Pesquisa Operacional (2023) 43(spe1): e263696 p.1-24
doi: 10.1590/0101-7438.2023.043spe1.00263696

Printed version ISSN 0101-7438 / Online version ISSN 1678-5142
www.scielo.br/pope
ARTICLES

PRIORITIZATION OF IMPROVEMENT ACTIONS IN INDUSTRIAL PRODUCTION: APPLICATION OF THE FITRADEOFF METHOD TO ORDER IMPROVEMENT ACTIONS IDENTIFIED THROUGH THE FAILURES MODES AND EFFECTS ANALYSIS (FMEA)

José Francisco Zanazzi[1*], José Luis Zanazzi[2] and Daniel Pontelli[3]

Received May 3, 2022 / Accepted September 26, 2022

ABSTRACT. The Failures Modes and Effects Analysis (FMEA) method is applied to different activities in order to improve production processes. Its operation allows to analyze failure modes, describe their effects, identify causes and design control systems. In addition to assessing these factors, it contributes to the formulation of various improvement actions; however, it has an intrinsic weakness when it comes to prioritizing these actions. Although recent versions acknowledge that it is convenient to regulate the beginning of the proposed actions, the method does not provide indisputable tools to establish priorities and organize action plans due to the fact that the Risk Priority Level traditional indicator has been questioned. In face of this need, this contribution proposes to complement the application of the FMEA with an individual multi-criteria compensatory method that allows actions to be programmed in a participatory manner to improve their management. This proposal provides an example of a real world application. The results and limitations of this work are presented in the conclusion.

Keywords: individual multi-criteria decision methods, FITradeoff method, quality systems , prioritization of improvement actions, Failure Modes and Effects Analysis (FMEA).

1 INTRODUCTION

This work applies a multi-criteria decision model to prioritize actions resulting from the analysis of a productive process. The management systems foresee studies to identify prevent or mitigate the effects of possible failure modes. At present, the Failure Mode and Its Effects Analysis

*Corresponding author

[1]Laboratorio de Ingeniería y Mantenimiento Industrial (LIMI), Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba, Córdoba, Argentina – E-mail: jfzanazzi@gmail.com http://orcid.org/0000-0002-3214-9761

[2]Laboratorio de Ingeniería y Mantenimiento Industrial (LIMI), Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba, Córdoba, Argentina – E-mail: jl.zanazzi@gmail.com http://orcid.org/0000-0002-0010-7831

[3]Laboratorio de Ingeniería y Mantenimiento Industrial (LIMI), Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba, Córdoba, Argentina – E-mail: dpontelli@gmail.com http://orcid.org/0000-0002-6016-6550

(FMEA) method is widely used in organizations, especially in the automotive industry (AIAG - Automotive Industry Action Group & VDA - Verband Der Automobilindustrie - FMEA Handbook, 2019). The FMEA allows to obtain different improvement actions which, according to the recommendations provided in the Handbooks, should be gradually implemented in order to avoid introducing unwanted variations or partial failure. One of the characteristics of the FMEA methodology is that it must be carried out in groups by the people who manage the process. Analyzes must be reviewed periodically in order to strengthen the operations of the processes. Different versions of the FMEA have difficulties regarding prioritization of the proposed actions. This flaw undermines work operations and may generate the variations and failures which are meant to be avoided. Therefore, this paper proposes applying an individual additive compensatory multi-criteria method, known as FITradeoff, an acronym for the terms “Flexible and Interactive Tradeoff” (de Almeida et al. 2016) in order to solve this problem, overcome the shortcomings of the FMEA and obtain a well-grounded action plan. This methodology allows to order the actions and support the production line leader activity planning.

The FMEA is considered one of the fundamental tools of the automotive industry. Although it has several applications, the most well-known can be found in the product design phases and in the study and improvement of productive processes (Liu et al. 2019). In its application to the productive processes and in its different versions, the method has a typical base form that separates the process into operations and distinguishes the technical requirements from each operation. Then, the model requires to identify possible failure modes and state their effects. Based on these effects, a table is used to evaluate the seriousness of the problem by means of an indicator (S). The next step requires to analyse the causes of each failure mode and to evaluate the likelihood of occurrence by using the indicator (O). Next, the control systems implemented in each job position are examined and their ability to prevent or detect failure modes is measured by means of a third indicator (D). These three indicators are defined on a scale from 1 to 10, where 1 is the best situation and 10 is the worst situation. The product of these indicators is called the Risk Priority Number (RPN). Until 2008, companies had to adopt an RPN threshold to identify cases in which improvements were mandatory (Kluse, 2020).

However, these strategies have some flaws. On the one hand, they encourage the tendency to manipulate indicators in order to avoid exceeding RPN limits. On the other hand, organizations tend to focus their controls on the number of apparently solved nonconformities and require to show these advances. In this way, organizations focus on superficial actions that are usually costly. Due to these distortions, the practice of using RPN indicator thresholds to identify the need for improvement actions was abandoned. Instead, a wide variety of methodologies were tried out with different levels of difficulty (AIAG & VDA - FMEA Handbook 2019; Maisano et al. 2020)

Nonetheless, the various solutions that were implemented to determine whether improvements should be made still have shortcomings, such as the following (Maisano et al. 2020):

- The number of implemented actions may be very high, which lowers the quality of improvement tasks that are actually carried out. The AIAG FMEA Handbook itself suggests that the factory should analyze not more than five or six failure modes at the same time.
- The tool does not provide control mechanisms to reduce uncertainty due to missing or wrong basic data in the analysis.
- The method requires the analysis to be carried out with multidisciplinary groups of experts, but it does not include a mechanism to promote consensus or degrees of agreement.

These are not minor issues. According to Mzougui et al. (2020), the possibility of significant risks during the processes is reduced when effective decisions are taken. For this reason, they suggest applying Multiple-Criteria Decision Making (MCDM) methods to plan actions, not only from a group perspective but also from an individual perspective.

However, the literature shows that multi-criteria methodologies applied to FMEA generally recommend altering the framework of the method by incorporating criteria or descriptions which are not included in the formats used by big clients. The consequence of these changes is that companies cannot adopt these improvement proposals. In many cases, the most frequently proposed methods are those that classify different elements within a set of previously defined categories (Dias et al. 2018; Doumpos & Zopounidis 2018; Köksalan et al. 2017; Zanazzi & Alberto 2020). These contributions agree on the convenience of incorporating other criteria, such as action costs.

In general, the dominant paradigm is that of individual decisions; therefore, the specialized literature refers to applications that include decision models according to this approach. This is not a minor issue since it implies prioritizing individual actions, while the FMEA is essentially a group methodology. According to the authors' opinion, current dynamics that organizations face in their decision-making processes require them to back up their actions, share their work plan and increase implementation flexibility and speed.

The leader's individual decision to plan actions may generate conflicts and it may affect the subsequent commitment of the work groups that make the FMEA. On the one hand, the group does not know the criteria used to sort out actions; and on the other hand, they do not know the way in which this selection is carried out.

The previously mentioned aspects affect the performance of the leader who faces several challenges, such as planning the actions and putting together a work plan; sharing with the participants the conditions to select the proposals; obtaining the support of those who implement those proposals, and at the same time, managing follow-up interventions. Hämäläinen et al. (2020) acknowledges that leadership in organizations is essential to the effectiveness of interventions and that participatory modeling is a learning instance aimed at working together with stakeholders in order to create formalized and shared representations of reality.

In light of the abovementioned reasons, this work puts forward an improved proposal for FMEA process management. On the one hand, it presents group analysis with the FMEA format used by the companies without modifications. On the other hand, it proposes and analyzes a set of actions aimed at reducing the probability of failures, improving the available controls and eliminating or reducing the effects of failure. As De Almeida et al. (2015) explain, this situation is a decision problem with multiple objectives and various aspects or dimensions, which requires participants who are committed to the success of these activities. Once these improvement actions have been identified, it is suggested to prioritize them with a multi-criteria model called the FITradeoff method (De Almeida et al. 2016), whose dynamics allow for considering the work group's opinions. To facilitate an understanding of the proposal, this paper includes the treatment of a real world production process.

Regarding the organization of this article, Section 2 presents a review of the paradigms of organizational interventions. Next, Section 3 describes the tools used in this work and section 4 summarizes the methodological approach. In section 5, the application example is described. Section 6 presents the findings and section 7 puts forth the general conclusions.

2 MANAGEMENT OF ORGANIZATIONAL INTERVENTIONS

Organizational interventions are referred to in the specialized literature as improvement actions and activities which are proposed in organizations to correct mistakes, improve operations, increase reliability and control variability, among many other possibilities. According to the analysis presented by Midgley & Rajagopalan (2020), these interventions, which derive from the concept of systemic intervention, are defined by deliberate actions implemented to achieve a change.

These actions have a high failure percentage when solving problems or implementing continuous improvement processes. They usually fail in some of their different stages due to multiple factors. According to McLean & Antony (2014), some reasons can be grouped around topics such as motives and expectations, organizational culture and environment, managerial leadership, implementation approach, training, project management, and levels actors' participation in the processes. In this case, the studies are aimed at analyzing the causes and mechanisms that generate failure (Rapp & Eklund 2007; McLean et al. 2017).

This perspective differs from the usual view of researchers who focus on observing instances of success to be replicated instead of analyzing failures (Fryer et al. 2007; Buech et al. 2010; Singh & Singh 2012; Meiling et al. al., 2012; Patidar et al. 2016; Lina & Ullah 2019).

Despite these different approaches, the authors agree that there are different variables, dimensions and factors that condition and generate uncertainty in improvement processes and organizational interventions (Morin & Pakman 1994; Midgley 2003; Rosenhead 2006; Mingers 2011a).

Therefore, problems may come out as the effects of causes which are difficult to attribute to a single dimension or to a specific issue. Some aspects that complicate situations that arise in the administration of production processes are the following: the organizational context of the problem, the interested parties, the multiple actors involved, the structure of the organization, applied regulations and systems, the productive market in which they operate, environmental requirements, the institutional culture, its vision and values.

Moreover, both approaches agree that organizations learn even in those circumstances. Some studies indicate that the experience of failure is forgotten more easily than the experience of success and that its impact influences the companies' learning effectiveness. Failure can be considered a gap in organizational knowledge; therefore, it not only increases the willingness of the members of the organization to look for solutions, but it also provides guidance about activities that could be more productive (Madsen & Desai 2010).

On the other hand, even in cases where there have been no significant failures in achieving objectives, the complexity of the organizational problems determines the performance of those who must lead the processes in uncertain contexts. Uncertainty affects the decision maker's ability and it may lead to indecision and fear (Phillips-Wren & Adya 2020). In these contexts, decisions are not exempt from conflicts causing stress on those who manage them, because it limits data and information processing capacity and is health damaging. Some authors point out that stress affects the ability to make decisions effectively at a neurophysiological level, since it impacts the area of the brain associated with decision making, i.e. the prefrontal cortex (Cote & García 2016).

For these reasons, it is advisable to approach problems from a holistic point of view so as to find solutions to remove the root of the problem (de Almeida et al. 2021). However, learning from this experience is considered more important than the solution of the problem itself.

According to the authors of this work, there are also divergences between methodological recommendations made by management models and those made by science. On the one hand, limited and apparently simple tools are suggested. On the other hand, the need to apply methodologies with multiple approaches is recognized, which promotes the combination of tools. Management systems evidence a tendency to develop ways to reduce analysis time. In general, these modifications are based on classic tools grounded on the P-D-C-A approach proposed by Deming & Edwards (1982) or recommendations of standardized regulations aimed at regulating quality systems used in organizations (Soković et al. 2009; Rewers et al. 2016).

However, there are criticisms of this type of approach to modern organizational situations. For instance, these tools do not incorporate previous analysis and structuring of the problem, and they have difficulties in discriminating the proposed improvement actions. Another crucial issue is that, in general, these tools are not aimed at promoting commitment to the implementation of improvements, which in turn does not encourage its monitoring. In relation to this, the specialized literature shows that there is an increased and constant growth of contributions aimed at complementing these traditional methods. Regarding quality systems and productive process management in particular, there are systemic intervention proposals for the resolution of problems. There is a clear interest in developing approaches to improve the results of efforts which focus on organizational initiatives (Midgley 2003; Braidot et al. 2003; Garcia-Sabater et al. 2012; Radano & Velinsone, 2015; Rajagopalan & Midgley, 2015; Lina & Ullah, 2019)

From this point of view, difficulties call for broad approaches that allow them to be shaped in a flexible and participatory way. There are situations in which they can be structurally shaped, while in other situations this is not feasible. Some situations have available information and allow for the application of a mathematical tool whereas in other situations this possibility is not evident. This interest is not a new one. For a long time, the combination of methodologies to improve organizational results has been an area of concern (Yolles 2010; Franco & Lord 2011; Aviles & Dent 2015; Henao & Franco 2016; Ferretti 2016). A growth in applications of problem solving methods can be observed in many areas (Lami & Tavella 2019; Tavella & Lami 2019; Júnior & Schramm 2021).

This article acknowledges the existence of multiple causes that trigger various production problems and holds that these situations configure uncertain scenarios with conflicting interests, which determine the success of a business action. It is also believed that the resolution of a problem contributes to the possibility of sharing knowledge and supporting learning so as to improve production processes. Common questions, such as the following, arise in the context of organizations: What interventions should be implemented? Should we apply several interventions or just a reduced amount? Why should certain actions be applied instead of others? How can their management be improved? Faced with this reality, the literature and the management models agree on the number of initiatives that should be managed in an action plan. According to Francozo et al. (2021), prioritizing the quantity of transformations improves their management. Quality systems also recommend not to work on a large number of variables at the same time.

3 APPLIED TOOLS

3.1 Failure Modes and Effects Analysis (FMEA)

The FMEA method was created to carry out a continuous revision of different types of systems, which is geared to identify possible failure modes and mitigate their consequences. Designed in the 1940s in the field of the aerospace industry, this resource has been applied to a significant variety of production activities (Mikulak et al. 2017). Over time, the methodology was adapted to other production schemes, especially in the area of automotive production. The FMEA has a predictive nature; it allows risks to be quantified according to the relevance of each failure mode, its occurrence and detection capacity. This method seeks to provide a prioritization of failure modes and a list of preventive actions for their control and removal (Frank et al. 2014).

Some examples of the multiple fields of application of this tool are the following: its use in activities of diverse nature such as the treatment of medical conditions (Chiozza & Ponzetti, 2009; Thornton et al. 2011; Dastjerdi et al 2017); the assessment of risks in supplier selection (Li & Zeng, 2016); the prevention of problems in software development (Zhu 2017); the improvement of management systems in libraries (Zanazzi et al., 2010); and the design of a work plan for proposed improvement actions (Zanazzi et al., 2022).

In any case, when the method is applied to production processes in its different versions, it has a characteristic base form that leads to separating the process into operations and distinguishing the technical requirements of each operation. Then, it requires analyzing possible failure modes and stating the effects of those failures. According to the effects, there is a table where the seriousness of the problem can be assessed by means of an indicator (G). The next step requires analyzing the causes of each failure mode and assessing its probability of occurrence through another indicator (O). Afterwards, the control systems implemented in each job are recorded and their failure mode detection capacity is measured by means of a third indicator (D). These three indicators are defined on a scale of 1 to 10, where 1 is the best situation and 10 is the worst. The product of the previous indices is called the Risk Priority Index (IPR) or Risk Priority Level (NPR), depending on the version of the method (Kluse, 2020).

Until 2008, companies that applied the second or third version of the FMEA had to adopt an NPR threshold to identify when improvement actions should be implemented. Generally, improvement actions starded when the NPR was greater than or equal to 80.

The FMEA, in its second or third version, has some shortcomings. On the one hand, it encourages a tendency to manipulate indicators to avoid exceeding NPR limits. On the other hand, companies focus their controls on the number of apparently resolved non-conformities requiring evidence of those advances. In this way, the organization focuses on costly superficial actions.

These shortcomings are formalized in the fourth version of the FMEA proposed methodology, where the analyzes are aimed at implementing automated controls in key operations of the processes. In this edition, North American automotive manufacturers decided to abandon the practice of requiring actions from certain NPR thresholds. In its place, a great variety of criteria have emerged, some of which are highly complex. Different modalities have been proposed, such as the NPR indicator (the product of severity, occurrence and detection). An alternative to this is to compose a three-digit number where severity is expressed in hundreds, occurrence in tens, and detection in ones.

In June 2019, a joint effort between German and North American automotive industries imposed the use of a new Handbook, known as AIAG (Automotive Industry Action Group) & VDA (Verband Der Automobilindustrie) FMEA Handbook (2019), whose application, for the time being, is only mandatory in new processes. This Handbook includes an Action Prioritization table with high, medium and low categories. In addition, these categories are associated to traffic light colors, which helps to identified them more easily. Prioritization is based on the adopted indicators: G, O and D, and their respective tables.

However, different solutions adopted to define action performance still have some shortcomings, such as the following (Maisano et al. 2020):

- The number of compromised actions can be very high, which is detrimental to the quality of the improvement tasks which are actually carried out. The AIAG FMEA Handbook itself suggests that a company should not analyze more than five or six failure modes at the same time.

- The tool does not include control mechanisms to reduce uncertainty due to missing information or errors in the information base used in the analysis.
- The method requires the analysis to be carried out with multidisciplinary groups of experts. The aim is to encourage participation, exchange of different perspectives and the resulting commitment to the agreed action plan, but it does not foresee a mechanism for measuring consensus or degree of agreement.

4 A 12-STEP FRAMEWORK FOR PROBLEM DECISION MODELING

According to De Almeida (2013), structuring problem is a priority issue to model decision problems. He holds that the decision problem solving procedure includes choosing the most appropriate method to deal with it and that it is determined by its fundamental characteristics. He also describes and integrates three phases in a series of twelve (12) steps to approach the decision process.

Problem modeling generates multiple approaches that lead to the possibility of applying different models. The author proposes a procedure to build the decision support model that consists of three main phases which, in turn, are divided into several steps. The first and second phases correspond to the design stage of the decision process. The third phase is related to choosing the model.

4.1 FITradeoff Multi-criteria Method (Flexible and Interactive Tradeoff)

FITradeoff is a multi-criteria method proposed to obtain criteria weights in an interactive and flexible way (De Almeida et al. 2016). It uses partial information about the decision maker's preferences, according to an additive model in MAVT (Multi-Attribute Value Theory) scope. This method uses the concept of flexible elicitation to improve applicability. In this way, the required information for the decision maker is reduced and the comparisons of results are simplified. This makes it possible to assign criteria weights more easily.

It is a compensatory, additive and individual application method. It uses a flexible structure with graphs in order to determine criteria weights where various strategies are applied: elicitation by decomposition based on the classic tradeoff procedure and holistic evaluations, which allows to improve the modeling of decision makers' preferences (Frej et al. 2021). That is, FITradeoff performs combinations of two paradigms in preference modeling addressed by De Almeida et al. (2021): elicitation by decomposition and holistic evaluations. In addition, the use of the proposed methodology is a simple task that allows to return to any decision process stage in case of doubts or inconsistencies.

The aggregation or synthesis where recommendation is provided to the decision maker is carried out through the Linear Programming Application.

The method has several applications in various research fields (Fossile et al. 2020; Correia et al. 2021). Moreover, a support software called FITradeoff DSS (*Decision Support System* -

www.cdsid.org.br/fitradeoff) has been developed, which facilitates its use, allows for a sensitivity analysis to be performed by applying the Monte Carlo Method, and provides the option to set weight variation range (Silva 2021).

5 PROPOSED METHODOLOGY

The following approach to the problem of prioritizing improvement actions can be used with any version of Process FMEA. The application and monitoring of this methodology generate transformation proposals to remove the causes of failure modes. Even though the need to carry out all possible activities (improvement actions) is clear, it is always advisable to plan the work in such a way that its effectiveness can be improved. In general, trying to perform multiple actions simultaneously affects the ability to succeed. The proposal has four phases:

- Phase 1: The production process is reviewed with the responsible parties and in accordance with the FMEA methodological proposal. Improvement actions (alternatives) are obtained.
- Phase 2: The responsible parties define the problem, discuss the context, and establish objectives (criteria), among other issues. This information is used to select the decision-making model that will be used to order the actions.
- Phase 3: The process leader applies the most convenient method, in this case FITradeoff to obtain criteria weights and the ordering used when planning the actions.
- Phase 4: Finally, the work plan is shared and the way in which the actions were ordered for its implementation is explained.

Finally, the person responsible for the process confirms the plan for the selected activities, coordinates them with the work group and they agree on monitoring indicators.

Figure 1 summarizes the methodological approach applied for the combination of tools.

6 AN APPLICATION EXAMPLE

To exemplify the proposal, a car springs production process is analyzed. It begins when a steel bar enters a furnace, whose function is to bring the material to melting point, just over 900 degrees. The bar is then rolled to a pattern indicated by the geometry. The piece is then immersed in tempering oil at about seventy degrees Celsius; the sharp cooling increases the surface hardness of the steel but makes it fragile. For this reason, the next operation (tempering) consists of a stay of at least ninety minutes in a new furnace that works at four hundred degrees, allowing the tensions of the unit to be relieved. At the next station, the spring is bombarded with steel spheres to increase its working life (blasting). Then antioxidant is applied and it is painted. Finally, a test compresses the spring to verify that the required force meets the technical specifications (see Figure 2).

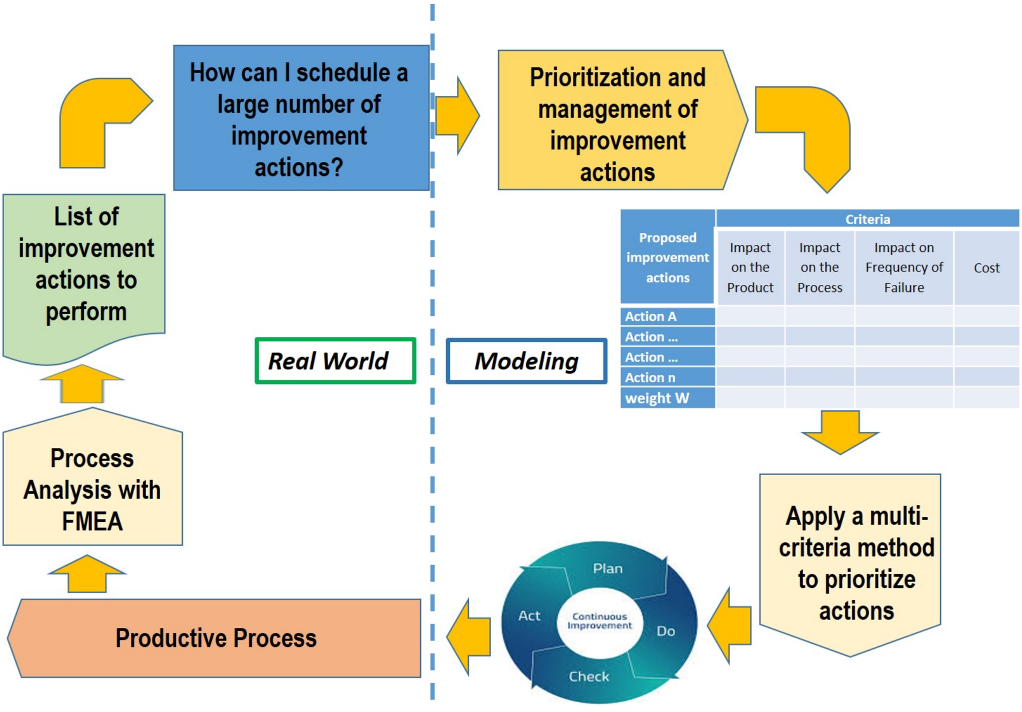

Figure 1 – Methodological approach
(Source: own elaboration).

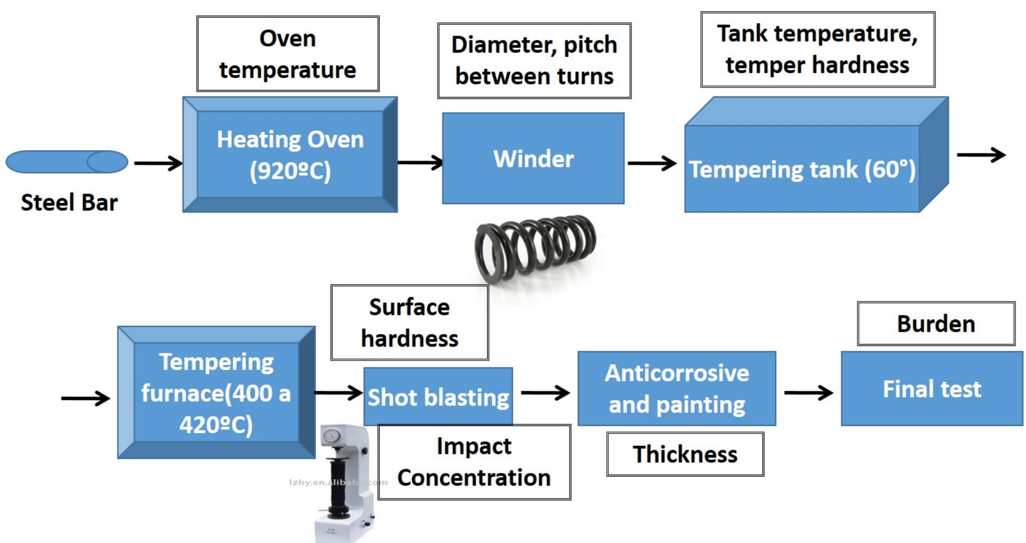

Figure 2 – Operations spring manufacturing process. Identification of critical variables
(Source: own elaboration).

Critical characteristics are identified in some operations of the production process. These variables must be controlled to avoid failures in the final product; controlling its variability is a central activity for the process stability.

7 RESULTS

In Phase 1, during the process review the responsible parties define the actions. They propose a total of seven (7) improvement actions. These actions are assigned to each operation of the process and they make up the alternatives that must be prioritized for subsequent implementation. Table 1 provides a summary of the FMEA analysis which was performed.

Proposals are suggested, such as the modification of a procedure, the purchase of an optical sensor or the change of a tempering furnace. In these cases, it is considered convenient to incorporate criteria that allow to differentiate and prioritize these actions, for example intervention costs.

As part of the information gathered in Phase 2, definitions about the problem, its context and objectives are grouped. This activity is summarized in Table 2.

In Phase 2, the people responsible for the process also define criteria in collaboration with the process leader. Table 3 shows the proposed criteria and categories to assess transformations.

This is the point where the most appropriate decision-making model to address the problem, its conditions and the context are determined. In this case, there is an individual decision maker who has to to sort out improvement actions through the evaluation of proposed transformations for each established criterion. Therefore, actions are ordered according to their performance in each criterion.

In Phase 3, the line leader evaluates the action (alternative) for each criterion based on the available categories. Table 4 summarizes valuations and categories.

Then, it applies the steps of the FITradeoff method to assign criteria weights and evaluate alternatives. In order to do this, the FITradeoff DSS software is used. This software requests information about the decision maker preferences and available alternatives. Finally, it applies evaluation strategies to each criterion action, where the ordering of actions is obtained by dominance relationship, as can be observed in Table 5.

According to these evaluations, the process leader should prioritize the implementation of the first two actions, modify maintenance criteria and place an optical sensor on the chunk to detect deformations. The software provides options to obtain different graphs, such as the dominance ratios of all the options for those criteria.

Finally, a sensitivity analysis is requested to assess whether there are changes in the choices due to changes in criteria weights. A variation of 10% is determined as it is shown in Table 6.

Table 1 – Automotive spring manufacturing process
(Source: own elaboration).

Process: Manufacture of car springs						
Operation	**Function. Requirements**	**Failure modes**	**Consequences**	**Cause**	**Frequency**	**Improvements proposed**
Heating the rod	Rod temperature to melting point	Temperature below specifications	May cause mild problems in the coiling	Fuel (gas) supply problems	1 every 20000	Place a pressure gauge in the gas circuit, which automatically stops the job in the case of excessive variations
Coiling	Space between coils	Very small space	May affect paint and cause cosmetic defects	Large rod diameter	1 every 30000	Install a go-no go gauge before entering the heating furnace, which prevents the treatment of parts with deformations
				Damaged chuck	1 in 300	Add an optical sensor that checks the chuck and detects possible deformations
Coiling	Outer diameter	Excessive outer diameter	May affect paint. Claims for assembly difficulties	Chuck maintenance	1 in 500	Modify the procedure used for chuck maintenance
Quenching	Sharply reduce spring temperature to harden the surface of the part	Out-of-spec quenching oil temperature	The required surface hardness is not reached	Oil cooling circuit runs with problems	1 every 9000	Change the components of the oil cooling system with high periodicity
Tempering	Reduce stress on the spring surface that originates from tempering	Non-homogeneous temperature profile inside the furnace	Heterogeneity in the surface hardness of the tempered parts	Failure in maintenance of the tempering furnace. Age of the tempering furnace	1 every 10000	Change the tempering furnace
Blasting	Blast the spring surface with steel balls, to extend the service life of the part	Nozzles deformed by use	Parts do not receive the density of impacts needed to achieve the service life required by design	Wear of nozzle material	1 every 25000	Implement a method of checking and maintaining nozzles

Table 2 – Activities developed in Phase 2. 12-step Problem Decision Framework Analysis (Source: own elaboration).

Analyzed problem	A productive process leader has to plan improvement actions resulting from the FMEA analysis, so that the team executes them. The FMEA has difficulties to discriminate the actions according to the adopted criteria, the indicators and their manipulation.
Context of the problem	The FMEA is a required tool by quality management systems. Clients, parent companies, managers, among other actors, request its implementation and require reports on the progress made. The operators of the process collaborate with the leader in its elaboration.
Available time	FMEA reviews are conducted regularly by the work groups between 6 and 12 months after the last analysis. In general, the term for the implementation of corrective and preventive actions is between 15 and 30 days. The term for improvement proposals is around 2 months. After implementation, its monitoring is continuous and results must be recorded.
Main objective	Prioritizing actions resulting from the FMEA in a systematic way, where aspects that the tool does not value are incorporated, so that it allows selecting a reduced number of activities to facilitate its implementation.
Specific objective	- Incorporating criteria that allow the proposals to be prioritized. - Evaluating the performance of actions according to the defined criteria. - Planning improvement actions.

Table 3 – Definition of criteria and establishment of categories (Source: own elaboration).

Criteria	**Definition**	**Categories**
Impact on the Product	Impact of the proposed action on the product. Target to maximize.	Slight Minor High Very high
Impact on the Process	Impact of improvement on the process. Criterion to maximize.	Slight Minor High Very high
Probability	Influence of the proposed transformation to reduce the likelihood of failure occurrence. Criterion to maximize.	Slight Minor High Very high
Cost	Cost of the improvement. Minimization Criterion.	Slight Minor High Very high

Table 4 – Classification of the proposed improvements (Source: own elaboration).

Proposed improvement actions	**Criteria**			
	Impact on the Product	**Impact on the Process**	**Impact on Frequency of Failure**	**Cost**
Place pressure gauge to regulate gas pressure	Slight	Minor	Slight	High
Go-no go gauge when entering the heating furnace	High	Slight	Slight	Slight
Optical sensor on the chuck, which detects deformations	Very high	High	Very high	High
Modify chuck maintenance criteria	Very high	High	Very high	Slight
Improve the oil circulation system in the quenching	High	Minor	High	Minor
Change the tempering furnace	High	Minor	Very high	Slight
Implement nozzle check and maintenance in the blaster	High	Slight	High	Minor

Table 5 – Prioritizing proposed improvements (Source: own elaboration).

Ranking Position	Alternatives
1	[Modify chuck maintenance criteria]
2	[Optical sensor on the chuck, which detects deformations]
3	[Change the tempering furnace]
4	[Improve the oil circulation system in the quenching]
5	[Implement nozzle check and maintenance in the blaster]
6	[Go-no go gauge when entering the heating furnace]
7	[Place pressure gauge to regulate gas pressure]

Table 6 – Criteria Percentage Variation. Source: FITradeoff DSS.

	Sensitivity Analisys			
Variation Percentage Values	Impact on the product	Cost	Impact on the Process	Probability
Max	+10%	+10%	+10%	+10%
Min	-10%	-10%	-10%	-10%

In Figure 3, you can see a summary of the modifications as a result of the variations of the weights.

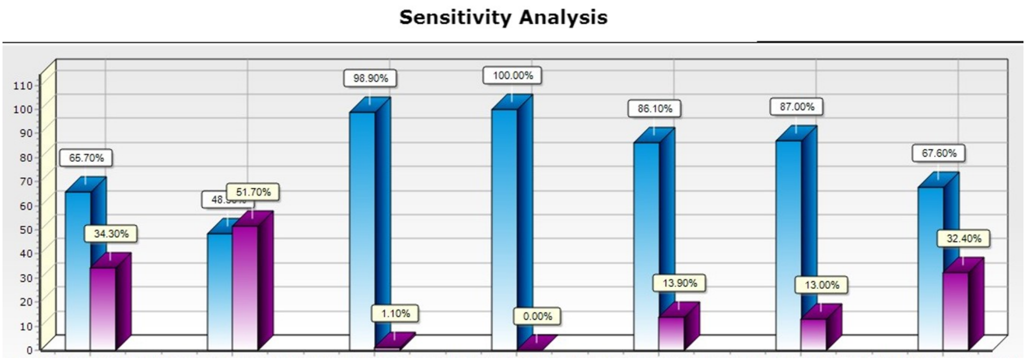

Figure 3 – Sensitivity analysis (Source: FITradeoff DSS).

In Phase 4, the leader of the process shared the proposal with the participants of the previous phases. In this case, the leader meets with the work group in charge of the spring production process and goes through the steps of the methodology that allowed them to discriminate actions. Discussions are held regarding implementation, execution deadlines, responsible parties, follow-up and the determination of management indicators. Finally, the work plan is formalized in a document including these specifications .

8 PREFERENCES ELICITATION WITH FITRADEOFF

This work focused on the application of the classical FITradeoff method and the choice of elicitation by decomposition was primarily used in preference modeling. This choice is associated with the type of decision problem and the developed process. The FMEA requires performing the actions proposed in order to improve and reverse the identified nonconformities, and the key is knowing the most convenient moment to execute them. A cause of failure in this kind of implementations is due to the lack of ability to sort out and prioritize proposed actions in a work program. In addition, for this particular application case, the organizational scheme requires the leader's individual decision to carry out the work plan to be executed by the team under his/her leadership.

The FITradeoff method was used in de Almeida et al. (2016) to choose the best alternative to solve problems and the possibility of using a holistic evaluation to finish the decision process was foreseen in case the decision maker had doubts about the prevalence of some of the selected alternatives. The use of the method and its multiple and diverse applications in different areas promoted research on the possibility of incorporating behavioral studies and neuroscience tools in order to include the flexibility of choosing elicitation by decomposition or holistic evaluation or the combination of these two approaches throughout the decision-making process. De Almeida et al. (2021) present the possibility of selecting the way of eliciting the preferences of the decision maker or a group of them according to different situations. The authors explore cases in which the convenience of the application of the proposed elicitation strategies is analyzed. There is a specific section where the new features of FITradeoff are illustrated, as well as examples about how each approach can be used to solve practical cases. For the holistic evaluation, the possibility of finishing a decision process or providing additional information to the elicitation procedure by decomposition is considered. In relation to the latter, it is possible to reduce the action space or remove an alternative by determining a new dominance relationship, depending on whether the problem is choosing the best alternative or achieving a ranking.

The results presented in the previous section show that the single decision maker possesses information coming from his direct participation in the spring production process, which makes it easier for him to identify his preferences in relation to the alternatives and their consequences. In this case, when evaluating the alternatives the decision maker was not faced with a dilemma regarding the ability to differentiate between two or more of them, which resulted in a quick and complete ranking (see Figure 4).

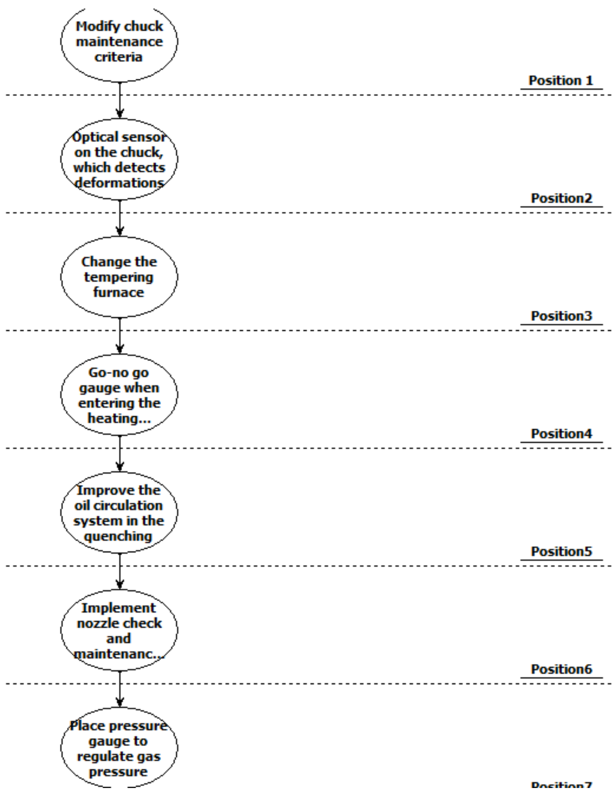

Figure 4 – Hasse Diagram (Source: FITradeoff DSS).

In any case, the FITradeoff method flexibility and the possibility of applying different approaches to elicit preferences improve the study of the problem and of the incorporation of different perspectives. For example, for the practical application presented in this paper, the FMEA is a tool applied through group dynamics to encourage the exchange among participants. The group dis-

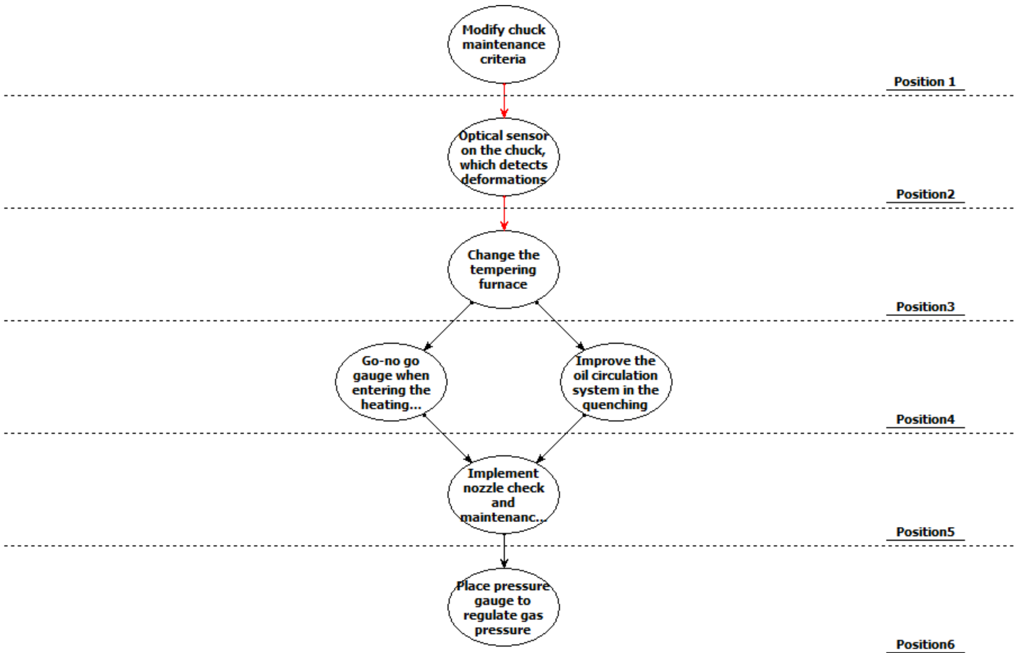

Figure 5 – Hasse Holistic Evaluation Diagram (Source: FITradeoff DSS).

cussion and analysis of failures and nonconformities facilitate the shared knowledge of the problem and the agreement of definitions among participants. These issues correlate with the resulting participants' commitment to the proposed improvement actions.

In this sense, the holistic evaluation approach encourages the participants' exchange about the so important decision-making process. The strategy coincides with the FMEA proposal and with the possibility of complementing joint learning. In this way, it is possible to improve information and discussion about the analyzed problem, use software outputs graphics in order to contrast the opinions of multiple decision-makers, and facilitate the commitment to the agreed action plan. For example, in case of doubts about the performance of two alternatives, joint discussion could be used to reach agreement among the participants (See Figure 5).

Thus, when two or more alternatives cannot be easily differentiated (Example position 4 Figure 5), there is an opportunity for a plenary discussion in which the analyst may show the alternative performance graphs and make the paired comparisons proposed by the software (See Figure 6).

Some situations related to group interaction may arise during the experiment, which allow the analyst to explore whether there is cohesion among the opinions and perceptions of the participants. If there is agreement about the choice, the analyst will be able to conclude that the exchanges converged in shared meanings, and therefore, a good degree of commitment to the adopted interventions could be expected. In the event that sharp differences in preferences are identified and there is no agreement on the choice of alternative, the analyst has the opportunity to develop a new space for discussion that facilitates the final decision. In this way, it is possible to keep

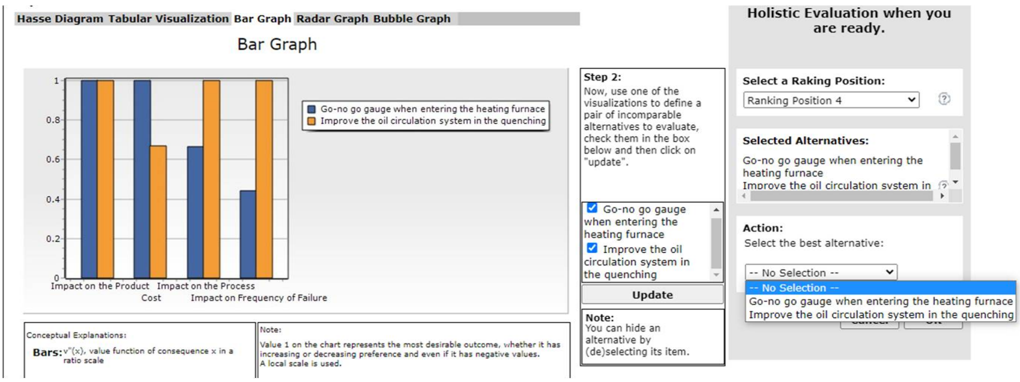

Figure 6 – Bar Graph Holistic Evaluation - Ranking Position 4 (Source: FITradeoff DSS).

on encouraging joint learning and the possibility of completing available information about the problem under analysis.

9 CONCLUDING REMARKS

This work shows how the problem of prioritizing improvement actions resulting from the application of the FMEA methodology is solved. Shortcomings of the FMEA were identified in relation to the following aspects: the ability to sort out and prioritize proposed actions, the implementation modality which hinders the free contribution of opinions, the manipulation of its indicators, the modeling of uncertainty due to lack or omission of information, and the impossibility of measuring the degree of agreement between the participants.

To overcome these weaknesses, phases with different activities were applied. In phase one, the spring production process was analyzed in collaboration with the participants involved. Different perspectives about the identified failures were shared, key characteristics (variables) that must be controlled were defined, and improvement actions were proposed to remove causes and mitigate their effects. In phase two, the work group identified the need to make decisions regarding the ordering of improvement actions. The application of the recommendations of the twelve-step framework to model decision problems allowed to contextualize the problem and define objectives for its resolution.

In phase three, the FMEA was complemented with an individual compensatory multi-criteria method known as FITradeoff. The method allowed the leader to incorporate participants' proposals in relation to criteria not valued by the FMEA and to weigh these objectives interactively. The multi-criteria model used in this work has a support software that makes it possible to go through the proposed operation easily. Outputs such as graphs and tables were requested to share the results. In phase four, the production process leader provided participatory feedback on the obtained results. The leader and the work group coordinated activities related to the prioritized interventions. The work group actively participated in the feedback and the work plan. The implementation stage of the first actions was started.

The importance of designing organizational interventions in order to reduce the possibilities of failure is a lesson learned by the participants. The possibility of integrating multi-criteria methods using tools inherent in management systems can be applied to other organizational interventions. As to the limitations of this study, it is worth pointing out that it is not possible to measure consensus and subsequent participants' commitment to implement improvement actions. In this regard, this study did not examine the possibility of working with multiple decision makers and with the Holistic Evaluation approach proposed in the latest version of FITradeoff available in FITradeoff DSS. This strategy should be explored in future research on these issues.

References

AIAG (AUTOMOTIVE INDUSTRY ACTION GROUP) AND VDA (VERBAND DER AUTOMOBILINDUSTRIE). 2019. *Failure Mode and Effects Analysis – Design FMEA and Process FMEA Handbook*. Southfield, MI.

AVILES PR & DENT EB. 2015. The role of mindfulness in leading organizational transformation. A systematic review. *The Journal of Applied Management and Entrepreneurship*, **20**(3): 31-55.

BRAIDOT N, FORMENTO H & NICOLINI J. 2003. *Desarrollo de una metodología de diagnóstico para empresas PyMEs industriales y de servicios: Enfoque basado en los sistemas de administración para la Calidad Total*. Argentina, Universidad Nacional General de Sarmiento.

BUECH VL, MICHEL A & SONNTAG K. 2010. Suggestion systems in organizations: what motivates employees to submit suggestions? *European Journal of Innovation Management*.

COTE LP & GARCÍA AM. 2016. Estrés como factor limitante en el proceso de toma de decisiones: una revisión desde las diferencias de género. *Avances en Psicología Latinoamericana*, **34**(1): 19-28.

CORREIA MC, FREJ EA & DE ALMEIDA AT. 2021. Prioritizing Improvement Actions in a Fish Distribution Company: Integrating Elicitation by Decomposition and Holistic Evaluation with FITradeoff Method. In: *International Conference on Group Decision and Negotiation*. Springer, Cham, p. 41-54.

CHIOZZA ML & PONZETTI C. 2009. FMEA: a model for reducing medical errors. *Clinica chimica acta*, **404**(1): 75-78.

DASTJERDI HA, KHORASANI E, YARMOHAMMADIAN MH & AHMADZADE MS. 2017. Evaluating the application of failure mode and effects analysis technique in hospital wards: a systematic review. *Journal of Injury and Violence Research*, **9**(1): 51.

DE ALMEIDA AT. 2013. *Processo de Decisão nas Organizaç ões-Construindo Modelos de Decisão Multicritério*. Atlas.

DE ALMEIDA AT, CAVALCANTE CAV, ALENCAR MH, FERREIRA RJP, ALMEIDA-FILHO AT & GARCEZ TV. 2015. *Multicriteria and multiobjective models for risk, reliability and maintenance decision analysis*. 1st ed. Recife: Springer. http://dx.doi.org/10.1007/978-3-319-17969-8

DE ALMEIDA AT, ALMEIDA JA, COSTA APS & ALMEIDA-FILHO AT. 2016. A new method for elicitation of criteria weights in additive models: Flexible and interactive tradeoff. *European Journal of Operational Research*, **250**(1): 179-191.

DE ALMEIDA AT, FREJ EA & ROSELLI LRP. 2021. Combining holistic and decomposition paradigms in preference modeling with the flexibility of FITradeoff. *Central European Journal of Operations Research*, **29**(1): 7-47.

DEMING WE & EDWARDS DW. 1982. *Quality, productivity, and competitive position*. Vol. 183. Cambridge, MA: Massachusetts Institute of Technology, Center for advanced engineering study.

DIAS LC & MOUSSEAU V. 2018. Eliciting multi-criteria preferences: ELECTRE models. In: *Elicitation: The science and art of Structuring Judgement*, p. 349-375.

DOUMPOS M & ZOPOUNIDIS C. 2018. Disaggregation approaches for multicriteria classification: an overview. In: *Preference Disaggregation in Multiple Criteria Decision Analysis: Essays in Honor of Yannis Siskos*, p. 77-94.

FERRETTI V. 2016. From stakeholders analysis to cognitive mapping and Multi-Attribute Value Theory: An integrated approach for policy support. *European Journal of Operational Research*, **253**(2): 524-541.

FITRADEOFF DSS (DECISION SUPPORT SYSTEM). http://www.cdsid.org.br/fitradeoff.

FOSSILE DK, FREJ EA, DA COSTA SEG, DE LIMA EP & DE ALMEIDA AT. 2020. Selecting the most viable renewable energy source for Brazilian ports using the FITradeoff method. *Journal of Cleaner Production*, **260**: 121107.

FRANCO LA & LORD E. 2011. Understanding multi-methodology: Evaluating the perceived impact of mixing methods for group budgetary decisions. *Omega*, **39**(3): 362-372.

FRANÇ OZO R, PAUCAR-CACERES A & BELDERRAIN MCN. 2021. Combining Value-Focused thinking and soft systems methodology: A systemic framework to structure the planning process at a special educational needs school in Brazil. *Journal of the Operational Research Society*, 1-20.

FRANK AG, PEDRINI DC, ECHEVESTE ME & RIBEIRO JLD. 2014. A systematic of QFD and FMEA integration for decision-making in the product development process. *roduction*, **24**(2): 295-310.

FREJ EA, EKEL P & DE ALMEIDA AT. 2021. A benefit-to-cost ratio based approach for portfolio selection under multiple criteria with incomplete preference information. *Information Sciences*, **545**, 487-498.

FRYER KJ, ANTONY J & DOUGLAS A. 2007. Critical success factors of continuous improvement in the public sector: a literature review and some key findings. *The TQM magazine*.

GARCIA-SABATER JJ, MARIN-GARCIA JA & PERELLO-MARIN MR. 2012. Is implementation of continuous improvement possible? An evolutionary model of enablers and inhibitors. *Human Factors and Ergonomics in Manufacturing & Service Industries*, **22**(2): 99-112.

HÄMÄLÄINEN RP, MILISZEWSKA I & VOINOV A. 2020. Leadership in participatory modelling–Is there a need for it? *Environmental Modelling & Software*, **133**: 104834.

HENAO F & FRANCO LA. 2016. Unpacking multimethodology: Impacts of a community development intervention. *European Journal of Operational Research*, **253**(3): 681-696.

JÚNIOR ADG & SCHRAMM VB. 2021. Problem Structuring Methods: A Review of Advances Over the Last Decade. *Systemic Practice and Action Research*, 1-34.

KLUSE C. 2020. A critical analysis of the AIAG-VDA FMEA; does the newly released AIAG-VDA method offer improvements over the former AIAG method. *Journal of Management & Engineering Integration*, **13**(1): 71-85.

KÖKSALAN M, MOUSSEAU V & ÖZPEYNIRCI S. 2017. Multi-criteria sorting with category size restrictions. *International Journal of Information Technology & Decision Making*, **16**(01): 5-23.

LAMI IM & TAVELLA E. 2019. On the usefulness of soft OR models in decision making: A comparison of Problem Structuring Methods supported and self-organized workshops. European Journal of Operational Research, **275**(3): 1020-1036.

LI S & ZENG W. 2016. Risk analysis for the supplier selection problem using failure modes and effects analysis (FMEA). *Journal of Intelligent Manufacturing*, **27**(6), 1309-1321.

LINA LR & ULLAH H. 2019. The concept and implementation of Kaizen in an organization. *Global Journal of Management and Business Research*.

LIU HC, CHEN XQ, DUAN CY & WANG YM. 2019. Failure mode and effect analysis using multi-criteria decision making methods: A systematic literature review. *Computers & Industrial Engineering*, **135**: 881-897.

MADSEN PM & DESAI V. 2010. Failing to learn? The effects of failure and success on organizational learning in the global orbital launch vehicle industry. *Academy of management journal*, **53**(3): 451-476.

MAISANO DA, FRANCESCHINI F & ANTONELLI D. 2020. dP-FMEA: An innovative Failure Mode and Effects Analysis for distributed manufacturing processes. *Quality Engineering*, 1-19.

MCLEAN R & ANTONY J. 2014. Why continuous improvement initiatives fail in manufacturing environments? A systematic review of the evidence. *International Journal of Productivity and Performance Management*.

MCLEAN RS, ANTONY J & DAHLGAARD JJ. 2017. Failure of Continuous Improvement initiatives in manufacturing environments: a systematic review of the evidence. *Total Quality Management & Business Excellence*, **28**(3-4): 219-237.

MEILING J, BACKLUND F & JOHNSSON H. 2012. Managing for continuous improvement in off-site construction: Evaluation of lean management principles. *Engineering, Construction and Architectural Management*.

MIDGLEY G. 2003. Science as systemic intervention: Some implications of systems thinking and complexity for the philosophy of science. *Systemic Practice and Action Research*, **16**(2): 77-97.

MIDGLEY G & RAJAGOPALAN R. 2020. Critical systems thinking, systemic intervention, and beyond. In: *Handbook of Systems Sciences*, 1-51.

MIKULAK RJ, MCDERMOTT R & BEAUREGARD M. 2017. *The basics of FMEA*. CRC Press.

MINGERS J. 2011a. Soft OR comes of age—but not everywhere! *Omega*, **39**(6): 729–741. https://doi.org/10.1016/j.omega.2011.01.005.

MIDGLEY G & RAJAGOPALAN R. 2020. Critical systems thinking, systemic intervention, and beyond. *Handbook of Systems Sciences*, 1-51.

MORIN E & PAKMAN M. 1994. *Introducción al pensamiento complejo*. Barcelona: Gedisa.

MZOUGUI I, CARPITELLA S, CERTA A, EL FELSOUFI Z & IZQUIERDO J. 2020. Assessing supply chain risks in the automotive industry through a modified MCDM-based FMECA. *Processes*, **8**(5): 579.

PATIDAR L, SONI VK & SONI PK. 2016. Continuous improvement philosophy for manufacturing productivity: critical review. *Trends in Industrial and Mechanical Engineering*, **30**: 34-45.

PHILLIPS-WREN G& ADYA, M. 2020. Decision making under stress: the role of information overload, time pressure, complexity and uncertainty. *Journal of Decision Systems*, **29**(sup1): 213-225

RADANO E & VELINSONE D. 2015. Un modelo de análisis para diagnóstico de empresas pymes familiares. *European Scientific Journal*.

RAJAGOPALAN R & MIDGLEY G. 2015. Knowing differently in systemic intervention. *Systems Research and Behavioral Science*, **32**(5): 546-561.

RAPP C & EKLUND J. 2007. Sustainable development of a suggestion system: Factors influencing improvement activities in a confectionary company. *Human Factors and Ergonomics in Manufacturing & Service Industries*, **17**(1): 79-94.

REWERS P, TROJANOWSKA J, CHABOWSKI P & ZYWICKI K. 2016. Impact of Kaizen Solutions on Production Efficiency. *Modern Management Review*, **13**(23): 177-192.

ROSENHEAD J. 2006. Past, present and future of problem structuring methods. *J Oper Res Soc* **57**(7): 759–765. https://doi.org/10.1057/palgrave.jors.2602206.

SILVA ALDD. 2021. *Melhorando procedimentos e design no sistema de apoio a decisão do FITradeoff usando ferramentas de neurociencia*.

SINGH J & SINGH H. 2012. Continuous improvement approach: state-of-art review and future implications. *International Journal of Lean Six Sigma*.

SOKOVIĆ M, JOVANOVIĆ J, KRIVOKAPIĆ Z & VUJOVIĆ A. 2009. Basic quality tools in continuous improvement process. *Journal of Mechanical Engineering*, **55**(5): 1-9.

TAVELLA E & LAMI L. 2019. Negotiating perspectives and values through soft OR in the context of urban renewal. *Journal of the Operational Research Society*, **70**(1): 136-161.

THORNTON E, BROOK OR, MENDIRATTA-LALA M, HALLETT DT & KRUSKAL JB. 2011. Application of failure mode and effect analysis in a radiology department. *Radiographics*, **31**(1): 281-293.

YOLLES M. 2010. Exploring complex sociocultural situations through soft operational research. *Pesquisa Operacional*, **30**(2): 345-370.

ZANAZZI JF & ALBERTO CL. 2020. Método multicriterio cardinal de decisión en grupo con alternativas clasificadas por categorías. *Revista de la Escuela de Perfeccionamiento en Investigación Operativa*, **28**(47).

ZANAZZI JF, ZANAZZI JL, PONTELLI, D. 2022. Group multicriteria method to prioritize actions in failure mode and effects analysis. *Production*, **32**: e20210057. DOI: https://doi.org/10.1590/0103-6513.20210057.

ZANAZZI JL, PEDROTTI BI, ARIAS FH, DIMITROFF M & BLÁZQUEZ, M. 2010. Enfoque de procesos en la gestión de servicios: estrategias para lograr aplicaciones exitosas. *Revista de Ciencia y Tecnología*, **13**: 0-0.

ZHU YM. 2017. Failure-Modes-Based Software Reading. In: *Failure-Modes-Based Software Reading*. Springer, Cham, p. 29-37.

How to cite

ZANAZZI JF, ZANAZZI JL & PONTELLI D. 2023. Prioritization Of Improvement Actions In Industrial Production: Application Of The Fitradeoff Method To Order Improvement Actions Identified Through The Failures Modes And Effects Analysis (FMEA). *Pesquisa Operacional*, **43**(spe1): e263696. doi: 10.1590/0101-7438.2023.043spe1.00263696.