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A case study on FMEA-based improvement for managing new product development risk

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Abstract

Purpose – The purpose of this paper is to explore the applicability of the failure mode and effects analysis (FMEA) as an effective tool for decreasing failure risk in the early phase of the new product development (NPD), which adds to existing literature on the application of FMEA in NPD.

Design/methodology/approach – Through the application of action research (AR) methodology, it was possible to develop a case study examining the use of FMEA to decrease NPD risk in an early phase of NPD execution.

Findings – The importance and immediate gains of identifying NPD failures support FMEA's usefulness for NPD risk decrease. Moreover, its user-friendliness, timeliness and cost advantages facilitate the introduction of FMEA in the early phase of NPD execution.

Originality/value – FMEA is a well-known method used in manufacturing companies to identify and correct failures in products, processes and systems. This article explores the lack of practice-oriented evidence on the use of FMEA in the early phase of NPD execution and provides support to its applicability and effectiveness.

Keywords NPD, Failure mode and effects analysis, Case study, Risk management, Action research

Paper type Research paper

1. Introduction

New product development (NPD) has a central role in companies' success (McCarthy *et al.*, 2006). The purpose of NPD processes is to transform market opportunities and sets of assumptions into marketable products (Krishnan and Ulrich, 2001). The success of NPD is important for companies to maintain a competitive advantage and reach a high level of profits in a context of increasing market competition (Carrizo-Moreira and Karachun, 2014; Lin *et al.*, 2015). Highly innovative companies such as Amazon, Samsung or Boeing spend billions of dollars yearly on R&D (PwC, 2016). New products have also been shown to be responsible for 50% of sales revenues and 40% of total profits among US companies (Cooper *et al.*, 2000). Efficient NPD process management, therefore, plays an essential role in companies' current and future endeavors.

However, NPD processes are lengthy and challenging for companies. Griffin (2002) found that companies take up to 27 months on average to develop their most innovative products.

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Furthermore, failure rates in these products are common (Simon, 2009). For example, Ozer (2006) mentioned that the new products success rate is 15% in industrialized countries, while Castellion and Markham (2013) show that the failure rate of new products is around 40%. Moreover, many projects suffer delays, changes in scope, cancellations or failure to reach the market (Shenhar, 2001). The lack of effective use of tools and techniques in the process of NPD is among the main reasons for these problems (Yeh *et al.*, 2010).

NPD is a risky activity due to fierce market competition, a high technological development pace, an ever-increasing product complexity and the environmental pressure to decrease time-to-market and costs, while still improving quality (Bowers and Khorakian, 2014; Chin *et al.*, 2009; Srinivasan *et al.*, 2007). Decreasing risk in NPD can increase customer value (Browning *et al.*, 2002) and work as a foundation to improve NPD processes (Oehmen and Seering, 2011). To increase the likelihood of new product success it is important to have a strategy for the identification, understanding and management of risk (Mu *et al.*, 2009; Keizer *et al.*, 2005).

Considering the inherent risks of NPD, companies are constantly searching for new methods to decrease production-times and costs while simultaneously improving quality, with managers facing a continuous pressure to improve their firms' NPD performance (Yeh *et al.*, 2010). Nevertheless, scholars note that risk management in NPD in many companies is still conducted using informal and unsystematic methods based on management's perception (Cooper, 2006; Gidel *et al.*, 2005; Griffin, 1997). Kumar (2002) claim that the techniques and tools used to decrease risk management and increase the likelihood of NPD success are neither widespread nor generally adopted. In the same line of though, Segismundo and Miguel (2008) argue that risk management is still in its infancy and there is an increasing need to develop and test more systematic methods to evaluate risks in an early NPD phase, helping product development managers make better decisions from a risk decrease perspective. Bowers and Khorakian (2014) suggest that companies can address risk management in innovative projects by employing simple and practical tools initially, resorting to more comprehensive methodologies in the final stages of the development process. Over the years, several tools have been introduced for NPD process performance improvement such as quality function deployment (QFD), design of experiment (DOE), conjoint analysis, failure mode and effects analysis (FMEA) and benchmarking (Yeh *et al.*, 2010). However, there is a lack of empirical research on NPD risk management (Chauhan *et al.*, 2018), unlike in manufacturing, where these tools are widely used (Kumar and Parameshwaran, 2018; Selim *et al.*, 2016; Thia *et al.*, 2005).

The literature on risk management has focused on the topic of identifying risks in the development of a new product using FMEA (Carbone and Tippett, 2004). Nonetheless, although FMEA is used in NPD, in a recent survey examining the state of the risk management research, Chauhan *et al.* (2018) found only nine articles using FMEA specifically for risk assessment and evaluation in NPD contexts. These articles focus, on one hand, on extending the traditional FMEA (Carbone and Tippett, 2004; Zhang and Chu, 2011; Chang, 2014) and, on the other hand, on developing new frameworks for risk management in NPD projects and systems (Kirkire *et al.*, 2015; Segismundo and Miguel, 2008; Chaudhuri *et al.*, 2013; Dewi *et al.*, 2015; Mehrjerdi and Dehghanbaghi, 2013; Wu *et al.*, 2010). As a matter of fact, one of the major criticisms on FMEA has been its scarce use in design improvement, as FMEA can contribute to identifying which risks carry the greatest concerns and allow actions to be taken before problems arise (Ambekar *et al.*, 2013). Overall, the literature shows a lack of substantial evidence on the effectiveness of FMEA as a NPD support tool of the product development process. Also, as noted by Oehmen *et al.* (2014), there is a lack of empirical research exploring the integration of risk management practices proposed by various standards with NPD and their association with risk management project and product success.

This paper seeks to explore the feasibility of FMEA as an effective tool for decreasing risks of failure modes in the early phase of NPD execution (also known as specification and design), which according to Khurana and Rosenthal (1997) occurs after the front-end process.

In order to meet this research objective, a case study was conducted using action research (AR) at a hydro-sanitary company, which was having a high failure rate in one of its core products and was seeking for a tool that could be effective in improving its NPD process and that could be easily adopted and re-used in future projects. By introducing FMEA in the specification and design phase of NPD execution, design engineers can fully understand the underlying complexity of the process and identify *a priori* root causes for product failures, decreasing waste in the design phase rather than developing corrective measures later and, foremost, preventing poor products from reaching the market.

The article is structured as follows. After this introduction, the relevant literature is reviewed. Then, the research methodology is presented, followed by the results of the practical application. The paper concludes with the discussion of the results and limitations. Finally, suggestions for further research implementations are presented.

2. Literature review

The development of a new product involves "*a sequence of steps or activities which an enterprise employs to conceive, design and commercialize a product*" (Ayag, 2005, p. 693). A successful and timely NPD process is crucial to build a sustained competitive advantage (Cooper and Kleinschmidt, 1995; Hartley, 2006). Nonetheless, risk is intrinsic to NPD in all industries (Kwak and Laplace, 2005) and it is important for companies to search for procedures that decrease risk in NPD activities (Mu *et al.*, 2009). In the context of NPD, risk is related with the likelihood that a newly developed product might fail because of uncertain causes, which may include technical, commercial, market and organizational risks (Cooper, 2003; Keizer *et al.*, 2005). Companies therefore deploy strategies to identify, assess and mitigate risks as without those strategies, projects costs could get out of control and valuable resources could be wasted (Chauhan *et al.*, 2018).

The management of risk enhances the performance of the NPD process (Salavati *et al.*, 2016) and risk management practices have a positive impact on the performance of NPD initiatives (Oehmen *et al.*, 2014). Risk identification can be considered one of the first key procedures for risk management activities, as only this will lead to any risk management activity (Prakash *et al.*, 2017). Some of the methods used in NPD are benchmarking, brainstorming, Delphi method, focus groups or QFD (Thia *et al.*, 2005; Yeh *et al.*, 2010). Among the factors that determine the adoption of these tools are its user-friendliness, flexibility, time and cost (Thia *et al.*, 2005). Although these methods are useful to the success of the NPD process, they are not tuned to identify failure modes and their corresponding risks.

Early on, Cooper (1981) discussed the components of risk in NPD, while More (1982) explored risk factors in successful and failed new product activities. More recently, Chauhan *et al.* (2018) organized the literature on NPD risk management into generic risk management, risk identification, risk assessment and risk mitigation. Within the research focusing specifically on risk assessment, some of the most common methods used are: statistical rating and ranking, Bayesian network, probabilistic risk assessment, analytic hierarchy process, Markov processes and FMEA (Chauhan *et al.*, 2018). The studies using FMEA can be organized into research extending the traditional FMEA and research assessing the risk in projects and systems.

Regarding studies extending the traditional FMEA, Carbone and Tippett (2004) conducted a case study in the electronics industry, proposing a modified detection value for the standard FMEA. Zhang and Chu (2011), in the manufacturing of heavy engineering machines, proposed a new approach for evaluating and ranking failures using a new risk number integrating weighted least squares method. In the high-tech industry, Chang (2014) suggested a new set-based ranking for prioritization failures of FMEA.

Concerning research assessing the risk in projects and systems, Cassanelli *et al.* (2006) run several iterations of FMEA validating its usefulness in a more conceptual stage. Segismundo and

Miguel (2008) focused on the use and systematization of FMEA for risk monitoring in systems and subsystems project in the automotive industry. Wu *et al.* (2010) proposed a three-stage framework based on a product database management, a FMEA and a graphical evaluation and review technique for risk management in projects. Chaudhuri *et al.* (2013), analyzing the aircraft industry, proposed an approach to manage supply chain risk assessment during NPD. Mehrjerdi and Dehghanbaghi (2013) research in the textile industry applied a FMEA to NPD process risk, analyzing the system and the risk effects, identifying various types of risks such as economic, managerial, project management, organizational, quality, market, customer, social, legal, political, technical and supplier risks. In the fashion industry, Dewi *et al.* (2015) resorted to FMEA and the house of risk, identifying risk factors such as design and production, financial, management and marketing risk. Finally, Kirkire *et al.* (2015) conducted a case study comparing the effectiveness of FMEA and fuzzy FMEA for managing risks during medical products development. They found that risks could be categorized based on technical, strategy and market sources, arguing that fuzzy FMEA provides more logical results than the traditional FMEA.

The existing literature has sought to overcome shortcomings in risk assessment by producing more complex measurements and tried to integrate FMEA with other quality management tools to improve NPD processes. A major shortcoming of the literature is that researchers focus on decreasing system or project risks rather than on specifically addressing failure modes and risks in the early phase of NPD execution, which is assessed in the present study using the FMEA tool. Additionally, Chauhan *et al.* (2018) recognized there is clearly a need for more empirical studies on the application of risk analysis methodologies in the NPD process.

3. Research method

3.1 The case company

The featured company operates in the hydro-sanitary industry and is among the largest manufacturer of flush toilets in Europe. In 2017 the company produced 2 million flush toilets, exporting 80% of its production to over 80 countries around the world. According to the 2018 annual report of the European Patent Office (2018), the company is one of the five Portuguese companies that submitted most patents, currently holding more than 40 active patents. In addition to the investment made in the R&D area, the company has invested significantly in the introduction of the principles of continuous improvement in the industrial area with the objective of improving productivity. This investment has been recognized with international awards.

Also, the company has been committed with innovation for the last 15 years and worked closely with universities and research centers to create technologically advanced and sustainable bath solutions with the purpose of decreasing water consumption in flush discharges. In the past five years, the company invested 10 million euros in R&D and consolidated the implementation of a R&D department to support NPD, enabling it to launch new products and strengthen its international position.

The company's NPD process follows an adapted stage-gate framework composed by the following stages: stage 0 – Ideation, scoping and business case; Stage 1 – Specification and design; Stage 2 – Prototype testing and validation; and Stage 3 – Pre-series and launch. The company's NPD department classifies projects based on a combination of three factors: type of development (new product or a change in an existing product); duration of the project; and the degree of investment required.

It is important to note that the company already used some management tools at the time of NPD, namely brainstorming and benchmarking. However, these tools, despite helping in the management of the development process, do not allow the assessment of modes of failures and their likelihood, nor their impact, particularly in the case of new products. The head of the R&D department expressed his interest in having tools that would allow the early and systematic identification of "easy to solve" problems that arise during the development of new products.

Considering this particular context, the NPD department contacted the research team to develop a pilot project examining the introduction of a NPD tool in the development process. Bearing in mind that the company already used FMEA to improve industrial processes, it was decided jointly between the NPD department and the research team to adopt this tool to the NPD process, namely in Stage 1 – Specification and design. This project was implemented in the context of the development of new products, with innovative features, within the product category of flush control boards, which are very important for the company's activity. In this way, it was intended to anticipate expected failure modes and not as the usual process FMEA that is applied in the manufacturing or assembly stages to identify failure modes and corrective actions.

3.2 Action research

In this paper, the implementation of FMEA in the early phases of NPD process (Stage 1) goes hand in hand with gaining important insights into on how the use of these techniques and tools can contribute to increase the chances of NPD success.

Since this project was conducted in collaboration between the research team and the company's NPD department, an AR methodology (which can be considered a special type of case study) was used as research method (Westbrook, 1995; Coughlan and Coghlan, 2002; Hendry *et al.*, 2013). AR is a research approach designed to establish a close association between actions and problem solving, involving researchers and participants in a cooperative and participatory way. AR aims at generating knowledge starting by studying the theory to implementing actions (Coughlan and Coghlan, 2002), as such, AR supports the contribution of the research to solve a practical problem and the generation of knowledge by the solution of that problem.

AR is a common approach in operations management (e.g. Ferreira *et al.*, 2015; Silva *et al.*, 2016) and is based on various assumptions. First, it uses an empirical approach to study the solution of an organization's issues, together with the actors who experience these issues directly. Second, it implies that the members of the system being studied participate in the research process, thereby establishing a link between the company and the researchers. Third, AR aims to make the company's actions more effective while simultaneously build empirical knowledge. Last, it is both a sequence of events and an approach to problem solving (Coughlan and Coghlan, 2002). Two further conditions were met so that this project could be considered AR. The research objective was determined by the researchers' objectives (of exploring the applicability of FMEA in the early phase of NPD execution), and the project plan was driven by the need to improve the company's NPD performance (rather than by the goal of transforming the entire NPD process). AR is based on a set of stages, as specified by Meredith *et al.* (1989) or Coughlan and Coghlan (2009). The research process herein implemented is presented in Figure 1.

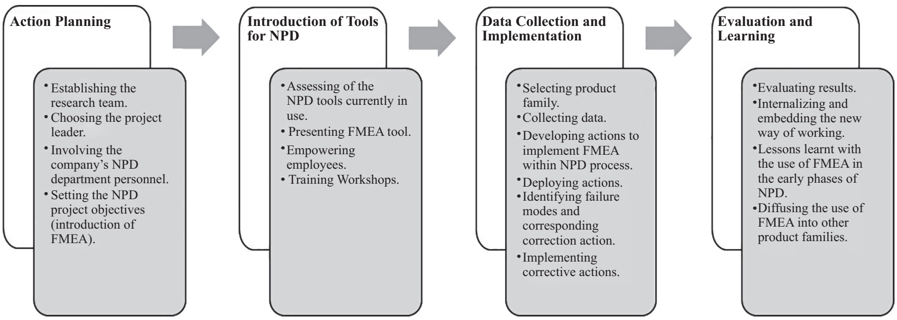

Figure 1.
Research process

The project lasted six months and, as suggested by AR, the researchers were directly involved in the case study and worked alongside members of the company's NPD department. This allowed that all relevant data could be easily accessed. Moreover, the company's NPD department head was fully committed to the project, ensuring that the rest of the NPD team was completely involved and entrusting the researchers with the management of the FMEA of the NPD process. The participation of the NPD team in this project was crucial to identify the training needs and to make operating preferences unambiguous in the identification of failure modes and in the implementation of actionable solutions and corrective actions.

Briefly, this paper sought to identify technical risks during the early design phase of the products, facilitating the implementation of effective corrective and preventive actions to decrease the impact of failures before the prototyping or ramp up stages of the NPD process. In addition, a more detailed analysis of possible failure modes (to assess their relative importance and identify the required corrective measures) was conducted.

4. NPD and FMEA implementation

4.1 FMEA tool

FMEA had its origins in systems engineering analysis in the 1950s in the aerospace and US military industries (Jordan, 1972). It was adopted by the private industry in the late 1960s. FMEA has been implemented particularly in the automotive and military industries and can be considered a living document which should be continuously updated when major changes are introduced in the design or manufacturing processes (Bhamare *et al.*, 2008). FMEA has remained a popular tool until nowadays, and is used as a standalone tool (Ouyang *et al.*, 2020) or as part of more integrated quality control frameworks in manufacturing industries (Shaker *et al.*, 2019).

FMEA is a tool for identifying and eliminating known or potential failures before they occur, enhancing the reliability of systems and providing information for risk management decisions (Braaksma *et al.*, 2013; Liu *et al.*, 2013). While other tools can be used for risk assessment (Chauhan *et al.*, 2018), the use of FMEA carries several advantages: it follows a logical and structured method to identify areas of concern, it allows the early identification of failure points, and it constitutes an improvement over risk analysis that treats each failure in isolation. Additional advantages often attributed to the use of FMEA are its flexibility, implementation time (Thia *et al.*, 2005) and usefulness (Chai and Xin, 2006). In turn, FMEA is only as good as the team member's knowledge, it is based on people's judgment and while it prioritizes risk, it does not eliminate the mode of failure, being an approach that requires regular updates.

Typically, FMEA begins with establishing a cross-functional team and identifying all possible potential failure modes of a product, process or system by conducting systematic brainstorming (Franceschini and Galetto, 2001; Liu *et al.*, 2013). Then, risk measurement analysis needs to be done based on a risk priority number (RPN) obtained by multiplying three risk factors: occurrence (O) or the probability of failure occurrence; severity (S) or the severity of the failure; and detection (D) or the capacity for failure detection before failure occurs ($RPN = O \times S \times D$). To compute the RPN, these three factors need to be evaluated using pre-established scales. FMEA prioritizes failure modes based on the assumption that the higher the RPN of a failure mode, the greater the risk for low product reliability (Liu *et al.*, 2013). High-risk failure modes need corrective actions, after which their RPN is recalculated. This cyclical process should continue until risks decrease to acceptable levels and the corrective and preventive actions' efficiency has been evaluated.

4.2 FMEA approach adopted for the project

Among the company's product portfolio, flush control boards were chosen because of their strategic importance. After the product category was selected, the researchers and NPD teams joined to discuss the most suitable FMEA approach to this NPD process.

Despite the extensive application of the traditional FMEA, the existing literature has shown some reservations on how to calculate RPNs and the prioritization of measures (Paciarotti *et al.*, 2014; Palady, 1997; Puente *et al.*, 2002; Zhang and Chu, 2011). For example, Puente *et al.* (2002) note that FMEA examines the severity of failures' impact on customers, as well as the failures' occurrence probability and detection likelihood. FMEA then prioritizes failures based on RPNs. The literature shows a consensus that severity assessment should be performed from the perspective of the causes' effect. However, scholars do not agree about how to assess occurrence or how to detect failure risk. Table 1 provides an overview of the various approaches evaluating the three factors in the occurrence of each failure.

Palady's (1997) FMEA approach was chosen as an alternative to the traditional FMEA because it is not RPN driven, overcoming the limitation of mistakenly prioritizing corrective actions based only on the RPN values. According to Palady (1997), a chart needs to be drawn using two assessment scales – severity and occurrence – both equal in length and scale size – on the horizontal and vertical axis, respectively. Then, three priority regions (low, medium and high) and their borders should be established by the FMEA research team based on the company's quality procedures. Failures with higher risk in both severity and occurrence are then prioritized regardless of their RPN values. In the case of similar RPN values (to the point that it is unclear which potential failure to address first), Palady (1997) suggests first to eliminate the occurrence, then, to reduce the severity of the occurrence, and finally, to improve detection.

As for the scales, a ten-point scale is commonly used in determining severity, occurrence and detection, to ensure precision and differentiation among results. However, a five-point scale increases consensus among team members on rating values (Welborn, 2007). Moreover, and following Guerrero and Bradley (2012), whenever possible, group consensus should be the preferred system of ranking, namely if the individuals engaged in FMEA are not highly trained in FMEA. Thus, considering the company's context and to facilitate FMEA's implementation in the NPD department, the researchers and team members agreed to use Welborn (2007) evaluation approach for occurrence, severity and detection. Tables 2–4 present the scales adopted.

Following Palady's (1997) recommendations, the three following priority rates (high, medium and low) were identified and established by the researchers and NPD project teams,

Source	Severity	Occurrence	Detection
ECSS-Q-30–02 A (2002)	Effect	Failure mode	Cause failure mode
Helman and Andery(1995)	Effect	Cause	Failure mode/effect
Pinto and Xavier (2001)	Effect	Failure mode	Failure mode
Layzell and Ledbetter (1998)	Effect	Failure mode	
MIL-STD-1629 A (2005)	Effect	Failure mode	Failure mode
Palady (1997)	Effect	Failure mode/cause	Failure mode/cause
IQA (1998)	Effect	Cause	Failure mode/cause

Source(s): Adapted from Fernandes and Rebelato (2006)

Table 1. Different approaches to severity, occurrence and detection assessment

Probability of failure	Possible failure rates	Rank
Very high	Persistent failure occurrences	5
High	Frequent failure occurrences	4
Moderate	Occasional failure occurrences	3
Low	Low failure occurrences	2
Remote	Unlikely failure occurrences	1

Table 2. Scale adopted to assess occurrence

considering the company's quality procedures (Figure 2). Due to the product's specificities, a slightly adapted FMEA table was used in the present study (see Table A1).

5. Results

To identify and evaluate potential causes of failures associated with the development of flush control boards, FMEA was conducted. The project team decided to define critical RPN values above 27 ($3 \times 3 \times 3$), considering the five-point scale used. After the first analysis, 22 failures were detected, of which nine exhibited an RPN above 27.

For reasons of parsimony, Table 5 presents only the potential failures with the highest RPN before any actions were undertaken. Moreover, the failure modes were also classified as being related, or not, to the NPD phase, so that the research team could later identify the marginal contribution of the NPD-related improvements regarding NPD-unrelated failure modes.

As previously mentioned, FMEA also needs to consider the severity and occurrence of modes of failure, regardless of their RPN. This additional procedure and visual analysis allowed the identification of three further failure modes that would otherwise have remained

Table 3.
Scale adopted to assess severity

Effect	Severity of effect	Rank
Very strong	System stops working, high levels of customer dissatisfaction and safety issues	5
Strong	System stops working, high levels of customer dissatisfaction	4
Moderate	Significant deterioration of component performance, customer dissatisfaction	3
Weak	Slight deterioration in component performance, slight customer dissatisfaction	2
Negligible	Customers unable to detect failure, no impact on customer satisfaction	1

Table 4.
Scale adopted to assess detection

Detection	Likelihood of detection by design control	Rank
Highly unlikely	Undetectable	5
Unlikely	Unlikely to be detected	4
Moderately easy	Likely to be detected	3
Easy	Highly detectable	2
Very easy	Certain detection	1

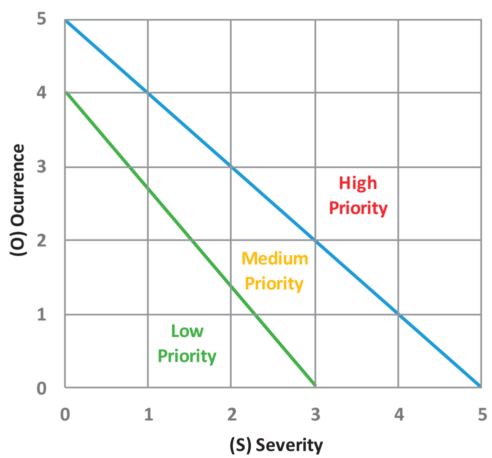

Figure 2.
Prioritization definition

#ID	(1) Description	(2) Potential failure	(3) Failure consequence	(4) Severity	(5) Cause of potential failure	(6) Occurrence	(7) Control action	(8) Detection	(9) RPN	NPD
5	Warped components	Warped components that cannot be used	Increase in number of rejections and costs	4	Mold issue, lack of mold maintenance	3	n/a	4	48	No
7	Rays	Broken parts	Increase in number of rejections and costs	4	Design issue	4	n/a	5	80	Yes
10	Chroming issues	Chromed part dimensions do not match pre-established dimensions	Malfunction	4	n/a	3	n/a	3	36	Yes
15	Fragile plywood in axes area	Plywood may break	Malfunction	4	n/a	4	n/a	4	64	Yes
17	Required force to push button above 20N	Not certified	Customers do not buy	4	Axis positioning	4	n/a	3	48	Yes
18	Chrome parts peel	Unkempt appearance affects aesthetics	Increased complaints and costs	3	Chroming issues	3	n/a	5	45	Yes
19	Broken locking springs	Plate cannot be assembled	Increased complaints and costs	4	Locking spring geometry	2	n/a	4	32	No
21	Logos inverted	Logos recorded in wrong positions	Increased complaints and costs	3	Anti-error failure in supports	4	n/a	4	48	No
22	Chrome treatments	Leaves hand marks	Unhappy customers	3	Lack of adequate treatment of better raw material	5	n/a	3	45	No

Note(s): Horizontal light grey cells concern to technical failures that could be addressed during the NPD phase

Table 5.
Initial FMEA for flush control boards

undetected if using only the RPN criteria equal or above 27. The failure modes identified in Table 6 were thus added to the analysis.

Out of the 22 failures identified initially, nine presented an RPN above the threshold and three more were added due to their high priority of severity and occurrence, as shown in Figure 3. Those failure modes can be associated with logistics risks, supply risks, design risks and product and manufacturing technology-related risks.

Those 12 most important failure modes were analyzed by the researchers and NPD teams to determine which of them were related to the early phases of the NPD process. It was possible to conclude that seven of them were detected early in the development process

#ID	(1) Description	(4) Potential failure	(5) Failure consequence	(4) Severity	(5) Cause of potential failure	(6) Occurrence	(7) Control action	(8) Detection	(9) RPN	NPD
2	Risks due to logistics	Boards and buttons damaged	Increased number of rejections and costs	2	Inadequate packaging, poor transportation	4	Operator examines visually	2	16	Yes
9	Stains related to chrome plating	Stained parts after chroming	Increased number of rejections and costs	3	Supplier and parts design issue as raw material needs higher temperatures, residual tensions due to component geometry	4	n/a	2	24	No
16	Injection issues	Components with poor aesthetics	Increased number of rejections and costs	3	Unforeseen use of raw materials in molds	4	n/a	1	12	Yes

Note(s): Horizontal light grey cells concern to technical failures that could be addressed during the NPD phase

Table 6.
Added failure modes

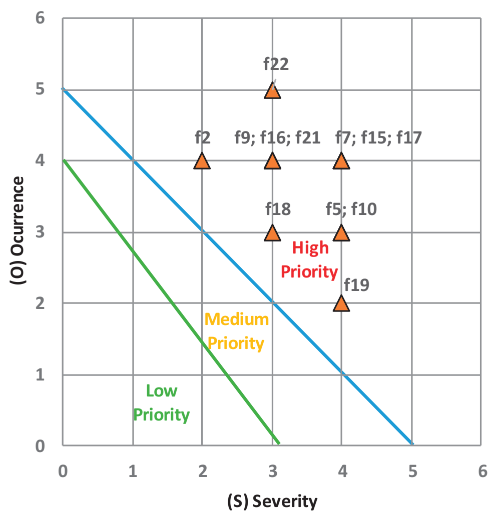

Figure 3.
Prioritization analysis of failure severity and occurrence

avoiding future failures in the succeeding stages of the NPD process. The subsequent discussion of each of the 12 failure modes led to the identification of preventive and corrective actions and of the agents responsible for their implementation. After these were implemented, a new analysis was conducted and a chart created to re-examine the revised RPNs.

Table 7 presents both preventive and corrective actions alongside the revised RPNs, while Figure 4 shows the revised severity and occurrence analysis. As no further failure modes were classified as high priority, FMEA was concluded. The analysis of the results carried out by the research and the development teams concluded that it was possible to identify several previously undetected failure modes. Moreover, the results elicited several risks in the early development stage of NPD that otherwise would have been detected only in prototyping or production stages.

Based on the application of FMEA, the researchers and NPD team were able to identify 12 high-priority failure risks and decrease their risk – seven of them in the early stage of development of the NPD process. The reduction achieved in the RPN of each failure mode

#ID	(10) Preventive action	(12) Corrective action	(13) Severity	(14) Occurrence	(15) Detection	(16) New RPN	NPD
5	Make prototype mold to check warp, pay special attention to full discharge button.	New prototype mold made – preliminary mold weekly analysis	2	2	2	8	No
7	When designer draws new system, ensure that system rays are located in reinforced areas and out of customers' sight.	New technical drawings – phase one	2	2	5	20	Yes
10	Redefine chroming dimensions.	New dimensions and size set with supplier – phase two	3	2	3	18	Yes
15	Design new plywood with reinforcing in most fragile areas.	New drawings, reinforce most fragile areas – phase one	2	2	4	16	Yes
17	Draw system and buttons, allowing button push force required for evaluation; test after prototyping.	New drawings – phase one	3	2	3	18	Yes
18	Examine issue with chroming suppliers, ask for samples, audit suppliers and set chrome thickness.	New supplier – guarantee chroming preservation	2	2	5	20	Yes
19	Because analysis demonstrated this is not a NPD issue, change supplier due to not meeting lock quality standards and/or quality.	New drawings – phase one	2	1	4	8	No
21	Make a new bracket allowing only a single position for assembly to prevent inverted logo recordings.	New support – phase two	2	1	4	8	No
22	Request more samples from suppliers, test which do not leave hand marks, but failure yet to be resolved.	Research on new suppliers	2	3	3	18	No
2	Examine packages of systems and buttons that get chromed.	New packaging – phase one	1	2	2	4	Yes
9	Find supplier who guarantees chroming has no stains.	New supplier – guarantee chroming without spots	2	3	2	12	No
16	Predict use of various raw materials in mold when developed.	New mold with new raw materials – preliminary mold weekly analysis	2	2	1	4	Yes

Note(s): Horizontal light grey cells concern to technical failures that could be addressed during the NPD phase

Table 7. New RPN after preventive and corrective action implementation

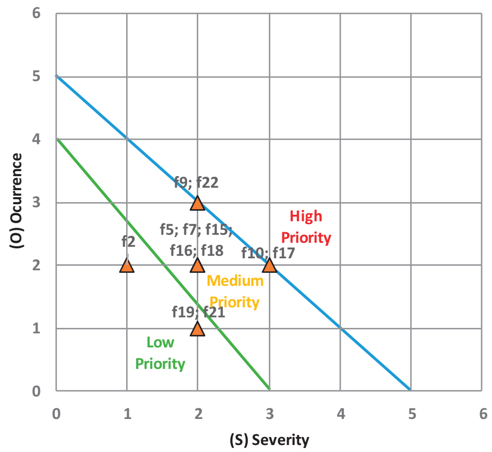

Figure 4.
Prioritization analysis of failure severity and occurrence after corrective actions

ranged from 50 to 83.3%. Figure 4 presents the analysis of the results and Figure 5 the change in RPN before and after the application of FMEA.

Only the detected failure modes related to the chroming process remained unsolved during the life span of the FMEA project as it involved the development of the supplier and the collaboration of the purchasing department as the company outsourced this process. For the remaining failures identified, all recommended actions proved adequate as the risk fell to acceptable levels.

The use of FMEA resulted in a substantial decrease of the risks of failure in flush control boards (Δ RPN = 69%), with gains related to NPD representing around 58% of this improvement. After the implementation of FMEA in the development stage of the NPD process, the head of the R&D department noted how the use of the tool carried additional benefits besides the ones initially scoped, such as a decrease in the time of the NPD process and a reduction of non-quality costs.

Considering the improvements achieved, the company decided to provide further training to their employees on FMEA, as well as to implement it as a supporting tool of the NPD process, turning this research project into a current practice. This decision was also

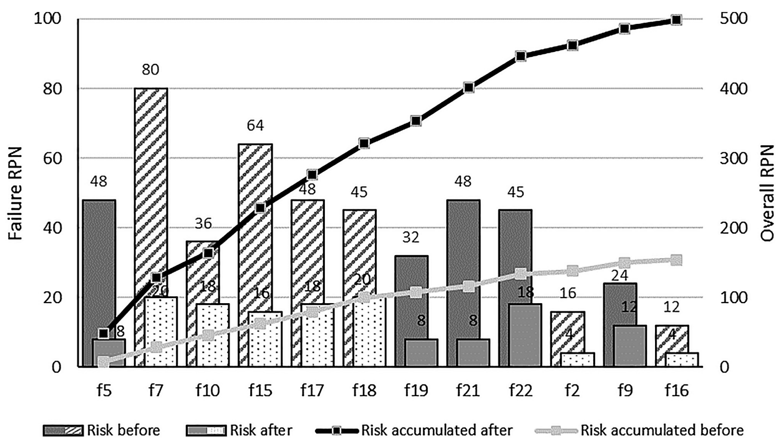

Figure 5.
RPN analysis before and after FMEA

supported by the perception of the user-friendliness, usefulness, timeliness and cost advantages of the tool, as it facilitates easiness of learning and provides added value to the user in terms of benefits in time and cost.

6. Discussion of results and lessons learned

NPD is a multidimensional and multifaceted process in which companies need to understand the inherent nature of their projects so that they may select, plan and execute NPD projects appropriately. FMEA helps in the reduction of unrecognized, unmanaged, or unmitigated failure modes. Decreasing risk and failure modes is essential to reducing costs, time-to-market and improves quality, which is of the utmost importance for companies' success and survival. Ineffective NPD activities, especially in the early development stage of NPD process, can lead to project delays and, ultimately, to product cancellations.

The customization of FMEA for its deployment in the development stage of the NPD process enabled the identification of several failure modes, which otherwise would not be identified. These failure modes were identified combining RPN scores and the relationship between severity and occurrence, which allowed the identification of nine failure modes initially and three more later. This allowed the early identification of seven high-priority NPD-related failure modes before the prototyping or production stages.

After implementing preventive and corrective measures, the results demonstrate that FMEA helps decrease the risk of future failures, which is in line with previous findings (Liu *et al.*, 2016; Yeh *et al.*, 2010). Overall, the RPN decreased by 69% after implementing FMEA. Furthermore, approximately 58% of this improvement was achieved by the reduction of RPN of failure modes that take place in the early development stage of the NPD process, whereas 42% of this improvement is related with production process-based activities. As such, this result is of added value as it reports results achieved during the early phase of NPD execution. The implementation of FMEA, which involved several employees in the judgment on perceived risks, allowed the identification of product and production process-based risks earlier and with more detail. Moreover, the implementation of FMEA, apart from its important direct effect on the reduction of the risks of failures, it also has an indirect important effect as it improves product success through better timing (earlier detection) and improved decision making. These results are aligned with the findings reported by Oehmen *et al.* (2014).

Previous research dealt with tools for decreasing NPD risk (e.g. Chen and Ko, 2009; Lin *et al.*, 2015; Liu *et al.*, 2016; Wu *et al.*, 2010). However, those tools often lack applicability in the early development stage of the NPD process. Moreover, FMEA is a relatively simple tool, and the results obtained corroborate its ability to identify preventive and corrective measures to eliminate future failures. Furthermore, unlike other tools such as QFD for example, which seek to improve overall NPD processes, FMEA itself can effectively decrease failure risk in the early phase of NPD execution. This paper provides evidence that FMEA is a user-friendly, timely and cost-conscious tool, especially because it allows its customization and an effective integration in early phases of the NPD process, as opposed to other strict, inflexible tools based on rigid procedures. Even though implementing FMEA can be a demanding task that requires a deep knowledge of the examined products and failure modes, its user-friendliness makes FMEA an appropriate and effective tool to be used in the early phase of NPD execution.

7. Conclusions and implications

The study was conducted using an AR methodology involving a collaborative approach between industry and academy. The use of the FMEA tool allowed the identification of high-priority failure modes that helped the firm successfully improve its NPD process in flush control boards' failure risks (Δ RPN = 69%). In this study, FMEA highlighted the failure modes that could be addressed in the development stage of the NPD process. The implementation of preventive and corrective actions diminished the risk of failure in the subsequent stages. Therefore, the results support the assertion that FMEA is an effective tool for decreasing risks of failure modes not only in manufacturing processes, an area in which FMEA application is widely accepted, but also in NPD processes. Moreover, regardless the fact that risk failure gains appeared similar between NPD and non-NPD failures, approaching the former ones prevents products from reaching customers and constitutes a proactive NPD approach.

This paper encompasses several lessons for managers. First, an early diagnosis of failure modes allows addressing the causes of the problems and has an important role in the improvement of the NPD process. Second, it is important to understand the usefulness of certain techniques and tools for improving the NPD process since their lack of adoption is the consequence of lack of familiarity of the NPD team with them. Consequently, training involving those tools is of the utmost importance. Third, the use of FMEA allowed a deeper understanding of the NPD process, providing a tool for increasing the knowledge of managers and finding out new solutions. In our case study, the use of FMEA allowed the identification of failure modes associated with supply risks, design risks and production process-based related risks. Overall, this research supports that the earlier identification of failure modes is of added value for developing better products.

The AR method used in this paper contributed to obtaining practical results and to developing new knowledge. This was achieved through the active participation of both researchers and company employees in the research process encompassing several activities from action planning to evaluation and learning, which characterizes the AR model.

This research had several limitations. First, the lack of historical data regarding failure rates, rework and repair costs made this research more complex. This limited the research team's ability to assess the risk severity and occurrence of each failure mode. In addition, this research concerns to a single case study, therefore, the study lacks the generalizability of the results that a survey-based approach could provide. The results, however, support the conclusion that FMEA can positively enhance NPD processes and decrease risk, preventing faulty products from reaching end customers.

Future studies could examine whether FMEA is also effective in the context of radical NPD and explore how the use of fuzzy sets theory or Weighted Aggregated Sum Product Assessment (WASPAS) could help to handle uncertainty, vagueness and hesitancy that exists in the risk evaluation process.

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Appendix

(1) Description	(2) Potential failure	(3) Failure consequence	(4) Severity	(5) Cause of potential failure	(6) Occurrence	(7) Control action	(8) Detection	(9) RPN	(10) Preventive action	(11) Responsible	(12) Action	(13) Severity	(14) Occurrence	(15) Detection	(16) New RPN

Table A1.
Adopted FMEA table

The FMEA table was filled out as follows:

(1) *Description*: Description of the function that is subject to failure

(2) *Potential failure*: Way in which the process may fail regarding its process requirements or service objectives

(3) *Potential failure consequence*: Impacts of the type of failure on customers from the customers' perspective

(4) *Severity*: Importance of impact on customers' requirements, which can also be related to safety or other risks in cases of failure

(5) *Cause of potential failure*: In which ways can failures occur, described in terms of something that can be corrected or controlled

(6) *Occurrence*: Frequency with which a certain cause occurs and generates a failure mode

(7) *Control action*: Control actions conducted to detect the type of failure that might happen

(8) *Detection*: System's ability to detect causes before failures occur or before the products reach the end customer

(9) *RPN*: Index used to establish process priorities, calculated based on the product of severity, occurrence and detection; in cases of extreme severity, priority may be given to those processes regardless of their RPN

(10) *Preventive action*: Actions that can decrease or eliminate eventual failures

(11) *Responsible*: Identification of those responsible for implementing preventive actions

(12) *Action executed*: Description of action implemented with the date

(16) *New RPN*: New indexes and RPNs calculated after corrective actions are defined, but, in the cases in which the new RPN falls above the threshold value, further corrective actions are undertaken