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Applied multicriteria methodology under Pythagorean
fuzzy environment with FMEA to appraise new product
development process

Proyecto que presenta

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1. Introduction

This chapter depicts the introduction of this work research, where the background, problem statement, objectives, hypothesis, and justification are detailed.

1.1. Background

New Product Development Process (NPDP) is today critical for global firms, that require to shorten their cycle times to launch new products. New products require advanced manufacturing processes, better technology knowledge, more resources, and additional cross-functional areas interaction, these new NPDP requirements, are due to the global customers and markets are eager to get the new and best version of the product.

Moreover, NPDP is getting more complications day to day, is a long and complex process, and it requires new tools to solve the different emerging problems, one of the most important problems is the evaluation of the risk along all the NPDP. Although there are diverse tools to perform Risk Assessment (RA), RA is now challenged because of the extra requirements and NPDP complexity.

Literature regarding new product design process, is still in full development, and the industrial NPDP practice shows diverse disadvantages, pinpointing the need

to improve the NPDP Risk Analysis (NPDP-RA), helping the stakeholders to make better decisions assigning resources where required, moreover, avoiding product failures in the field, these improvements because of using a confident risk analysis free of uncertainty.

1.2. Problem statement

Global companies look to introduce new products into the marketplace in the fastest, easiest, and cheapest possible way, to reach the customers into the diverse global markets, and to get better products free of failures. The current New Product Development Process (NPDP) methodologies have weaknesses identified, [1], [2], [3]. Among the problems in manufacturing during NPDP, products field failures are reflected, these failures can be harmful for the companies representing significant economic losses, i.e. Samsung company recalled more than 2.5 million of their smartphone Note 7, because of an imperfection in the battery, defect not detected during the NPDP, ending with a smartphone product in the field, making the devices to explode without any warning [4].

Similarly, other companies lost reputation while dishonest practices, like Volkswagen in their new Passat model 2014 introduction, they modified the vehicles software to show less contaminant gases emitted, while the vehicles generated more toxic gasses that the allowed amounts by the international standards, the company faced different countries charges and recalls, the calculated spend for this issue for

Volkswagen was about seven billion Euros, and the worst part for the company, they lost credibility from their global customers [5].

Based on literature review, there are clear problems identified at present NPDP methodologies, along all the NPDP stages, as well as the RA tools used during NPDP, some gaps were identified as following [6], [7], [8], [9], [10].

- NPDP risk assessment adding uncertainty because of the human judgement.
- NPDP risk assessment encloses wrong risks ranking while using traditional FMEA.
- NPDP resources incorrect application because of inaccurate NPDP-RA.
- Mistakes at NPDP decision-making, based on poor risks assessment due to conventional scale.

As identified in the literature, one of the main problems detected during the RA is the uncertainty while the assessment is performed, mainly because of the human contribution along all the process adding uncertainty.

This research is suggesting a new multicriteria methodology called PFDA-FMEA-VSM, this tri-acronym came from Pythagorean fuzzy Dimensional Analysis (PFDA) [10], Failure Mode and Effect Analysis (FMEA) [11], and Value Stream Mapping (VSM) [12]. PFDA-FMEA-VSM integrates Pythagorean fuzzy sets (PFS) [13], Dimensional Analysis (DA) [14], and Value Stream Mapping (VSM) [15], pointing

to improve the NPDP while performing risk assessment for NPDP, as well as while removing the uncertainty added by human involvement during the judgment and classifying of the NPDP risks, furthermore, helping the stakeholders to make better decisions assigning the resources depending of the NPDP stage, likewise, launch projects on time, besides avoiding product failures in the field.

Finally, in this research we attack the gap's regarding to appraisal uncertainty, the subjective related to human intervention during risk assessments, providing a practical manner to identify harmful NPDP risks in the industry. In addition to improve the Failure Mode and Effect Analysis tool adding Pythagorean fuzzy sets Dimensional Analysis methodology, which assists to disperse the uncertainty implied at the human risk assessment along NPDP.

1.3. Objectives

This section describes the main objective and the particular objectives.

1.3.1. Main objective

The main objective is to provide a practical Multicriteria methodology under Pythagorean environment to identify harmful NPDP risks in new product development process. To improve the Failure Mode and Effect Analysis tool adding Pythagorean fuzzy sets Dimensional Analysis methodology, which assists to disperse the uncertainty implied at the human risk assessment along NPDP.

1.3.2. Particular objectives

Following are listed the particular objectives of this research.

1. Create a novel multi-criteria methodology helping to remove the uncertainty added by the human intervention while performing risk assessment at any NPDP stage.
2. To present a fuzzy linguistic scale to appraise the FMEA
3. Allow the stakeholders to clearly identify risk at any stage of the NPDP, getting an organized and visual risk identified diagram.
4. Apply proposed new methodology, PFDA-FMEA-VSM to the local industry, in a technological product, as a practical validation of it.
5. Perform experiments comparing the proposed methodology PFDA-FMEA-VSM and other already proved methods.

1.4. Hypothesis

The multicriteria methodology PFDA-FMEA-VSM improves the NPDP, while Pythagorean fuzzy sets is embedded into the proposed method, PFDA-FMEA-VSM assures to have a better NPDP risk assessment, removing uncertainty added because of the human intervention while identified risks are ranked.D

1.5. Justification

The trend of the scientific researches publications regarding Pythagorean fuzzy sets (PFS) is increasing since its first publication by Yager [16], the trend graphic is shown in Figure 1. Where is shown a solid and constant publication using this methodology, with a high interest latest years.

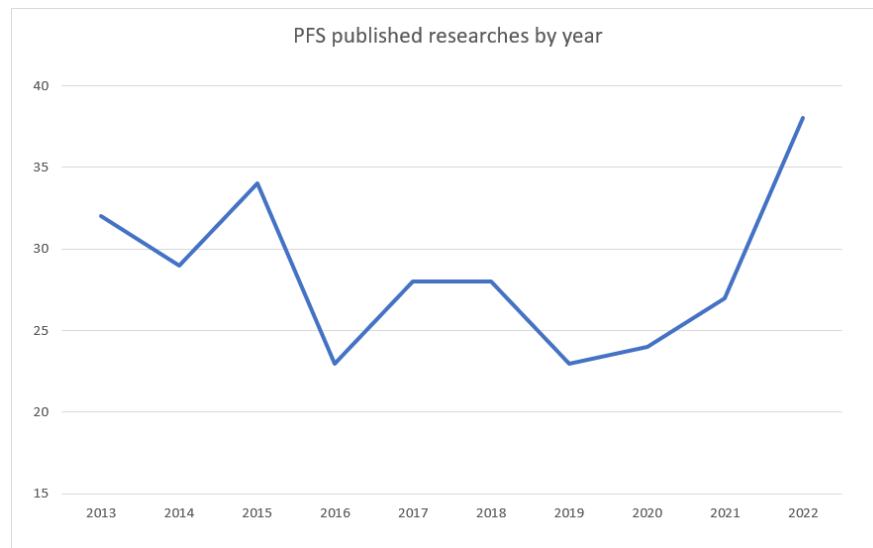


Figure 1. PFS scientific publications trend.

The PFS methodology allows uncertain values as inputs over the risk assessment performed at the NPDP, in this manner, PFS is an optimum tool which complements the proposal methodology.

The expected benefits of proposed PFDA-FMEA-VSM methodology, constitute important contributions to the advancement of the MCDM theory, while the novel

integration of other methodologies, the use of VSM, assuring to visualize the value added at the risk analysis, and using this method in the industry.

Likewise, PFDA-FMEA-VSM helps stakeholders to make better decisions at NPDP, including to reduce flaws at launching new products into the market. Moreover, if companies decide to use PFDA-FMEA-VSM in their NPDP, they will have significant savings because of the minimum number of resources assigned to mitigate just the value-added risks, as well as minimizing product failures in the field.

Highlighting the main improvements for the companies if they adopt PFDA-FMEA-VSM method to their processes, they mainly reduce the time to launch the new product, enhance design efficiency, and decrease the engineering changes/running changes for the new products, all of these at the end represents economical savings (cost avoidance) positive impact, and increase the company competitiveness.

Even though current NPDP methods are strong using current risk analysis tools, success is no longer guaranteed when uncertainty prevails. Integrating FMEA, PFDA, and VSM, methodologies, will improve the NPDP methodology aiding for a better risk analysis, removing the uncertainty during the NPDP-RA, and help stakeholders for a robust decision making, in specific adding resources to mitigate risks, just where required.

1.6. Scope

The scope of this project is to integrate different MCDM tools to create a new method capable to improve the risk assessment during NPDP. This project was developed under industrial environment, in specific at NPDP area. Additionally, the proposed method can be applied at any stage of the NPDP, as well as many times as required to perform PFDA-FMEA-VSM assessment and analysis.

1.7. Limitations

This investigation was limited to analyze the application of the PFDA-FMEA-VSM method to a NPDP environment. Moreover, the investigation proved thru index journal publication and Technologic Product applied to a real industrial process, that PFDA-FMEA method which is the base of the PFDA-FMEA-VSM, can be used to perform any risk assessment, at any industry, process, scenario, and functional area. In other words, PFDA-FMEA can be used at any scenario where the conventional FMEA can be applied.

2. Theoretical framework

This document section presents the theoretical framework including previous research of the different methodologies used in PFDA-FMEA-VSM method.

2.1. New product development process

NPDP is a complex and usually long process, requiring a cross-functional team for multiple activities, the complexity of this process add uncertainty all along the NPDP [17]. Kahn [18], analyzed the requirements of the NPDP at different companies around the world, Shafqat et al [19] investigated about the uncertainty and risks over the NPDP.

A nonstop effort to improve the NPDP, some authors are using a mix of different methodologies with the objective to reinforce the NPDP and get better results. Susanto and Andriana [20], used Quality Function Deployment (QFD) to analyze New Product Development, other authors used Fuzzy sets and TRIZ with the objective to make robust the NPDP [21]. Even there are broad variety of tools and methodologies applied to the NPDP, it is detected that there is not an integral model which use key methodologies to identify possible failures during the NPDP. Another researches are analyzing the new challenges at the NPDP [22], as well as multiple applications [23].

NPDP is an essential activity for the industry nowadays to give competitive advantages [24], and it is required to keep the global economy healthy. Most of the

companies have important investments in new product research and development area [25], because this helps to launch products focused to the different markets, launching the products in the fastest way as possible [26], and within the customer desired quality. Moreover, the companies struggle getting right tools to simplify the NPDP and to assure the expected results of the final products, even some companies has as dedicated teams and resources to create their own manuals to manage their NPDP internally, [27].

Another critical and constant concern for new product developers are the new product field failures [28], [29]. The developers have activities to validate the product and to avoid these possible failures, but these validations take times that can cause delays on the product launches, and even worst for the companies, if the product is launched into the market without the proper validations, the product can fall into a failure in the field, causing in some cases, millionaire loses and sometimes loss of reputation for the companies.

Global companies are constantly trying to improve their NPD procedures, keeping the experience, reducing the time to learn in their experimental activities and teaching better their developers [30], [31], [32] , the competence between companies also is forcing them to implement novel NPD Processes in order to be more efficient and profitable. This effort includes a mixture of different methodologies like Quality Functional Deployment (QFD) and TRIZ [33]. Other companies bet to other proven methodologies like Design For Manufacturing and Assembly (DFMA) which is a

combination of Design For Assembly (DFA) and Design for Manufacturing (DFM) methodologies [34], and some other firms are implementing fuzzy logic and others like Chia-Chung et al, use Multi-Criteria Decision Making (MCDM) to evaluate the NPD performance [35]. Tian et al [36] and Marini et al [37] used AHP, Gray Correlation and TOPSIS Combined proposing a green product design. Even there are broad variety of tools and methodologies applied to the NPD process, it is detected that there is not an integral model which use key methodologies to identify possible failures during the NPDP.

One of the most common and most used process for NPDP is the stage-gate process by Cooper [38], Cooper proposed to use six phases and an exit gate on each gate, Figure 2 shows the stage-gate diagram that Cooper proposed in 1990.

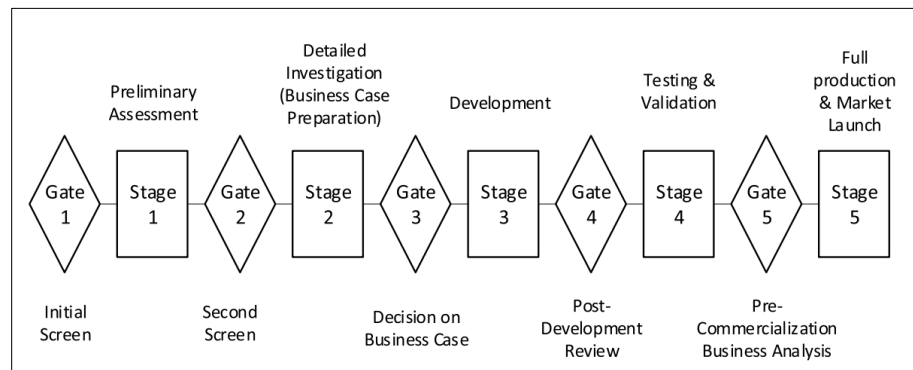


Figure 2. Stage-Gate diagram by Cooper [32], later used by Garcia et al [33].

2.2. Failure mode and effect analysis

A popular tool for risk analysis at NPDP is the Failure Mode and Effect Analysis (FMEA) [39], FMEA is a sustained tool which allows to analyze the risk of possible impact on any process [40]. The FMEA was used by the first time at the military forces since the 70s [41], FMEA was rapidly used at diverse industries, the most important changes to this tool were made at the automotive and the electronics industries [42], later FMEA is constantly be enhanced.

Automotive Industry Action Group (AIAG) has a dedicated segment for FMEA tool, as well as regulates it based on the Automotive industry requirements [43]. A remarkable addition to the tool, was the Risk Priority Number (RPN), established by Braband, [44]. The RPN, is now used to rank the main risks at certain process under scrubbing. The RPN is created by the product of three numbers, each risk has their own RPN value, first RPN number is assigned at the severity of the risk identified (S), usually the value goes from 1 to 10, been 1 a minimum risk and 10, the maximum risk. Then the Occurrence (O) gets the value using same scale as the Severity. Finally, the Detection (D) is assessed, in this case the scale to assign a value is in the opposite order, 10 means a low detection of the risk, while 1 is the highest detection value. The final value of the RPN ranks the critical potential failure on the process analyzed, helping to take the decision if the possible failure mode is a risk or not then, based on the previous range established of the RPN value, contingency plans must be applied to avoid the risk of the possible failure.

Furthermore, as the FMEA gains popularity as risk assessment tool, different authors integrate it to improve existing methods or create new ones. Lui et al [45] added Multi-criteria to the FMEA, later Pillay and Wang [46] combine FMEA and grey relational theory making improvements to the RPN. Likewise Zhou and Thai [47] make failure predictions using fuzzy and grey theories, similarly, Safari et al [48] mix fuzzy VIKOR and FMEA evaluating building design risks, Kutlu and Mehmet, [49] used TOPSIS, AHP and FMEA improving the FMEA RPN, Braglia et al [50] improved the RPN applying fuzzy TOPSIS, supporting mixing fuzzy to the FMEA, the quantitative and qualitative information can be treated similarly obtaining reliable results. Figure 3, depicts a FMEA template by the AIAG 4th edition [43].

**POTENTIAL
FAILURE MODE AND EFFECTS ANALYSIS
(PROCESS FMEA)**

FMEA Number _____
Page _____ of _____

Item: _____ Process Responsibility _____ Prepared By: _____
Model Year(s)/Program(s) _____ Key Date _____ FMEA Date (Orig.) _____
Core Team: _____

Process Step / Function Requirements	Potential Failure Mode	Potential Effect(s) of Failure	Severity Classification	Potential Cause(s) of Failure	Occurrence	Current Process Controls Prevention	Current Process Controls Detection	Detection	RPN	Recommended Action	Responsibility & Target Completion Date	Action Results					
												Actions Taken & Effective Date	Severity	Occurrence	Detection	RPN	

Figure 3. FMEA template by AIAG 4th edition [43].

2.3. Pythagorean fuzzy sets

Since 1965 Fuzzy logic was introduced by Zadeh [51], the main contribution of fuzzy logic is that it accepts error and mixed data as an input in a process, giving an accurate output. Later, Atasanov in 1986, documented the Intuitionistic fuzzy sets (IFS) [52], after that, in 2013 Yager established Pythagorean fuzzy sets (PFS) [16].

Yager improved the IPS helping to get more accurate method removing the uncertainty, since PFS models the uncertainty on the input data and it can handle the square value of the sets of information, it is important to remark since this is the main ability of this method.

Later, with the intention to use PFS and enhance it combining it with different proved methods, different authors used PFS in their researches, like Wichmann et al. [53], published a document using PFS to minimize the uncertain on the NPD project master scheduled, and recent publications, are mixing PFS with different methods, Villa et al. [54], used PFS and Dimensional Analysis (DA), in an industrial application, reducing costs in a supplier selection problem. Likewise, Perez-Dominguez et al. [55], used multi-objective optimization on the basis of ration analysis (MORA) and IPS, to create a novel method allowing to solve complex multi-criteria problems.

Additionally, further studies shown PFS can be blended within different methods having similar or improved results. Wang [56], presents an hybrid method based on IFS. Chen and Ko [57], [58], [59], blended QFD, FMEA, and fuzzy improving

the NPD, as well as enhance customer satisfaction by a risk analysis approach. Fahmy et al. [60] similarly used FMEA combined with other tools making risk assessment for NPD. Dagdeviren and Yuksel [61], mix Fuzzy and AHP to rank risks in a new proposal for risk assessment method. Later Wen, Zhao, and Chen [62] used PFS to predict the metro traffic. Thao and Smarandache [63] also used PFS, they suggested a new fuzzy entropy, an established method later used on this study to validate the proposal methodology.

PFS as part of fuzzy logic, depends on the basic steps ruled by fuzzy logic principles [52], an important Fuzzy logic basis is the Membership Functions (MF). Until now the MF methods are widely explored, and nowadays there are different ways to describe them. Triangular function is one of the most well adopted by the different researches [64], [65], [66]. Figure 4 shows an example of the Triangular MF according [67].

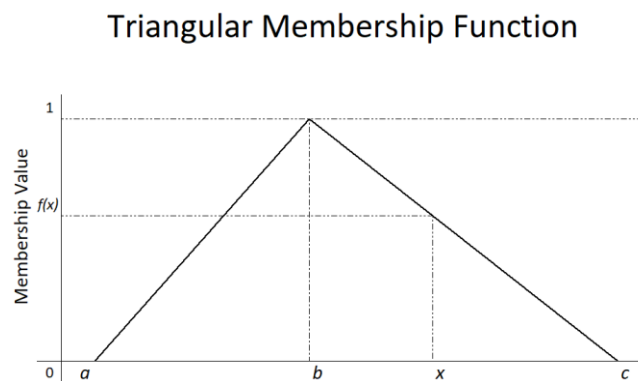


Figure 4. Triangular Membership Function, graphical example [51], [67].

The mathematical function of the triangular Membership Function first explained by Zadeh [51], then by other researches like Zhao and Bose [64] is expressed as follows in Equation 1.

$$f(x; a, b, c) = \max \left\{ \min \left(\frac{x-a}{b-a}, \frac{c-x}{c-b} \right), 0 \right\} \quad (1)$$

While $b \leq x \leq c$

Other Membership Functions used are trapezoidal, gaussian, two-sided gaussian, bell-shaped, sigmoid-right, sigmoid-left, difference-sigmoid, product-sigmoid, polynomial-Z, polynomial-S, polynomial-PI, just to mention the most common MF functions.

Pythagorean Fuzzy Sets (PFS) was proposed by Yager [16], making possible to increase the fuzzy sets used, adding more granularity, and helping to remove in a better way the uncertainty while are utilized for multicriteria problems. As mentioned before in this document, PFS handles the square value of the information in sets. Figure 5 is an image extracted from Yager [16], it shows the difference between fuzzy sets limited to single subsets from 0 to 1, while PFS uses the square of the values on each subset.

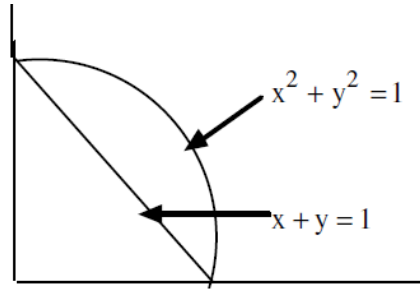


Figure 5. PFS by Yager compared with FS by Zadeh. Yager [16].

Previous research has proven that PFS can give best results handling the uncertainty over multicriteria problems, that is the reason that PFS was used for proposed method in this work.

2.4. Dimensional analysis

Dimensional Analysis (DA) can handle simultaneously different dimensional values and the result can be represent in a single scale as professor Bridgman described, [14], Bridgman introduced the Dimensional Analysis for first time. Later Mahoney and Yaralan [68] wrote about DA different researches.

Perez-Dominguez et al. [69] used DA within IFS, improving the FMEA ranking process. Villa et al. [70] implement a new method combining DA and PFS for risk assessment. Shen et al. [71], wrote a study about the DA applied to the statistics.

2.5. Analytic hierarchy process

Analytic Hierarchy Process (AHP) was proposed for first time by Saaty [72], later different authors were presented research works using this methodology to solve real life problems or mixing AHP with other methodologies. Muqimuddin [73], used AHP for FMEA prioritization.

AHP and DA methodologies are not components of PFDA-FMEA-VSM directly, however, starting this research, AHP was used to prove that it can be added to the FMEA, later adding DA, the AHP-FMEA-DA method [74], was presented in the International Congress on Innovation and Sustainability (ICONIS) 2020 congress, and published in a peer-review Journal, International Journal of Innovation and Sustainable Development (IJISD) by Inderscience and Scopus in 2023.

2.6. Risk and risk assessment

The International Organization of Standardization (ISO), define Risk Management as the uncertainty on objectives [75]. Risk is currently analyzed from different perspectives, and the researchers analyze risk at different processes, Bustos and Pomares-Quimbaya work to reduce the risk at stock market movements [76], then Martinez et al. [77], studied the risk to improve the product development. Later Wu, Liu, and Nie [78] published a literature review focused on the development of the risks

assessment based on FMEA. Later Goswami [79] use the risk assessment framework applied to new product development process.

2.7. Stakeholders

The examined literature reveals that there is uncertainty identifying stakeholders, published by Gregory and Keeney [80], Likewise, Woolridge, McManus, and Hale, published a research based on the stakeholder risk assessment [81], likewise, the reputation of the stakeholder is also analyzed by Alderibigbe [82], and later by Benn, Abratt, and Kleyn [83], also there are researches applied to the Integrated Supply Chain (ISC), like the documented investigation by Menon et al. [84].

2.8. Value stream mapping

VSM was introduced by Womack and Jones [15], later Urnauer et al. [85], used multicriteria tools to adapt a new version of the VSM. Tobias, Mettermich, and Abele [86], performed an holistic analysis of the VSM. Sawhney, Kannan, and Li [87], utilize VSM to evaluate the operations breakdown on maintenance. According Mahadeo and Jayadeva [12], VSM is a valuable tool for Subject Matter Experts(SMEs).

VSM is currently used at the industry mainly under a Lean Manufacturing scope, to improve any kind of industrial process. Recently a VSM lean thinking model

was proposed by Ahmad et al. [88], to identify the non-value added activities in a process. Qui and Liu [89], use VSM for e-commerce analysis reducing errors during the process.

3. Methodology

This section describes the details of the proposed method PFDA-FMEA-VSM, including the materials used during the development of it.

3.1. Materials

The materials used for this investigation are described below, as well as a briefly description about how each material was used during this research.

Computer packages and Software. The use of a personal computer with Windows OS and MS Office were used to write the documents, make basic calculations, and templates. Minitab software used to analyze the data and compute the statistics Later during the project a custom PFDA-FMEA Software, Intellectual Property (IP) in process was created during a technologic stay (virtual), in collaboration of the *Universidad Pedagógica y Tecnológica de Colombia*, and based on the previous research, a PFDA-FMEA Software was developed, the first beta version was used in the industry, at electronic devices factory to perform a product outsource risk analysis, PFDA-FMEA Software was accepted by the Advanced Manufacturing Director, and the company shown interest to use the final version of this software.

3.2. Methods

This part of the document declares the methods used during this research, and a briefly description where were used during the PFDA-FMEA-VSM integration.

Stage-Gate new product development process by Cooper [38]. Cooper's methodology was use as the environment where PFDA-FMEA-VSM was deployed. Likewise, during the implementation of the proposed method, the Stage-Gate methodology was modified and adjusted to make possible the adaptation of the different methodologies embedded on PFDA-FMEA-VSM method, later detailed in this document.

Pythagorean fuzzy dimensional analysis (PFDA) [70]. PFDA is a proved method used to remove the uncertainty on the decision-making process, moreover, the PFDA was utilized and adapted to the FMEA to remove the uncertainty on the risk analysis process.

Failure Mode and Effect Analysis (FMEA) [43]. PFDA-FMEA-VSM was base the risk assessment using the rules and format of the FMEA methodology, other proved tool, and widely used at all the industries nowadays to perform risk analysis in different processes.

Value Stream Mapping. The value stream mapping (VSM) [86] is another extensively used tool in the industry, to help to visualize the process is the VSM, this tool allows the easy visualization of the process under analysis, VSM is usually used as a guide to identify the opportunities and improve the process under analysis.

Subject Matter Expert. The subject matter expert (SME) is defined as a person with remarkable experience in a specific topic. During this research, the participation of different SMEs is essential to performed and validate the assessments.

3.3. Methodologies integration. PFDA-FMEA-VSM method

This section reveals the PFDA-FMEA-VSM method [90] steps, likewise, the results of a real case scenario are presented to explain the proposed method. Figure 6, depicts the flow diagrams with the main activities of the PFDA-FMEA-VSM method.

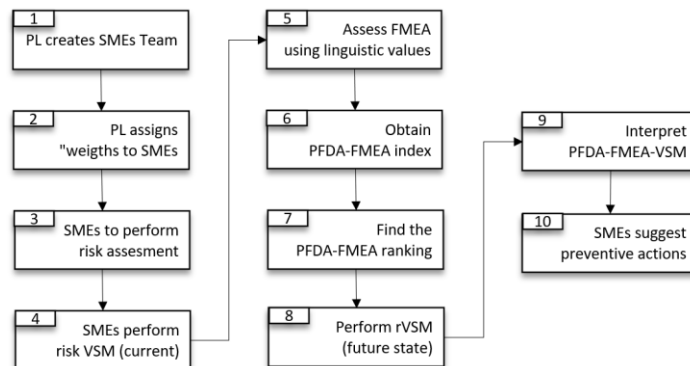


Figure 6. PFDA-FMEA-VSM flow diagram including main activities

Step 1. The first step is to create the team of experts on NPDP topics, it is suggested to organize a kick-off meeting, usually commanded by the project leader (PL) who is the person who organize and drive the exercise, involving the cross-functional leaders, and the stakeholders of the project, it is recommended to involve subject matter experts (SMEs) from different expertise level, as well as include a minimum of three SME members to perform the PFDA-FMEA-VSM.

Step 2. PFDA-FMEA-VSM method requires to add a weigh to each SME participant of the assessment. The weights should be assigned based on the expertise level, as well as the seniority level of each SME. If the PL does not know the SMEs background or expertise level, it is suggested to perform this action in conjunction to the NPDP expert, and a leadership senior level member who do not belongs to the SME team. Moreover, if NPDP expert or senior leadership members are not available during the assessment, or if is difficult to differentiate the expertise of each SME, it is recommended to add the weight as equally among team members.

Step 3. SME team performs the risk assessment. SMEs performing risk assessment. This can be the longest step of the process, here the SME group should complete the risk assessment, using as the FMEA rules combined with the PFDA-FMEA methodology [10]. The assessment should be performed considering the risks that impact direct or indirect to the project, considering the stakeholders interests. Moreover, this stage of the process organizes the identified risks, adding to each

PFDA-FMEA row, a risk identification (RID), which is a consecutive number helping to track each risk for future reference as required. See column 3 in Table 1.

Table 1. PFDA-FMEA Scale to appraisal the main NPDP risks

Column 1	Column 2	Column 3	Column 4		Column 5
SN	Sub-class	RID	Potential Stakeholders	Risk	for "Phase"
1	M	RID1	Potential stakeholders 1	risk	for Phase 1
2	I	RID2	Potential stakeholders 2	risk	for Phase 2
3	P	RID3	Potential stakeholders 3	risk	for Phase 3
4	Q	RID4	Potential stakeholders 4	risk	for Phase 1
5	T	RID5	Potential stakeholders 5	risk	for Phase 2
6	B	RID6	Potential stakeholders 6	risk	for Phase 3

Step 4. SMEs performing rVSM current scenario. This step should be performed by the same SME group previously identified, and it is recommended to get support from a VSM expert if possible. Furthermore, the rVSM is following the conventional VSM rules, focusing on the NPDP as the whole process, omitting conventional VSM details if required.

The rVSM can show the reference identification for each risk identified during the risk assessment, as well as the connections between the different affected areas. The rVSM represents the first visualization of the risks in a diagram, and the map of the process links. In this example the rVSM is the primitive version of the risk assessment visualization. Figure 7 shows the rVSM example, for reference.

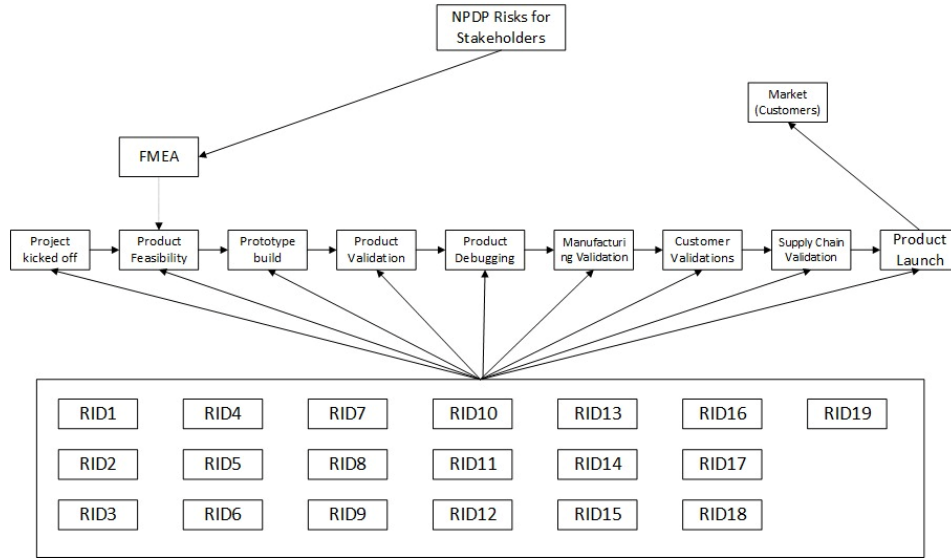


Figure 7. rVSM current scenario example. Garcia et al. [33].

Step 5. Assess PFDA-FMEA using linguistic values. This step uses the linguistic values previously arranged by the MCDM expert, considering the Triangular fuzzy membership function, [91] to get membership and non-membership values, first proposed by Atanassov [92].

This step is also considering, the linguistic expression, linguistic value (membership function and no-membership function), the abbreviation, and the hint, later explained in detail.

There are different methods to get linguistic values, PFDA-FMEA-VSM uses linguistic values as per Du et al proposed in [93], following described mathematically in Equation 2.

$$P = \{(x, \mu_p(x), \nu_p(x)) | x \in X\} \quad (2)$$

Where μ_p and ν_p are sets belong to [0, 1] interval.

Table 2 shows the details for the linguistic values, the hint, and the abbreviation, using example used in [90]. Linguistic variables in this research were chosen following the rules proposed by Yager [16], and triangular function was used to select the MF as described before in the methodology. "Hint" is an adaption used to make easier the integration of the VSM later in the process, this hint helps to visualize the area of the risk identified during the risk assessment, and it allows the stakeholders to easy detect where to focus the resources to mitigate the identified risks. Then the linguistic values were chosen as simples as possible, to make easier to complete the assessment by the SMEs, maintaining "low", "medium", and "high", the options for any risk identified, make faster the risk assessment process, and minimize any SME confusion during the assessment process.

Table 2. Linguistic expressions, values, abbreviation, and hint utilized for PFDA-FMEA by Garcia et al. [90].

Hint	Linguistic expressions	Abbreviation	Membership function, no membership function
Quality	Low affectation to quality	LQ	0.15, 0.95
Quality	Regular affectation to quality	RQ	0.5, 0.55
Quality	High affectation to quality	HQ	0.9, 0.15
Time	Low affectation on time	LT	0.12, 0.92
Time	Regular affectation to time	RT	0.45, 0.56
Time	High affectation to time	HT	0.95, 0.1
Budget	Low affectation to budget	LB	0.11, 0.9
Budget	Regular affectation to budget	RB	0.5, 0.54
Budget	High affectation to budget	HB	0.92, 0.16
Market	Low affectation to market	LM	0.13, 0.91
Market	Regular affectation to market	RM	0.49, 0.51
Market	High affectation to market	HM	0.93, 0.17
People	Low affectation to human	LP	0.15, 0.92
People	Regular affectation to human	RP	0.48, 0.5
People	High affectation to human	HP	0.91, 0.15
Innovation	Low affectation to innovation	LI	0.07, 0.98
Innovation	Regular affectation to innovation	RI	0.47, 0.49
Innovation	High affectation to innovation	HI	0.98, 0.1

Dimensional analysis can be represented by Equation 3, introduced by Willis [94] and later adapted by Perez-Dominguez et al. [69].

$$IS_i(a_1^k, \dots, a_m^k) = \prod_{j=1}^m \left(\frac{a_j^i}{S_j^*} \right)^{w_j} \quad (3)$$

In Equation 3, IS represents the index of similarity for i , then, a_1^k shows a crisp value, and S_j^* is the ideal alternative value.

The SMEs team should use proposed linguistic expressions to assess the risks at the NPDP, it is recommended to use the abbreviations as well, to simplify and avoid confusions later in the process.

Depending on the identified risk on each row, the experts will agree and assign a single linguistic expression. The membership function and no membership function should be captured as well on each line accordingly for further calculation.

In addition to the conventional FMEA rules, there are some key steps to consider described as follows. Each risk should have their own NPDP phase, considering Figure 8 based on Cooper [38], to identify the phase of the risk captured, it is possible and common to have the same risk with different NPDP phase. During this step, it is recommended as well to capture the phase where the risk is being identified using column 5 in Table 1.

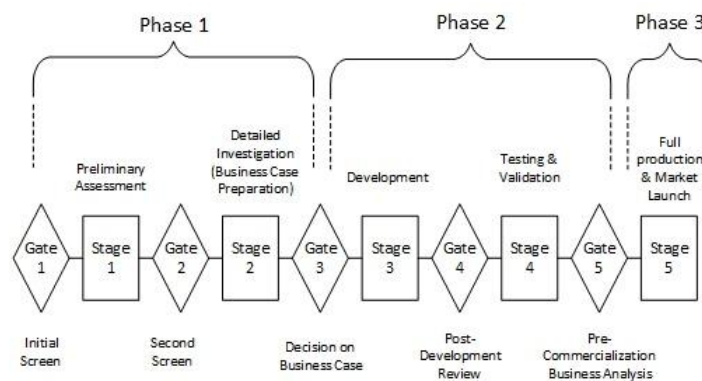


Figure 8. NPDP Phases referencing Cooper stage-gate process [38], adapted by Garcia et al. [90].

Supplementary key step is adding the sub classification of the risk, “sub-class”, which fits into the functional area where the identified risk is potentially affecting the NPDP step identified, this innovative step allows the stakeholders to identify in easiest way the area where the risks are located. This artifact is key to bind VSM to this methodology, since it helps to organize the risks in a visual manner. Table 3 contains the suggested “sub-classes” acronyms and description. Similarly, Table 1 previously explained in this document, depicts in column 2 an example of the sub-class applied to the risk assessment.

Table 3. Subclassifications, “sub-class” list suggested for PFDA-FMEA-VSM method by Garcia et al. [90]

Sub-class	Description
M	Market
I	Innovation
P	People
Q	Quality
T	Time
B	Budget

Step 6. Obtain PFDA-FMEA index. At this step it is required to compute the data to get the PFDA-FMEA index, is required to use Equation 4 by Villa et al. [70] and Garcia et al. [90], it is also required to have the SMEs assessment using the linguistic values in Table 2 to complete the calculation.

$$PFIS_i(\omega_1^i, \omega_2^i, \dots, \omega_m^i) = \left(\prod_{k=1}^n (\mu_{\xi_j^i})^{T_j}, \sqrt{1 - \prod_{k=1}^n (1 - (v_{\xi_j^i})^2)^{T_j}} \right) \quad (4)$$

Equation 4 is explained as follows:

PFIS is the Pythagorean fuzzy index of similarity for $i = 1, 2, \dots, m$. Then ω represents the Pythagorean sets, subsequent μ denotes the membership values assigned, and v the values of non-membership. The SME weights are represented by T , for $j = 1, 2, \dots, m$, $k = 1, 2, \dots, n$, and ξ representing the universe of the evaluated elements, where $T_j \in [0, 1]$, finally the index i is defined by the PFS.

Liu and Zhang [95], Yang and Hussain [96], and Y. Du et al [93] represented PFS in Equation 5, where P is PFS and X is the universe.

$$P = \{(x, \mu_p(x), v_p(x)) | x \in X\} \quad (5)$$

Where $\mu_p(x): X \rightarrow [0, 1]$ describes the degree of membership. Following $v_p(x): X \rightarrow [0, 1]$ defines the degree of non-membership of the component x , where $x \in X$ to P . Likewise, according Liu and Zhang [95], for any $FPS, p = (\mu, v), p$ is defined in Equation 6.

$$s(p) = (\mu)^2 - (v)^2 \quad (6)$$

Where $s(p) \in [-1,1]$

Getting the output crisp values, Equation 2 is used to defuzzifying the fuzzy values obtained from previous calculation.

Step 7. Getting the PFDA-FMEA ranking. This step is to reorganize the information obtained from the previous steps, and it is required in preparation for future steps. The process to obtain the PFDA-FMEA ranking is sorting the ranking values from the highest to the lowest, then classifying the capture RID follow by the consecutive number, being the number one the high risk, followed in consecutive other for the rest of the risks. Table 4 shows an example on how to re-arrange this data.

Table 4. PFDA-FMEA index re-arrange example for reference.

RID	PFDA-FMEA Index	PFDA-FMEA RID ranking
RID4	8.5 x 10 ⁻⁵	RID4-1
RID2	5.4 x 10 ⁻⁶	RID2-2
RID5	4.8 x 10 ⁻⁷	RID5-3
RID1	3.6 x 10 ⁻⁷	RID1-4
RID6	3.2 x 10 ⁻⁸	RID6-5
RID3	2.5 x 10 ⁻⁹	RID3-6

Step 8. Perform rVSM future state. This step is building a visual aid for the stakeholders, the different “sub-classes” are used as the swimlane title, besides, the risks are considered and arranged based on the “phase” of the project, use Figure 8 for reference. Figure 9 shows an example for this step.

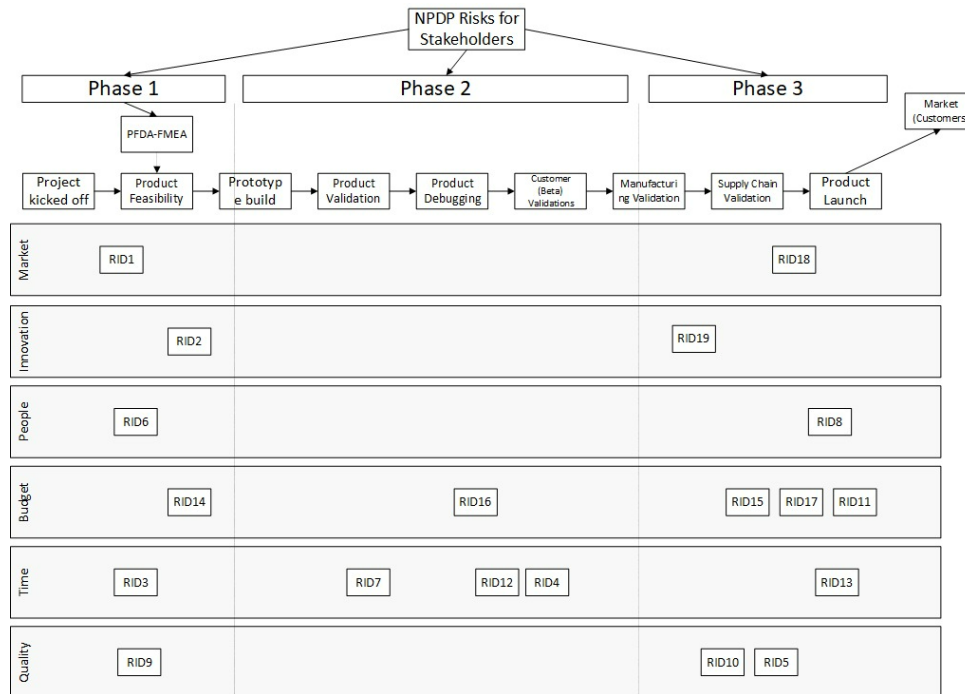


Figure 9. rVSM future scenario example used by Garcia et al. [90]

Later, the SME team will consider a certain number of higher risks, the highlighted risks will be considered to take actions later over the NPDP steps. Figure 10 shows an example of the rVSM (final scenario).

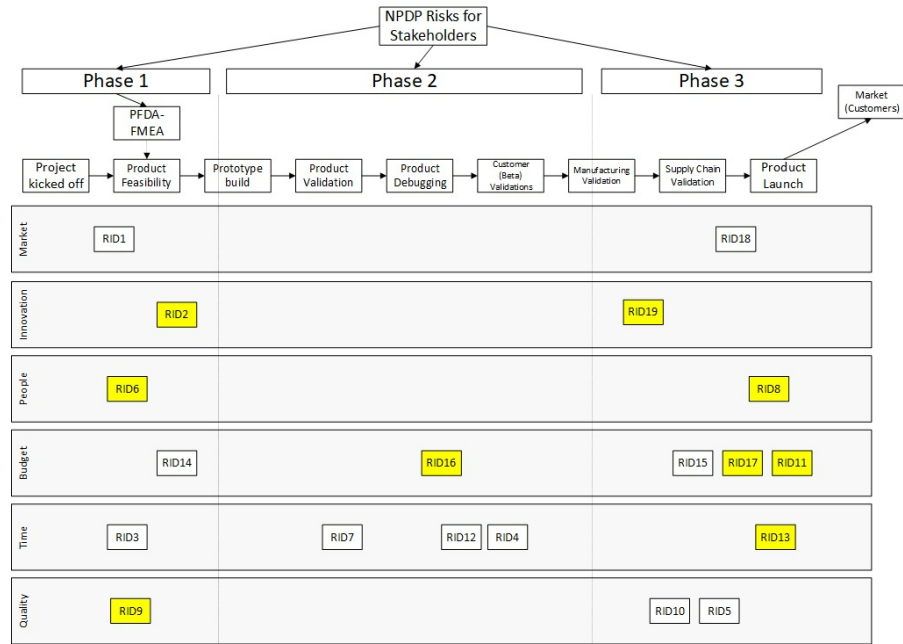


Figure 10. Visualization Areas Diagram (VAD) example, by Garcia et al. [90]

Step 9. Interpret PFDA-FMEA-VSM. This step request focus of the SME team, and it is recommended to perform this activity only by the original SME team, and only if required include in this step the VSM expert. The SME expertise will help to identify any missing information over the rVSM, and the VSM expert will validate any possible misinterpretation of the diagram and revise it if required.

Step 10. SMEs suggest preventive actions. According to the FMEA basics, the highest rankings need to be addressed by action items that prevent the potential failure to exist during the process. At this final stage of the process, the SME team analyze the risks along the rVSM future state diagram, to suggest preventing actions that mitigate the potential impact of the identified risks over the NPDP.

Furthermore, when the SME team presents the rVSM future scenario to the Stakeholders, they together, can adjust the suggested actions and modify them based on the Stakeholders strategy if required.

Highlighting key aspects to adapt multiple methods creating PFDA-FEMA-VSM, the introduction of “sub-class” and “NPDP phase division”, made a smooth fusion of the rest of the tools. Likewise, the Visualization Areas Diagram (VAD) was introduced to allow the stakeholders to visualize in a quick and clear way where are located the top offender risks, specifying the risk and the area in a clean diagram.

4. Results

This section presents the obtained results for PFDA-FMEA-VSM method. Furthermore, will be presented the summary of two publications at recognized International Journals regarding this method. Equally, this section is describing a technologic development tool, applied in a global electronic products industry at Ciudad Juárez, Chihuahua, Mexico factory, where the tool was used in an industrial problem, identifying risks for a NPI outsourcing project, helping to focus the available resources to the main risks, and removing the uncertainty along the process.

4.1. PFDA-FMEA results and application

The PFDA-FMEA method was presented by the first time at the MDPI institution at the Applied Sciences International peer-reviewed journal by Garcia et al. [10], where the method was validated after the analysis of a real case scenario. The summary of the application at MDPI Journal is as follows.

PFDA-FMEA method introduced performing a risk analysis at NPDP. This method was presented at seven steps, first the creation of SME team, second to assign weights to the SMEs, third the SME team executes the risk assessment, fourth apply the linguistic values as part of the risk assessment, fifth to compute the data, sixth to obtain the PFDA-FMEA index, and seven find the ranking.

Part of the validation of the results of this publication, includes the comparison between other proved methods, Pythagorean fuzzy MOORA (PF-MOORA) by Perez-Dominguez et al. [55], Pythagorean fuzzy entropy (PF-Entropy) by [96], and compared by the obtained results of PFDA-FMEA by Garcia et al. [10].

Figure 11, depicts the comparison between the three methods mentioned before, exercise presented in the same document validating PFDA-FMEA method, where it is visually clear the similitude in the values pattern of the tree methods, proving, the PFDA-FMEA method is solid, details in [10].

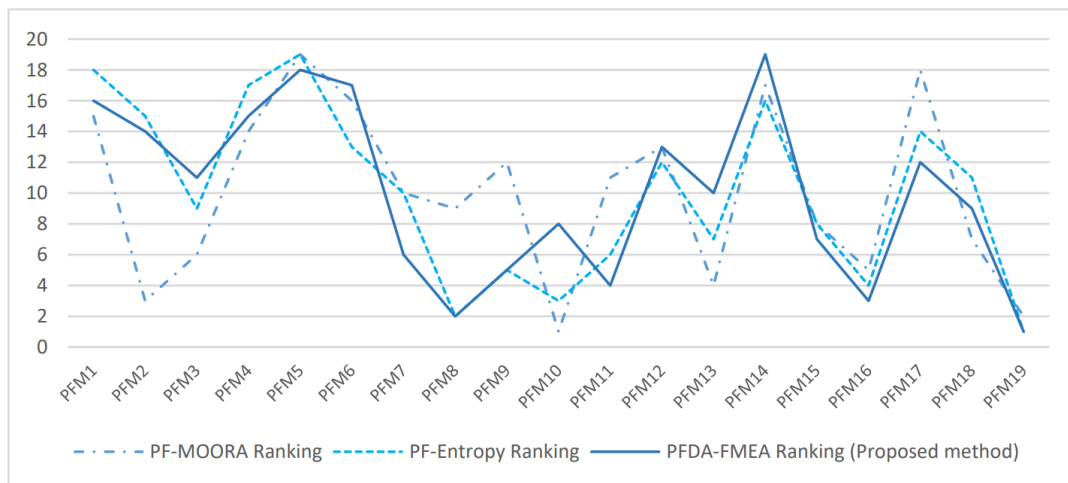


Figure 11. PFDA-FMEA vs PF-MOORA vs PF-Entropy, by Garcia et al [10].

Furthermore, the method put under test making twenty-two different runs using different SME weights randomly, this exercise proves that the uncertainty is removed

independently of the human intervention. The trend in Figure 12 shows a sensitivity analysis that proved that even when the SME weight is different, the result is similar and steady.

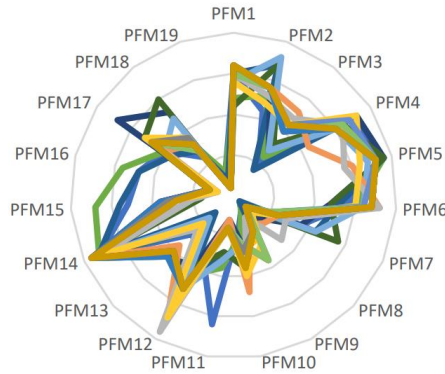


Figure 12. PFDA-FMEA sensitivity analysis by Garcia et al. [10].

Additionally, the PFDA-FMEA method was used in a local industry of electronic products under a Non-Disclosure Agreement (NDA), performing a risk assessment for outsourcing project using the first version of the PFDA-FMEA Software mentioned before, where the PFDA-FMEA method was applied to run a risk assessment free of uncertainty. The stakeholders of the project felt confident for the execution of the method, and the project finalized exceeding the expected cost savings. Different functional area directors of the company remarked that want to extend the use of this method thru the different processes of the company at different global locations.

4.2. PFDA-FMEA-VSM results and application

PFDA-FMEA-VSM method was also proven in a peer-review journal, at the Institute of Electrical and Electronics Engineers (IEEE) by Garcia et al [90], where the method was applied to a real case scenario and proved in the same scientific document. The summary of the method validation and results of it are presented as follow.

PFDA-FMEA-VSM method was used at industrial project, demonstrating it is robust and it can help to provide a clear picture of what are the real risks for the stakeholders in a NPDP project. This method follows the same steps of PFDA-FMEA methodology explained before, adding details to allow to clearly track the different areas where the risks are identified during the assessment. PFDA-FMEA-VSM method by [90] is described in a summary as following in Figure 13.

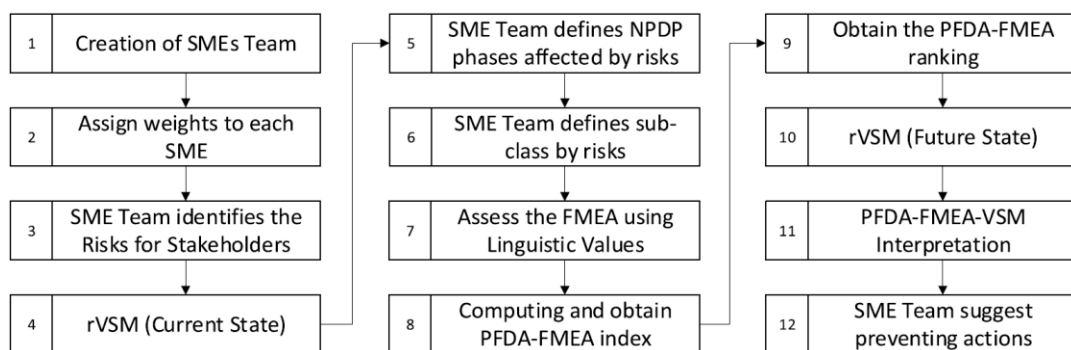


Figure 13. PFDA-FMEA-VSM integration flow diagram by Garcia et al. [90].

PFDA-FMEA-VSM method was presented at the IEEE Access Journal by Garcia et al. [90], Figure 13 contains the steps flow diagram for this method. PFDA-FMEA-VSM method is presented in twelve steps. First step, to create the team of experts to perform the risk analysis. Second step, assigning the weights to the SMEs. Step three, the SME team to assess the process getting risks for stakeholders. Step four, creating the rVSM current state. Step fifth, SME team defining the NPDP phases affected by the identified risks, this action is performed during the risk assessment. Step sixth, SME team to add the “sub-class” at each identified risk. Step seventh, SME with the help of the MCDM expert, use the linguistic values at this step. Step eighth, computing obtained data and present PFDA-FMEA index. Step ninth, obtain the PFDA-FMEA-VSM risk analysis index. Step tenth, creating the future rVSM scenario. Step eleventh, SME to interpret the risks, and identify any critical risks for stakeholders. Step twelfth is related to the SME team suggestions based on the identified risks.

Figure 14 shows the visualization areas diagram (VAD), where the stakeholders can visualize in a practical way, the areas where the main risks are, as well as the area where these risks can take place, and the scale of the risk, allowing to highlight the top ten, more, or less risks identified.

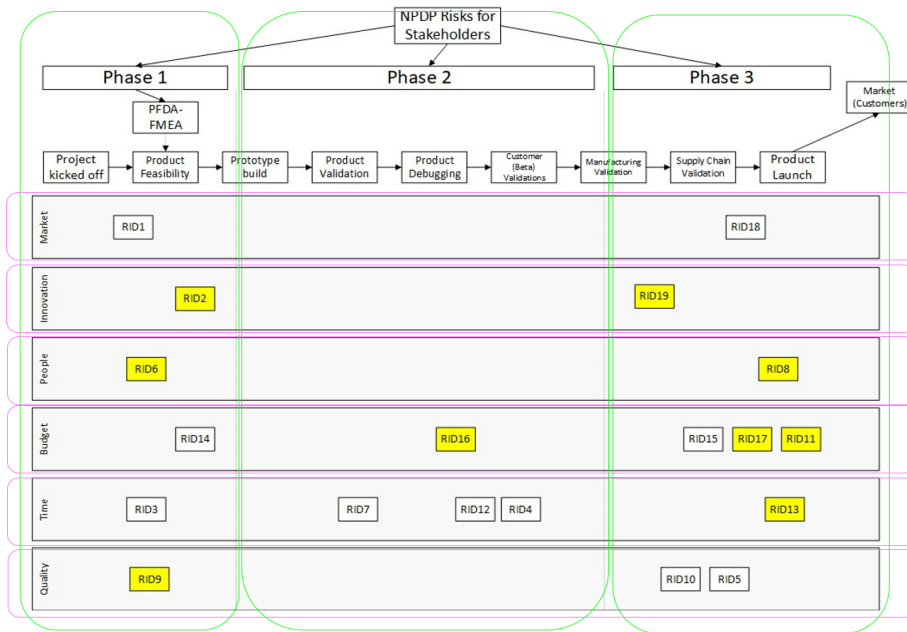


Figure 14. VAD highlighting SC, RID Scale, and phases by Garcia et al. [90].

PFDA-FMEA-VSM method validation is shown using an experimental run. Figure 15 shows the trend of the results while the weights are changed. During this experimental run, the weights of the three SME assigned were changed randomly, then the PFDA-FMEA-VSM method run, and the rank values were captured. While the rank values follow the same trend, the conclusion is that the method is consistent.

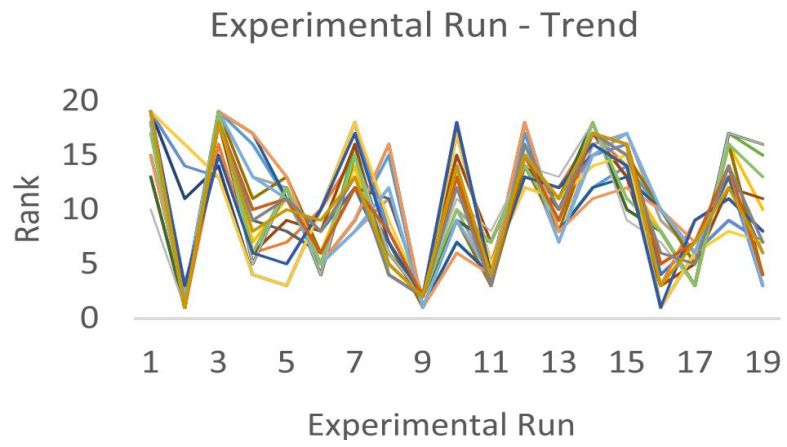


Figure 15. Experimental run for PFDA-FMEA-VSM validation by Garcia et al. [90].

5. Conclusions and recommendations

This section describes the conclusions and recommendations, Likewise, the future works identified are shown.

According to the literature reviewed during this investigation, NPDP is extensively used by a broad variety of industries, to make possible the conceptualization, prototyping, and launch into the market new technological products, moreover, the industries are in a continuous effort to improve the NPDP to avoid risks during the long and complex process.

After the extensive investigation, and validation, it was demonstrated that the PFDA-FMEA-VSM method enhances the NPDP improving the efficiency of the NPDP while this method is used at the various stages of the process. Mixing common industry tools like the FMEA and VSM, likewise, proved multi-criteria methods, the PFDA-FMEA-VSM method is accomplished, a robust and versatile tool to be use at NPDP.

The uncertainty added by the human intervention during the assessment is removed, since PFS method is embedded in presented method, while other common methods are showing ambiguity at the risk assessment, as per previous detailed explanations. Additionally, the application of DA is allowing to manage qualitative and quantitative inputs into the risk analysis, as equally, making the method PFDA-FMEA-

VSM adaptation being efficient and clear for the stakeholders, allowing any type of input, qualitative or quantitative, without affecting the assessment output.

Later adding the VSM, it grants the stakeholders to clearly identify the risks, and highlight the NPDP affected phase. Concluding this investigation, the PFDA-FMEA-VSM method enhances the NPDP, allowing any input to the assessment, removing the uncertainty, making easy to identify risks, and allowing the stakeholders to use the right resources to the right real risk, clearly identified at the specific NPDP area.

As a future works, it is planned to register as an intellectual property the PFDA-FMEA Software used in a local industry to apply the method to a real project, as exposed before. Likewise, to explore the use of PFDA-FMEA-VSM applying artificial intelligence to create real time predictive scenarios for NPDP. Furthermore, a mid-term work is considered to create a PFDA-FMEA-VSM automated template, making easier the use this method at any industry and by any stakeholder group to optimize the NPDP resources.

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