzing the failures due to system/component interactions	2008	Nepal B.P., Yadav O.P., Monplaisir L., Murat A.	22
19	A FSA based fuzzy DEMATEL approach for risk assessment of cargo ships at coasts and open seas of Turkey	2015	Mentes A., Akyildiz H., Yetkin M., Turkoglu N.	21
20	FM—A pragmatic tool to model, analyse and predict complex behaviour of industrial systems	2007	Sharma R.K., Kumar D., Kumar P.	21
21	Real time implementation of PI and fuzzy logic controller based 3-phase 4-wire interleaved buck active power filter for mitigation of harmonics with id-iq control strategy	2014	Patel R., Panda A.K.	19
22	Fault-tolerant control of three-pole active magnetic bearing	2009	Agarwal P.K., Chand S.	19
23	Using fuzzy self-organising maps for safety critical systems	2007	Kurd Z., Kelly T.P.	18
24	Comprehensive hybrid framework for risk analysis in the construction industry using combined failure mode and effect analysis, fault trees, event trees, and fuzzy logic	2012	Abdelgawad M., Fayek A.R.	16
25	Advanced fuzzy power extraction control of wind energy conversion system for power quality improvement in a grid tied hybrid generation system	2016	Bhattacharjee C., Roy B.K.	15
26	Fuzzy-reasoning-based approach to qualitative railway risk assessment	2006	An M., Lin W., Stirling A.	13
27	New FMECA methodology using structural importance and fuzzy theory	2011	Lee Y.-S., Kim D.-J., Kim J.-O., Kim H.	10
28	An extension to Fuzzy Developed Failure Mode and Effects Analysis (FDFMEA) application for aircraft landing system	2017	Yazdi M., Daneshvar S., Setareh H.	8
29	Fault diagnosis and failure mode estimation by a data-driven fuzzy similarity approach	2012	Zio E., di Maio F.	8

Table 5 (continued)

#	Title	Year	Authors	Cited by
30	A fuzzy group multi-criteria enterprise architecture framework selection model	2012	Zandi F., Tavana M.	8
31	A fuzzy quality control-decision support system for improving operational reliability of liquid transfer operations in laboratory automation	2009	Ozgur Unver H., Wendel G.	8
32	Estimation of corrosion failure likelihood of oil and gas pipeline based on fuzzy logic approach	2016	Zhou Q., Wu W., Liu D., Li K., Qiao Q.	7
33	Assessing the risks of airport airside through the fuzzy logic-based failure modes, effect, and criticality analysis	2013	Feng C.-M., Chung C.-C.	4
34	Novel type-2 fuzzy logic approach for inference of corrosion failure likelihood of oil and gas pipeline industry	2017	Jana D.K., Bej B., Wahab M.H.A., Mukherjee A.	3
35	Fuzzy-based failure mode and effect analysis (FMEA) of a hybrid molten carbonate fuel cell (MCFC) and gas turbine system for marine propulsion	2017	Ahn J., Noh Y., Park S.H., Choi B.I., Chang D.	3
36	Measuring the benefit of investing in pipeline safety using fuzzy risk assessment	2017	Guzman Urbina A., Aoyama A.	3
37	A state of the art review of fuzzy approaches used in the failure modes and effects analysis: A call for research	2016	Chrysostom S., Dwivedi R.K.	3
38	Investigating the impact of social sustainability within maintenance operations An action research in heavy industry	2015	Savino M.M., Macchi M., Mazza A.	3
39	Project risk management using fuzzy failure mode and effect analysis and fuzzy logic	2015	Roghanian E., Moradinasab N., Afruzi E.N., Soofifard R.	3
40	A new model to implement Six Sigma in small- and medium-sized enterprises	2017	Ben Romdhane T., Badreddine A., Sansa M.	2
41	Using fuzzy failure mode effect analysis to model cave-in accidents	2012	Al-Humaidi H.M., Tan F.H.	2
42	Fuzzy logic used in FMEA analysis	2011	Duminică D., Avram M., Apostolescu T.C.	2
43	Fuzzy Decision Support System (FDSS) for conducting FMEA	2007	Sharma R.K., Kumar D., Kumar P.	2
44	Failure Mode and Effects Analysis by Using the House of Reliability-Based Rough VIKOR Approach	2018	Wang Z., Gao J.-M., Wang R.-X., Chen K., Gao Z.-Y., Zheng W.	1
45	Fuzzy based risk prioritisation in an auto LPG dispensing station	2018	Maniram Kumar A., Rajakarunakaran S., Pitchipoo P., Vimalesan R.	1
46	Occupational risk assessment in the construction industry in Iran	2017	Seifi Azad Mard H.R., Estiri A., Hadadi P., Seifi Azad Mard M.	1
47	Minimization of risk assessments' variability in technology qualification processes	2017	Samindi S.M., Samarakoon M.K., Ratnayake R.M.C.	1
48	Incorporation of novel model in failure analysis of propeller operations of sea going vessels	2017	Nwaoha T.C., John A., Adumene S.	1
49	Prioritization of Failures in Radiation Therapy Delivery	2016	Abbasgholizadeh Rahimi S., Jamshidi A., Ait-kadi D., Ruiz A., Rebaiaia M.L.	1
50	Operational risk assessment of offshore transport barges	2018	Abdussamie N., Zaghwan A., Daboos M., Elferjani I., Mehanna A., Su W.	0
51	Distributed collaborative probabilistic design of multi-failure structure with fluid–structure interaction using fuzzy neural network of regression	2018	Song L.-K., Wen J., Fei C.-W., Bai G.-C.	0
52	A novel type-2 fuzzy logic for improved risk analysis of proton exchange membrane fuel cells in marine power systems application	2018	Bahrebar S., Blaabjerg F., Wang H., Vafamand N., Khooban M.-H., Rastayesh S., Zhou D.	0
53	A proposed model to estimate shear contribution of FRP in strengthened RC beams in terms of Adaptive Neuro-Fuzzy Inference System	2017	Naderpour H., Alavi S.A.	0
54	A Failure Mode Effect and Criticality Analysis of Conventional Milling Machine Using Fuzzy Logic: Case Study of RCM	2017	Gupta G., Mishra R.P.	0
55	Evaluation of safety risks in construction using Fuzzy Failure Mode and Effect Analysis (FFMEA)	2016	Ardeshir A., Mohajeri M., Amiri M.	0
56	Fuzzy-based risk prioritization for a hydrogen refueling facility in Malaysia	2013	Chong H.-Y., Dahari M., Yap H.-J., Loong Y.-T.	0

Table 5 (continued)

#	Title	Year	Authors	Cited by
57	Multiple failure modes and effects analysis of gas turbine based on similarity measure	2013	Yang H., Xu H.	0
58	Methodology to estimate remaining service life of steel structure by possibilistic reliability theory	2010	Xu G., Yang R., Zhou K., Fan X.	0
59	Efficient tools for managing uncertainties in design and operation of engineering structures	2010	Menčík J.	0
60	A fuzzy expert system model for RF receiver module testing	1997	Luf J., Brinkley P., Fang S.C.	0
61	A systematic approach to the design and reliability analysis of a fault-tolerant controller-II. Reliability analysis and assurance	1989	Liang E., Rodriguez R.J., Husseiny A.A.	0

Table 6 Filtered literature from the systematic literature review

#	Authors	Year	Exclusion explanation
3	Xu K., Tang L.C., Xie M., Ho S.L., Zhu M.L.	2002	Not excluded
11	Liu H.-T., Tsai Y.-L.	2012	Not excluded
12	Guimarães A.C.F., Lapa C.M.F.	2004	Not excluded
17	Savino M.M., Brun A., Riccio C.	2011	Not excluded
21	Patel R., Panda A.K.	2014	Fuzzy logic applied on a non-FMEA context
22	Agarwal P.K., Chand S.	2009	Fuzzy logic applied on a non-FMEA context
36	Guzman Urbina A., Aoyama A.	2017	Fuzzy logic applied on a non-FMEA context
39	Roghanian E., Moradinasab N., Afruzi E.N., Soofifard R.	2015	The authors present a proposal of a FMEA risk assessment tool for project management (out of our scope)
40	Ben Romdhane T., Badreddine A., Sansa M.	2017	Not excluded
50	Abdussamie N., Zaghwan A., Daboos M., Elferjani I., Mehanna A., Su W.	2018	Fuzzy logic applied on a non-FMEA context
52	Bahrebar S., Blaabjerg F., Wang H., Vafamand N., Khooban M.-H., Rastayesh S., Zhou D.	2018	Mamdani's work only appears in the title of a paper listed on the bibliographical references.
60	Luf J., Brinkley P., Fang S.C.	1997	Fuzzy logic applied on a non-FMEA context
61	Liang E., Rodriguez R.J., Husseiny A.A.	1989	Fuzzy logic applied on a non-FMEA context

- Subject area: Engineering.
- Language: English.
- Source: Journals.
- Publish year: all.

This search resulted on 61 documents, listed on Table 5. Among these documents, 47 are published in the last 10 years.

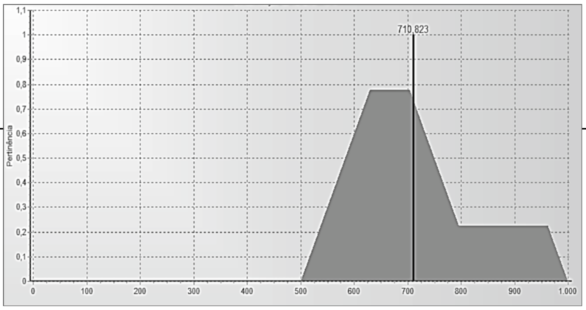
As a second filter, it has performed a search using the string "Mamdani" in the full text of the selected papers. The term "Mamdani" corresponds to the author of the fuzzy method employed on our proposal. It resulted on 13 papers to be further evaluated, represented by the numbers: 3, 11, 12, 17, 21, 22, 39, 40, 50, 52, 60 and 61. At this point, the papers passed through a reading process of theirs full text, resulting on the selection of five papers to be included on the research, as explained in Table 6. The remaining papers are part of the research described on this paper.

Appendix B

A numerical example for the calculation of the fuzzy RPN in a failure risk with severity = 6, occurrence = 5 and detectability = 10.

```
===================================== FUZZIFICATION
=====================================
Crisp input for "Severity" = 6,00
      Membership degree "Very_low" = 0,00
      Membership degree "Low" = 0,00
      Membership degree "Moderate " = 0,78
      Membership degree "High " = 0,22
      Membership degree "Very_high " = 0,00
Crisp input for "Occurrence" = 5,00
      Membership degree "Very_low" = 0,00
      Membership degree "Low" = 0,22
      Membership degree "Moderate " = 0,78
      Membership degree "High " = 0,00
      Membership degree "Very_high " = 0,00
Crisp input for "Detectability" = 10,00
      Membership degree "Very_low" = 0,00
      Membership degree "Low" = 0,00
      Membership degree "Moderate " = 0,00
      Membership degree "High " = 0,00
      Membership degree "Very_high " = 1,00
======================================= INFERENCE
=======================================
(...)
 RULE=88
   If  (Severity= Moderate ) AND (Occurrence= Moderate ) AND (Detectability= Very_high )  So  (RPN=
Nearly_High )
   If  (Severity=0,78) AND (Occurrence=0,78) AND (Detectability=1,00) So  (RPN=0,78)
(...)
 RULE=94
   If  (Severity= High ) AND (Occurrence= Low) AND (Detectability= Very_high )  So  (RPN= Nearly_High )
   If  (Severity=0,22) AND (Occurrence=0,22) AND (Detectability=1,00) So  (RPN=0,22)
(...)
 RULE=109
   If  (Severity= High ) AND (Occurrence= Moderate ) AND (Detectability= Very_high )  So  (RPN= High )
   If  (Severity=0,22) AND (Occurrence=0,78) AND (Detectability=1,00) So  (RPN=0,22)
(...)
================================ AGGREGATION FINAL RESULTS
================================
      Membership degree "Very_low" = 0,00
      Membership degree “Low" = 0,00
      Membership degree “Nearly_Low" = 0,00
      Membership degree “Moderate " = 0,00
      Membership degree “Nearly_High " = 0,78
      Membership degree “High " = 0,22
      Membership degree “Very_high " = 0,00
===================================== DEFUZZIFICATION
=====================================
Defuzzification by the Center of Gravity method

Fuzzy RPN = 710,82
```



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