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Improving reliability engineering in product development based on design theory: the case of FMEA in the semiconductor industry

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Abstract

In industry, the failure mode and effect analysis (FMEA) methodology is one of the main tools used for reliability management in product design and development. However, the academic literature highlights several shortcomings of the FMEA methodology. Therefore, the main purposes of this paper are the analysis of the weaknesses of FMEA, the improvement of the method, and the implementation of a new methodology able to support quality and reliability management in a more efficient way. Motivated by these objectives, a formal new methodology is proposed by extending the classic FMEA methodology through C-K design theory. To test the effectiveness of the proposed approach and analyze the acceptance of this method by users, a case study is conducted in STMicroelectronics, one of the European leaders in the semiconductor industry.

Keywords: FMEA, quality management, reliability management, operations management, design theory, C-K design theory

1. Introduction

In the high-technology industry, the management of quality and reliability in product design and development is becoming a fundamental issue (Jegadheesan et al. 2006; Schroeder et al. 2008; Marucheck et al. 2011; Singh et al. 2017). The main challenges for product development are identifying operations processes and methods for the analysis, control, reduction and elimination of product and process failures. This focus of identifying potential failures and analyzing reliability is mainly due to competition, time to market, market pressure, customer requirements, continuous improvement philosophy, warranty and service cost (Stamatis 2003; Liu et al. 2013; Haughey 2019). Consequently, the main objectives of reliability analysis are to focus on the prevention of problems, elimination of waste and reduction of unreliability. This means that the aim is to prevent the causes and consequences of potential problems and errors. In many science-based organizations, such as automotive, aerospace, defense and semiconductor organizations, the failure mode and effect analysis (FMEA) methodology is the main tool used to identify, prevent and reduce problems and errors during product design and development (Lodgaard et al. 2011; Singh et al. 2017; Spreafico et al. 2017; Subriadi and Najwa 2020). FMEA is a systematic procedure to identify, anticipate and evaluate failure modes and their consequences on the system, product, technology, process and services. In this context, a failure mode can be understood as deviation between the actual and desired status of a system property (Würtenberger et al. 2014). However, practitioners and academic literature in engineering design highlight many difficulties in implementing and efficiently using FMEA. Moreover, the use of FMEA information to improve the quality of product and process design is often unclear and not obvious (Lodgaard et al. 2011; Banduka et al. 2016, 2018; Peeters et al. 2018). Several FEMA weaknesses have been clearly identified. Among them, Joshi and Joshi (2014) claim that FMEA often fails to identify all failure modes and does not allow the discovery of unexpected potential failures. Henshall et al. (2014, 2015) highlight that each technical team tends to develop its own FMEA approaches without connection between them, which makes it difficult to manage quality and reliability in a holistic manner. Lodgaard et al. (2011) note that it is difficult to support dynamic updates of FMEA reports, which means that the information is often out of date.

Therefore, this paper aims to answer the following two research questions: How can FMEA weaknesses and limits be explained? How can FMEA methodology be upgraded to improve reliability engineering in product design and development?

To answer our research questions, we use recent advances in design theory (Le Masson et al. 2015; Hatchuel et al. 2018) to discuss the relevance of the FMEA methodology and to improve it. We used C-K design theory (Hatchuel and Weil 2003; 2009) as a theoretical framework. C-K design theory is both a unified theory of design and a theory of reasoning in design (Le Masson et al. 2013; Hatchuel et al. 2018). According to Hatchuel and Weil (2003), C-K design theory allows us to model innovative design as the interaction and the co-evolution of two interdependent spaces: the space of concepts [C] and the space of knowledge [K]. In this paper, C-K design theory is used both to analyze FMEA weaknesses and limits and to provide a new pragmatic tool for action. Based on a collaborative management research methodology (Shani et al. 2008), we conducted an empirical case study to test and validate a new FMEA methodology called CK-FMEA.

The paper is organized as follows. We first discuss the FMEA procedure, its history, its main concepts and its current weaknesses. We show that current FEMA shortcomings can be linked to the use of the brainstorming method to identify potential failure modes. We demonstrate that creativity and rigorous analysis are not intrinsically incompatible when using the C-K design theory. To evaluate this assertion, we present an in-depth case study based on the experimentation of the C-K design framework in FMEA processes at STMicroelectronics, one of the European leaders in the semiconductor industry. Several insights into the CK-FMEA new method are highlighted, and operational implementations of CK-FMEA are discussed. The paper concludes with limitations of the research and further perspectives.

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2. Literature review on FMEA

2.1. FMEA approach: a general overview

In 1949, the U.S. Armed Forces (Military Procedures document MIL-P-1629) introduced the failure mode and effects analysis methodology (FMEA) to analyze and organize failures according to their impact on mission success and equipment safety (Stone and Tumer 2005). Since that time, the use of the FMEA methodology has increased considerably across the industry, from the Apollo space program (1960s) to the semiconductor industry, foodservice, software, and the automotive industry (1980s). In major industries, problem prevention and design/process improvement are the main focus of FMEA (Lodgaard et al. 2011). Preventing problems is clearly more advantageous—in terms of cost, quality and reliability—than fixing problems. As a tool, FMEA allows for the prevention of problems before design reach testing, and it can drive design and process improvements. Achieving safe, stable, trouble-free designs and error-proof manufacturing processes are the main objectives (Punz et al. 2011). According to the Quality System Requirements QS-9000[1], FMEA is one of the most basic processes to evaluate the extent of risk as a prerequisite to risk reduction. This process aims to achieve defect prevention rather than defect detection, and organizations should conduct FMEA review and approval prior to production phases. For the IATF 16949:2016 standard[2], industrial firms should document processes for the management of product safety-related products and manufacturing processes, which should include FMEA. Given that effective product testing and manufacturing process controls are critical elements of successful product development, FMEA is also used to improve test plans and process controls. Other benefits of conducting FMEA

[1] International quality management system (QMS) standard for the automotive industry originally developed by the American auto industry (Daimler Chrysler Corporation, Ford Motor Company, and General Motors Corporation).
[2] IATF 16949 is a global Quality Management System Standard for the Automotive industry. It was developed by the International Automotive Task Force (IATF) with support from the Automotive Industry Action Group (AIAG).

include its ability to select alternatives (in system, design, process, and service), define opportunities for achieving fundamental differentiation, improve the company's image and competitiveness, and increase customer satisfaction (AIAG 2008).

According to the most influential handbook (Stamatis 2003; AIAG 2008; Ford Motor Company 2011; Carlson 2012; AIAG[3] and VDA[4] 2019), FMEA is divided into three types: system FMEA, design FMEA and process FMEA. System or concept FMEA is the highest-level analysis of an entire system composed of different subsystems. Design FMEA, usually managed by product/design engineers, aims to identify and demonstrate engineering solutions to conform to system FMEA requirements and customer specifications. Process FMEA addresses manufacturing processes. The focus is to define how manufacturing and assembly processes can be developed to ensure that products or technologies are built according to design requirements while maximizing the quality, reliability, productivity, and efficiency of the different processes. As illustrated by Figure 1, these types of FMEA are used to support the product development process and are interdependent (AIAG 2008; Bharathi et al. 2018; Feng et al. 2018; Haughey 2019).

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[3] Automotive Industry Action Group
[4] German Automotive Industry Association

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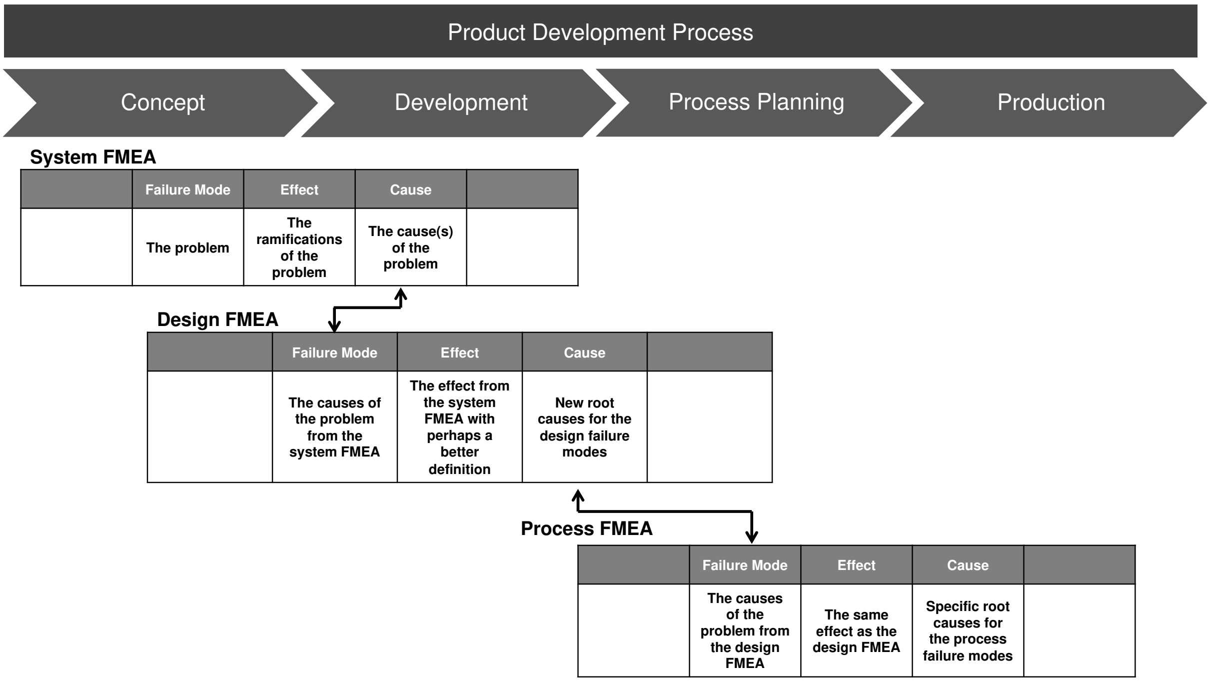

Figure 1. Relationship of system, design, and process FMEA (Stamatis 2003, Wurtenberger et al. 2014)

2.2. FMEA methodology and implementation

The FMEA methodology is based on a tabular method of presenting data. Information from the analysis is visually displayed in a series of worksheet rows and columns (Figure 2). According to industrial handbooks (AIAG 2008; Ford Motor Company 2011; AIAG and VDA 2019), the FMEA methodology is based on three main steps: (1) potential failures and effects analysis (in green in the figure below), (2) cause and detection analysis (in yellow in the figure below), and (3) improvement actions (in red in the figure below).

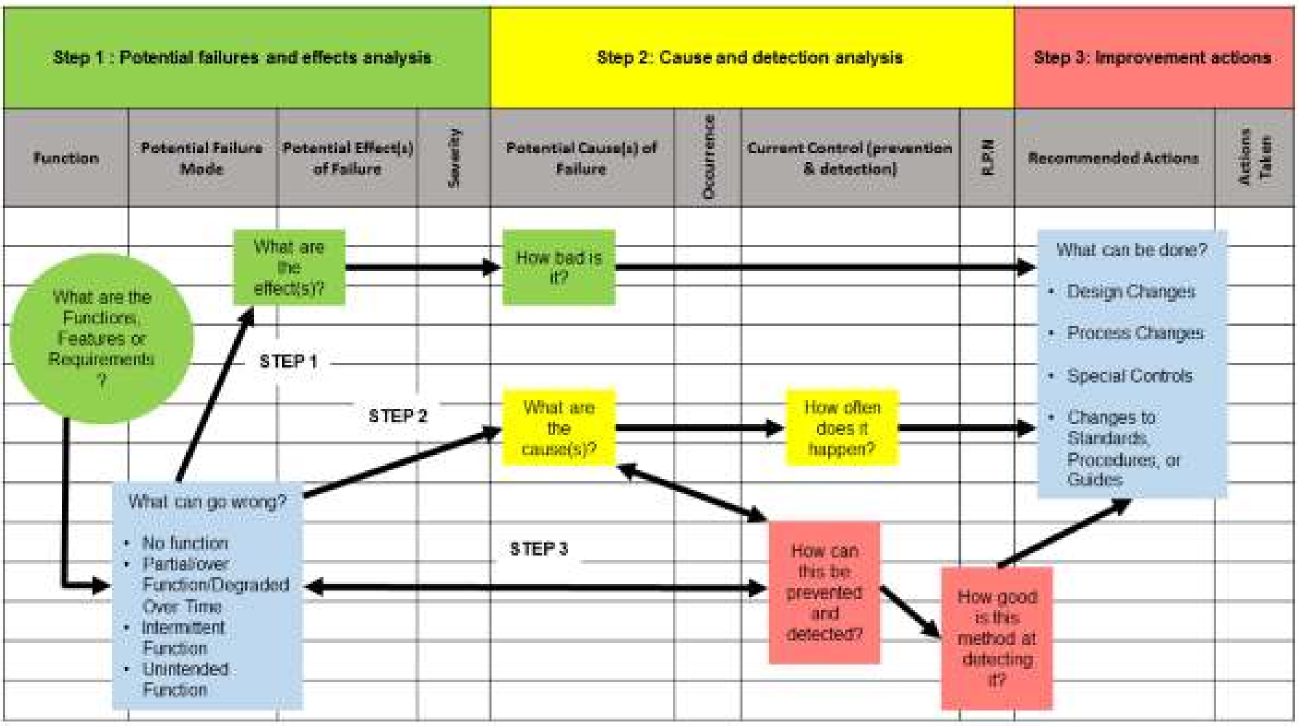

Figure 2. Generic FMEA worksheet (AIAG 2001; Ford Motor Company 2011)

A function corresponds to the task that the system, design, and process must perform. Usually, a function is described by an active verb. Potential failure mode is defined as the way in which a product or process could fail to meet design intent or process requirements. Each function may have several different kinds of potential failure modes, which should be described in *"technical terms, not as a symptom necessarily noticeable by the customer"* (AIAG 2008). A potential effect is the outcome and the consequence of the failure on the system, design and process. This is what happens when a failure occurs. Potential effects of failure must be analyzed from two perspectives: local consequences and global consequences. Local consequences mean that the failure can be isolated and does not affect anything else. Global consequences mean that the failure can affect other functions. Potential cause is defined as the reason for the failure, i.e., the root cause of the failure. Potential cause of failure may be an indication of a design weakness, the consequence of which is the failure mode (AIAG 2008).

In most industries, FMEA procedures are recommended in the case of new product or process development, modifications of existing products or processes, customer requests, quality improvement, and reliability management.

The basic FMEA procedure uses the following systematic approach (AIAG 2008, Ford Motor Company 2011; Carlson 2012):

2.2.1. Step 1: potential failures and effects analysis

- Identifying the team: FMEA cannot be performed by an individual person. FMEA must be created by a cross-functional and multidisciplinary team. This team must be defined depending on the nature of the project (new design, new process, modifications to existing design/process, use of an existing design/process in new environment, etc.).
- Identifying functions: The purpose of this activity is to identify, clarify and understand the functions, requirements and specifications relevant to the defined scope. In this case, it is advisable to use a functional block diagram (for system and design FMEA) and process flowchart (for process FMEA).
- Identifying potential failure modes: The purpose of this phase is to list each potential failure mode associated with the particular function. The assumption is that failure could happen but is not necessary. Four types of failure models could occur: (1) no function (system is totally nonfunctional); (2) partial/over function/degraded over time (degraded performance); (3) intermittent function (complies but loses some functionality or becomes inoperative often due to external factors); and (4) unintended function (interaction of several elements whose independent performance is correct adversely affects the product or process). One way to proceed is to conduct a review of past things that have gone wrong, concerns, and reports and to use the brainstorming method, storybook method and cause-and-effect diagram.

- Identifying potential effects of failure: For each of the failure modes, the issue is to list and describe the effects/consequences of the failure on the system. Determining potential effects includes the analysis of the severity of those consequences.

2.2.2. Step 2: cause and detection analysis

- Identifying potential causes: The purpose of this phase is to identify every conceivable cause of failure for each failure mode. There may be one or several causes for each failure mode, and by definition, if a cause occurs, the corresponding failure mode occurs. Determining potential causes includes the occurrence ranking, i.e., the likelihood that a specific cause will occur during the design life.
- Identifying current controls (prevention and detection): For each cause, the issue is to identify the design or process controls. Design or process controls are those activities that prevent or detect the cause of potential failures. Prevention controls describe how a cause, failure mode, or effect is prevented based on current or planned actions. The goal is to reduce the likelihood that the problem will occur. Detection controls describe how a failure mode or cause is detected before the product design is released to production. The aim is to increase the likelihood that the problem will be detected before it reaches the end user.

2.2.3. Step 3: improvement actions

The purpose of improvement actions is to establish engineering assessments to reduce overall risk and the likelihood that the failure mode will occur. This can be done by identifying preventive actions that reduce or eliminate potential failure modes or detective actions (e.g., testing) aimed at helping to identify a weakness.

The critical part of an FMEA process is the first two steps (step 1 and step 2): potential failures and effects analysis (identifying potential failures and effects) and cause and detection analysis (identifying potential causes and controls). Indeed, the performance of the improvement actions depends on these two steps. If potential failure modes, effects and causes are wrongly identified or not identified, prevention and detection analysis, as well as improvement activities, no longer make sense. Thus, the success of the initial step guarantees the global performance of the FMEA methodology. Therefore, our research focuses on the analysis and improvement of these first two steps.

2.3. Current challenges and weaknesses of FMEA

Although FMEA is a widespread method used across industries, practitioners and academic research highlight many challenges in efficiently implementing FMEA (Breiing and Kunz 2002; Liu et al. 2013; Banduka et al. 2016; Balaraju et al. 2019; Geraminian et al. 2019). In many cases, it is difficult to demonstrate that FMEA information improves the quality of product and process design. We identify several weaknesses and limits.

2.3.1. The analysis of a new and complex system

The analysis of new and complex systems presents a number of issues. First, the failure behavior of new systems is not known from practice (Peeters et al. 2018). Therefore, the lack of historical data leads to difficulties in conducting potential failure analyses and identifying effects and causes (Dağsuyu et al. 2016). It is also difficult to determine “where to search for failure modes” and to identify potential root causes when there is a lack of practical experience (Peeters et al. 2018; Subriadi and Najwa 2020). Second, in science-based industries, new systems are typically large and complex, and it may be difficult to identify the most critical failures and to obtain a full understanding of their behaviors. For example, in the semiconductor industry, the pace of technology development is very high and the renewal of products is very fast, which involves potential failures that were not previously expected (Qian et al. 2017; Sun et al. 2017). In addition, unexpected potential failures may still occur even if the correct FMEA procedures have been respected. Joshi and Joshi (2014) note that FMEA often fails to identify all failure modes and does not allow the discovery of complex failures involving a combination of failures. This is due to the complexity and novelty of systems and because experts tend to make more use of existing generic listings of potential failures, effects, and causes. These types of listings provide standardized descriptions and limit the creativity of the FMEA team to "think outside the box" and to identify problems not previously observed (Carlon 2012).

2.3.2. The analysis of interfaces and multidomain integration

According to Carlson (2012), empirical data show that at least 50% of field problems occur at the interfaces between subsystems. However, system, design and process FMEA are not effectively connected. The FMEA methodology tends to study the risks on a per-system basis regardless of a global vision. Each system carries different effects, and these effects may involve undesired effects and problems in other modules and subsystems (Punz et al. 2011; Wurtenberger et al. 2014). As underlined by Henshall et al. (2014, 2015), the FMEA process provides little or no guidance concerning the mechanics of linking system levels within a complex system. Moreover, there is no advice on effective deployment and management across engineering teams. For example, Sun et al. (2017) observe that previous FMEA is often isolated from production and that there is no automatic link to make FMEA function as guidance for production. Modern technologies, such as semiconductors, involve several design teams from different engineering disciplines. Each team tends to develop its own FMEA approaches without connection between them, which makes validation of the functional integration of the system as a whole a very difficult task (Henshall et al. 2014, 2015). Information in FMEA is often uncertain or imprecise and is expressed in a specific technical language that makes common understanding difficult (Chanamool and Naenna 2016). In addition, as an inductive method, FMEA is often restricted to examining the consequences of unwanted and known events. This shortcoming makes it difficult to support dynamic updates of FMEA reports

(Lodgaard et al. 2011). Therefore, organizations are more interested in implementing FMEA as a customer requirement rather than for internal benefits (Banduka et al. 2018).

2.4. FMEA production and creation

The FMEA Guidelines (AIAG 2008; Ford Motor Company 2011) provide a clear definition of what must be reviewed, but provide little instruction on how to proceed (Breiing and Kunz 2002; Johnson and Khan 2003; Henshall et al. 2014, 2015). For example, there are some recommendations for identifying and determining potential failure modes, effects and causes.

2.4.1. Complementary and auxiliary tools for FMEA analysis

Although they are few recommendations on how to proceed, the professional and academic literature highlighted several complementary and auxiliary tools, such as boundary diagrams, p-diagram, interfacing diagram, FTA, brainstorming, etc. (Table 1).

Principal complementary tools for FMEA	**Description**
Boundary Diagrams	A boundary diagram is a tool for qualifying and clarifying the relationships between systems/subsystems/components. It bases on a visual depiction of the entire system to show clearly the boundaries of the FMEA analysis. (Stamatis 2003; Ford Motor Company 2011; Carlson 2012)
Parameter Diagram (P-Diagram)	The P-diagram is a tool to identify intended input and outputs of a system. It uses to identify error states based on the analysis of these inputs and outputs. (Stamatis 2003; Carlson 2012)
Interface Diagram	An interface diagram is a tool for identifying and quantifying the strength of system interactions. (Stamatis 2003; Carlson 2012)
Ishikawa “Fishbone” Diagram	Also known as a cause & effect diagram, is a deductive analytical technique. It uses a graphical “Fishbone” diagram to show the cause, failure mode, and effect relationships between an undesired event and the various contributing causes. (Ford Motor Company 2011)
Fault Tree Analysis (FTA)	FTA is a graphical “tree” to show the cause-effect relationships between a single undesired event and the various contributing

	causes (Ford Motor Company 2011; Peeters et al. 2018)
Characteristic Matrix	Characteristic Matrix is a tool to develop product-to-process and product-to-product linkage. (Stamatis 2003; Ford Motor Company 2011)
Brainstorming	Brainstorming is a process of creative thinking and a method of generating ideas. (Ford Motor Company 2011)

Table 1. Principal complementary tools for FMEA

These tools allow a better understanding of the system and are used to ensure a robust analysis of the system. For example, Joshi and Joshi (2014) explain that FTA allows the evaluation of risk by tracing backwards in time or backwards through a causal chain. According to Peeters et al. (2018), the use of FTA increases the quality of the content generated for the FMEA. For Tsai et al. (2017) multiple-criteria decision analyses are interesting tools to examine interactive effects and causal relationships through a system. From a general point of view, these tools offer a large scope of structured approaches allowing a better understanding of complex system and improving information sharing between teams across the organization (Breiing and Kunz 2002; Henshall et al. 2014, 2015; Banduka et al. 2018; Subriadi and Najwa 2020).

2.4.2. Systematic approaches to the development of FMEA

Although these tools are useful to collect data, information, and knowledge of product/system under consideration, they are not designed to develop the FMEA. They are analytical tools able to generate content for the FMEA, to support collective learning and knowledge sharing, but they are not systematic processes to the development of FMEA. Therefore, several works tackled this issue and have suggested new FMEA processes (Breiing and Kunz 2002; Henshall et al. 2014, 2015, AIAG and VDA 2019). The recent AIAG and VDA handbook (2019) proposes a new approach for FMEA development: the 7-step approach (Figure 3). This new procedure includes more emphasis on the system analysis, however, there are few modifications for the analysis of potential failures, effects and causes (Step 4 in the figure 3).

Figure 3. The 7-step FMEA approach (AIAG and VDA 2019)

In addition, the literature highlights that most FMEA is created through the classic brainstorming technique (Chanamool and Naenna 2016; Dağsuyu et al. 2016; Erbay and Özkan 2018; Tsai et al. 2018; Subriadi and Najwa 2020). Brainstorming methodology is also recommended by all reference handbooks (Table 2).

References to Brainstorming Methodology	Handbook References
"List each potential failure mode associated with the particular item and item function. The assumption is made that the failure could occur but may not necessarily occur. A recommended starting point is a review of past things-gone-wrong, concerns, reports, and group brainstorming."	AIAG 2001, p. 15
"List the potential failure modes based on failure of the component, subsystem or system under review to perform or deliver the intended function. A good starting point is a review of past things-gone-wrong, concerns, reports and group brainstorming."	Francis 2003, p.68
"The team may use brainstorming, cause-and-effect analysis, QFD, DOE, Statistical Process Control (SPC), another FMEA, mathematical modeling, simulation, reliability analysis, and anything else that team members think is suitable."	Stamatis 2003, p.37
"After determining all the failure modes, a validation of the completeness of the analysis can be made through a review of past things-gone-wrong, concerns, reports, and group brainstorming."	AIAG 2008, p. 31
"The determination of the potential failure modes (FM) can be supported by the following methods: creativity procedures (Brainstorming, 635, Delphi, etc.), [...]"	Bertsche 2008, p.138
"Knowledge of consensus-building techniques, team project documentation, and idea-generating techniques such as brainstorming are all necessary for FMEA team members."	Mikulak et al. 2009, p. 13
"Brainstorming techniques can be used to identify potential cause(s) of each Failure Mode. Consider how the item may fail (e.g., part Failure Mode – why the part would be rejected at that operation), and what process characteristics in each operation may cause the item Failure Mode."	Ford Motor Company 2011, p. 131
"Having selected the parameters, an introductory session was held to bring everyone up to speed to the DFMEA process, followed by a brainstorming session to qualitatively capture the failure modes with their effects and causes."	Carlon 2012, p. 221
"The first step in FMEA is listing all possible failure modes of a specific product or system through brainstorming session."	Liu 2019, p.17

Table 2. References to brainstorming methodology

Even if brainstorming is recommended, this is unlikely to systematically tackle the complexity challenge (Campean et al. 2011, Henshall et al. 2014, 2015). According to theses authors, there is a need for a structured tool to address the heavy reliance on less structured approaches, such as brainstorming, in carrying out practical function decomposition analysis. Henshall and Rutter (2014) proposed to introduce the 4-step FMA (Failure Mode Avoidance) process to support the effective deployment of FMEA. The 4-step FMA process consists of a structured framework for function analysis based on 4 steps: (1) function analysis, (2) failure analysis, (3) robust countermeasure development and (4) robust design verification (Campean et al. 2011, 2013; Kumar and Maass, 2013; Henshall et al. 2014). This framework is mainly focused on the development of design FMEA. Although it is possible to use a similar approach for the process FMEA, this framework implies a clear separation between the development of the different types of FMEA. However, based on Breiing and Kunz (2002), we believe that the separation into three types (system, design, process FMEA) is underperforming and is not reasonable. This is because many products are so complex that a correction in one type of an FMEA can cause new mistakes in the same type or in other type. According to Breiing and Kunz (2002), since a system FMEA is carried out before a design FMEA, a mistake discussed during design FMEA is not considered anymore in the system FMEA. This approach carries the risk that potential sources of error may be overlooked in the development of the FMEA. As Breiing and Kunz (2002), we believe that is more reasonable to carry out all three methods simultaneously in order to use synergies of the group. On the one hand, we agree with Henshall et al. (2014), that the used of unfocused brainstorming is less efficient than a structural approach. On the other hand, we think that the use of a too inflexible approach doesn't allow creativity in problem identification. Finally, our aim is not to replace these frameworks and tools with an alternative process. But to offer a new complementary approach combining creativity and robustness, and allowing the development of several types of FMEAs simultaneously.

3. Improving FMEA based on design theory

Brainstorming is a method for group creativity that aims to generate high volumes of creative ideas (Kohn and Smith 2011; Keeney 2012; Seeber et al. 2017). This method is focused on increasing the number of ideas created by groups with the aim of facilitating problem-solving solutions through the hypothesis that quantity breeds quality: *"It is almost axiomatic that quantity breeds quality in ideation. Logic and mathematics are on the side of the truth that the more ideas we produce, the more likely we are to think up some that are good"* (Osborn 1963, p. 131).

3.1. Limits of failure-effect-cause identification using brainstorming methodology

The use of brainstorming is not surprising in the sense that it is simply one of the best-known problem-solving techniques and is both analytical and creative (Rawlinson 2017). However, the analysis of failures, effects and causes is supposed to identify all potential failures but also to highlight relevant root causes and to take into account interdependencies among various failure modes and effects. According to Henshall et al. (2014), brainstorming is unlikely to systematically tackle the complexity challenge. For these authors, the use of brainstorming results in a significant number of potential root causes not being identified and hence the lack of establishment of effective countermeasures. In addition, the use of brainstorming could lead team members to often confuse failure modes and causes, causing them to document FMEA in an inappropriate way and leading to a loss of structure of the document.

Moreover, studies about brainstorming have highlighted several shortcomings (Kohn and Smith 2011; Keeney 2012; Gobble 2014; Kazakci et al. 2015). Based on a literature review, Reining and Briggs (2008, 2013) conclude that evidence that quantity breeds quality is not conclusive or is even conflicting. For example, Williams and Sternber (1988) found that teams are able to generate better solutions when they are focused on the production of a best idea rather than as many ideas as possible. This is because the objective of finding the best idea allows the evaluation of ideas through a reasoned process rather than a pure and unbridled generative process (Rowatt et al. 1997; Harms and Van Der Zee 2013). According to Rietzschel et al. (2010), idea generation is only part of the creative process and should not be a goal in itself. These authors also argue that idea generation and evaluation should not be separated into two phases; instead, it might be best to mix short idea generation sessions with evaluation sessions. Therefore, the main issue is to enhance the rigor of the analysis through a structured approach that is able to significantly and systematically identify the potential functional chains, root causes and effects.

3.2. Combining creativity and robust analysis through C-K design theory

The purpose of problem solving is to find solutions to an organization's problems. There are many routes that can be followed, and brainstorming is just one of these routes. In contrast to the brainstorming approach, based on the psychology literature, design research (Simon 1996; Dorst and Cross 2001; Taura and Nagai 2012; Kroll 2013; Hatchuel et al. 2018) emphasizes systematic approaches involving creativity (novelty, originality, variety), feasibility (quality, cost, delay) and robustness of solutions (performance). Among these approaches, Le Masson et al. (2007) show that creativity and design are not intrinsically incompatible when using the C-K design theory. They note that design reasoning based on the C-K design theory simultaneously increases variety, originality, value and robustness in a rigorous and controllable way. According to Gillier et al. (2010), C-K design theory is also a powerful framework to support collaborations during design reasoning. In particular, C-K design theory allows for the alignment of different interests and ensures cohesion and coordination between partners. In addition, Kazakci et al. (2015) use the C-K design theory to demonstrate that it is possible to produce and predict the outcome of a design process and its impact on performance in terms of feasibility, originality and the value of ideas.

C-K design theory aims to provide a unified and rigorous framework for design (Hatchuel and Weil 2003, 2009; Kazakçı and Tsoukiàs 2005; Kazakçı 2013; Le Masson et al. 2013; Hatchuel et al. 2018). According to C-K design theory (Hatchuel and Weil 2003, 2009), design is defined as the interaction between two interdependent spaces. On the one hand, K Space incorporates all the propositions with a logical status, i.e., all available knowledge that the designers are able to prove or disprove. On the other hand, C Space includes all the propositions that are neither true nor false in K space, i.e., concepts about partially unknown objects. Propositions in C space are qualified as *"undecidable"* relative to the content of a space K if it is not possible to prove that these propositions are true or false in K space. When designers are faced with concepts, they cannot affirm whether such a thing may be possible or whether this would never be the case. Design starts when an initial concept is created. The design process proceeds by expansion of this initial concept into other concepts (by partitioning the concept) and/or into new knowledge (Figure 4). During the design process, both C and K spaces are expandable, and these transformations between spaces and in the same spaces occur through four operations: C➔C, C➔K, K➔K and K➔C.

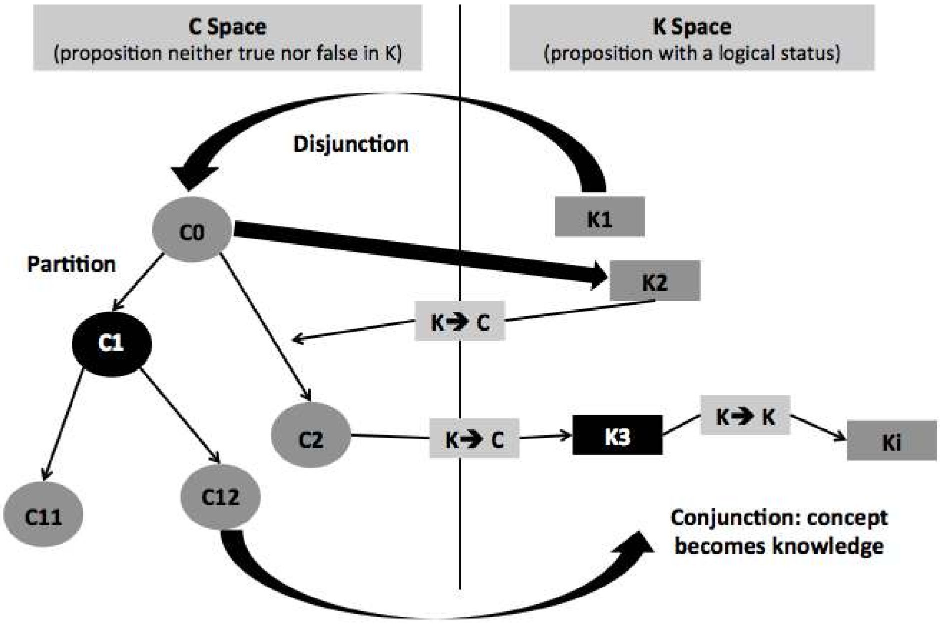

Figure 4. C-K design formalism (Hatchuel & Weil 2003)

The design process attempts to transform *"undecidable"* propositions into logical propositions in K; i.e., the design solution is when *"the first concept becomes a true proposition in K"* (a conjunction). The theory claims that C space has a determined tree structure. Each node represents a partition in various subconcepts (Hatchuel and Weil 2003), and only partitioning or inclusions are allowed in C space. The theory introduces two different types of partitioning for concepts: *restrictive partitions* and *expansive partitions* (Hatchuel and Weil 2003). Restrictive partitions add a property to a concept that is already known, unlike expansive partitions, which add properties that are not known in K as a property of the entities concerned. Therefore, *"creativity and innovation are due to expansive partitions of concepts"*. The design process must therefore be understood as interactions between these two spaces. Knowledge is used to elaborate concepts in C space, and concepts are used to expand knowledge in K space. The design process ends when an *undecidable* proposition (concept) becomes *decidable* in K space. Using a color code, the following table (Table 3) describes the various stages of the design process according to the C-K framework.

	Color Code	Industrial implications	Theoretical foundations
C space	Known concept	The concept refers to a set of known technical solutions whose performance is also known	There are many conjunctions
	Attainable concept	The concept is to be deepened but attainable	Restrictive partition
	Unexpected concept	The concept is far from the dominant design	Expansive partition
K space	Validated knowledge	Knowledge validated in-house	Stabilized knowledge base (including dominant design)
	Ongoing knowledge	Knowledge being acquired	K identified, conditions of validity and evaluation to define
	Missing knowledge	Absent or nonactionable knowledge in-house	Identification of need for K (expansion of the knowledge base)

Table 3. Grayscale code for the C-K framework (Agogué et al., 2014a)

4. Case study: Using C-K design theory to improve the FMEA process

4.1. Objectives

After identifying FMEA weaknesses the purpose of the case study is to improve FMEA methodology through the use of C-K design theory. The aim is to implement the C-K design process to improve the identification of potential failures, effects and causes during an empirical study. In addition, the study presents an opportunity to analyze the acceptance of this method by users (e.g., engineers, product managers, experts, quality managers).

4.2. Research methodology: collaborative management research

The present study is based on a collaborative management research methodology (Shani et al. 2008) conducted by academics and practitioners to create actionable knowledge for the organization and generic knowledge for design engineering (David and Hatchuel 2007). According to Pasmore et al. (2008), collaborative management research is defined *"as an* *emergent and systematic inquiry process, embedded in an agreed-upon partnership between actors with an interest in influencing a certain system of action and researchers interested in understanding and explaining such systems"*. We adopted this research methodology because it allows the production of powerful and relevant solutions to operations processes and management issues (Pasmore et al. 2008). The collaborative research process integrates scientific knowledge and methods with practical knowledge. Through a collaborative process, one aim is to produce knowledge that should be actionable to improve operations and engineering processes. Another aim is to generate new knowledge that should be relevant for the scientific community. Several research methodologies similar to our approach are proposed in the academic literature, such as action research (Lewin 1946; Coughlan and Coghlan 2002) and clinical field research (Schein 1987). The findings of this qualitative research are the result of an in-depth case study that lasted for 18 months (Eisenhardt 1989; Yin 1994) at STMicroelectronics, one of the European leaders in the semiconductor industry. Following the recommendations of Denyer et al. (2008) and Groop et al. (2017), our process of problem framing and solution development was based on four steps (Table 4).

Steps	**Description**	**Corresponding stages in the case study**
Step 1 - Framing the "wicked" problem in the context	Analyzing the problem in an authentic context, describing undesirable effects, identifying stakeholders	Stage 1
Step 2 - Understanding how undesirable effects are related	Identifying generative mechanisms of the problems, structuring current reality	Stage 1
Step 3 - Designing propositions	Interventions to address core problems, testing potential solutions	Stage 2, Stage 3, Stage 4
Step 4 - Evaluating consequences	Observe outcomes, intended and unintended effects	Stage 5

Table 4. Problem framing and solution development

4.3. Data collection process and data analysis

Collaborative management research methodology enables access to a large set of data and allows researchers to adjust their investigation to make sense of the field. During our interventions, data were collected in several ways: observations and analysis of internal process, interviews with key actors, analysis of internal documentation (checklists, FMEA, standard operating procedure, etc.), and participation in meetings and working groups concerning FMEA implementation. This variety of data was used to ensure data triangulation (Figure 5).

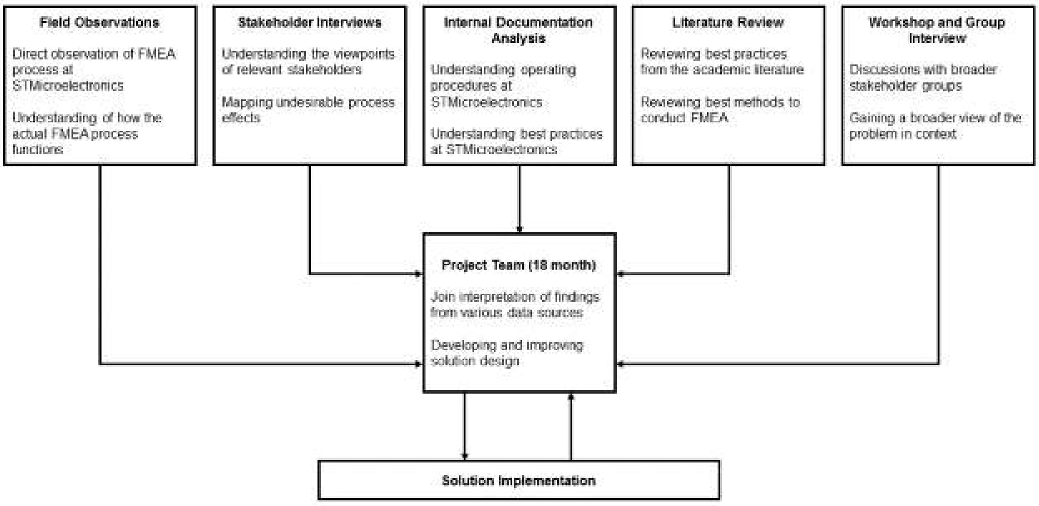

Figure 5. Data collection process and data analysis

The collaborative management research began by identifying problems and issues encountered by STMicroelectronics teams in implementing FMEA. Based on these data, we conducted a review of the academic literature to put the identified challenges into perspective. Then, we proposed a theoretical analysis and discussed the possibility of using C-K theory to organize the systematic exploration of potential failures, effects and causes. At this stage, our objective was to develop a shared view of a critical issue of interest to both practitioners and the researchers. The inquiry process was followed by the implementation of the C-K design process in the FMEA procedure. The objective was to test and empirically analyze the effects of the FMEA procedure using C-K design theory. This experimentation was collectively presented by the authors and project managers during steering committee meetings at STMicroelectronics. Furthermore, to evaluate the performance and user acceptance of the CK-FMEA methodology, we conducted several interviews with engineers, experts and quality managers. The collection and analysis of the facts, observations, and conversations allowed us to measure the acceptance and pertinence of the new process in a collaborative and innovative context.

4.4. Presentation of the case study

The research was conducted by three researchers in design engineering and by a STMicroelectronics senior expert in operations engineering. The purpose of this research was to investigate FMEA methodology and its use in the Engineering Competences Center of STMicroelectronics, located in Crolles (France). From the company perspective, the aim was to understand and explain the weaknesses of the FMEA procedure to improve the process and the performance of the firm. From an academic perspective, the FMEA tool is an interesting research object. It has been used since the 1980s by the main important industries; however, practitioners and researchers agree that this tool is weakly effective and efficient: How can we explain this paradox? The challenge was to bring new theoretical frameworks and new knowledge in the field of design and operations engineering. STMicroelectronics was chosen because of its ability to develop high-reliability products and technologies (Cabanes et al. 2016; Ben Said et al. 2016; Cabanes et al. 2020). Moreover, the semiconductor industry is subject to high standards concerning product and technology reliability issues (Sharma 1997; Lutz 2011). STMicroelectronics is a leading technology innovator with approximately 7,800 people working in R&D (engineers, researchers, scientists, etc.). With a turnover of $9.56 billion (2019), STMicroelectronics (Franco-Italian group) is among the world's largest semiconductor companies, such as Intel, Samsung and TSMC. In 2019, the company had approximately 46,000 employees, and almost one-fifth of people worked in R&D and product design. The company spends approximately 16% of its revenue in R&D and owns a substantial patent library

(~18,500 owned patents and 590 new patent filings in 2019). The empirical study started in 2016 over a period of 18 months and was based on 5 stages.

4.4.1. Stage 1: Identifying FMEA issues at STMicroelectronics

The preliminary stage aimed to identify and determine issues in conducting FMEA at STMicroelectronics. To do this, we conducted several interviews, and we organized a workshop to clarify the main challenges faced by practitioners. This step was fundamental for both practitioners and academics. For practitioners, this phase allowed them to share common knowledge about FMEA procedure issues and formalized the need to improve the methodology. For academics, this phase allowed us to collect precise data about FMEA weaknesses. Moreover, this first step also allowed us to engage in collaboration between practitioners and academics and align the interests of both parties in this research. Based on this work, we highlighted four main issues. First, we found that for several similar industrial processes (with 90% similar content: same technology process, same function), FMEA for these processes was often different (more than 50% mismatch). This means that for the same functions from different FMEA, the data into the FMEA (potential failures, effects and causes) were totally different and inconsistent. This observation illustrated that the FMEA design process is heavily dependent on the team and the expertise mobilized by the designers. Second, we found that the identification of potential failure modes, effects and causes that have not previously been encountered is extremely difficult and rare. According to STMicroelectronics experts, this is because FMEA is performed too late in the design cycle and because of the use of generic listings of past failures, effects, and causes instead of imagining new and unexpected failures. The experts also highlighted that it was particularly difficult to anticipate potential or unexpected failure modes using brainstorming because this method suffers from a lack of structure to collect and recognize interesting ideas. Third, we found that the management of interfaces between different kinds of FMEA (product FMEA, process FMEA, equipment

FMEA) was a great challenge. Based on several interviews, we discovered that when an unexpected problem appears, people from product design tend to blame process development teams or people in charge of the maintenance of equipment and vice versa. Most engineers recognized that the management of FMEA interfaces is difficult to capture. In theory, the causes in the system FMEA become the failure modes in the design, which in turn generate their own causes, which ultimately become the failure modes in the process FMEA. However, the relationships between these chain links are difficult to manage in practice. Finally, we found that the FMEA procedure is perceived by engineers as a reporting tool rather than a learning device to improve quality.

4.4.2. Stage 2: Identifying common knowledge and generating unexpected concept in each FMEA project

Following the first stage, we conducted an academic literature review to put into perspective the issues identified in STMicroelectronics. During a seminar, the authors of this paper presented the results and showed that most issues have been identified by the academic literature. We highlighted the limitations of an approach based on the brainstorming method. We presented the C-K design theory as a potential and powerful framework to support the collaborative identifications of potential failures, effects and causes. Then, we proposed to the practitioners to test the effectiveness of a C-K-based tool for FMEA production. Once we received their approval, we collectively decided to conduct an experiment. We first organized a workshop to briefly explain the C-K theoretical framework. This was an opportunity to discuss theoretical principles and practical elements and to share case studies. Second, we organized a series of workshops for several FMEA projects (design FMEA and process FMEA). The main objective of these workshops was to develop common knowledge shared by all FMEA designers. The constitution of the different teams was managed by STMicroelectronics according to its own procedure. Each workshop was based on the following steps (Figure 6):

- Step 1: Each team member individually collects data and knowledge from several sources of information, such as reports, past FMEAs and feedback based on past experiences. Then, they are encouraged to share validated knowledge on well-known functions and on known potential failures, effects and causes. The goal is to ensure that each member has the same level of knowledge and shares the same vision of the system under consideration (operator "K to K" in the C-K design theory). This step is based on the use of traditional auxiliary tools, such as boundary diagrams, p-diagram, interfacing diagram and FTA.
- Step 2: Based on this shared knowledge base, members identify functions and associated potential failures, effects and causes. To do so, members must elaborate a concept tree in which it is possible to highlight all identified potential failures, effects and causes for each function (operator "K to C" in the C-K design theory).
- Step 3: The challenge is no longer to identify failures, effects and causes that are already known, but to think about failures, effects and causes that have not previously been observed. In this phase, the aim is to generate unexpected concepts from previously identified concepts. The generation of unexpected concepts from previously identified concepts corresponds to the "C to C" operator in C-K design theory (Hendriks and Kazakçi 2010; Hatchuel et al. 2013). The aim is to generate new concepts through partitioning (Hatchuel and Chen 2017). According to the C-K design theory, a partition may be restrictive or expansive (Hatchuel et al 2011). A restrictive partition reduces the space of possibilities without changing the definition or attributes of the artifact to be designed. An expansive partition changes the identity of the artifact by adding unexpected attributes to the original concept. It is precisely because of these expansions that disruptive propositions, including surprises, are possible. In our case, we supported FMEA designers in the imagination of several expansive partitions to generate

unexpected failures, effects and causes. For example, we encouraged FMEA designers to imagine new concepts of failure and express them in technical terms. To achieve this, we used the main types of failure models, such as degraded, intermittent and unintended functions.

- Step 4: Based on these new concepts, this step must allow the sharing and creation of new knowledge related to the system under study (operator "C to K" in the C-K design theory). Knowing that unexpected potential failures/cause/effects remain concepts because they are still uncertain, the issue is not to convert concepts into knowledge. However, the goal is to evaluate the relevance of the new concepts to identify absent or non-actionable knowledge in-house.

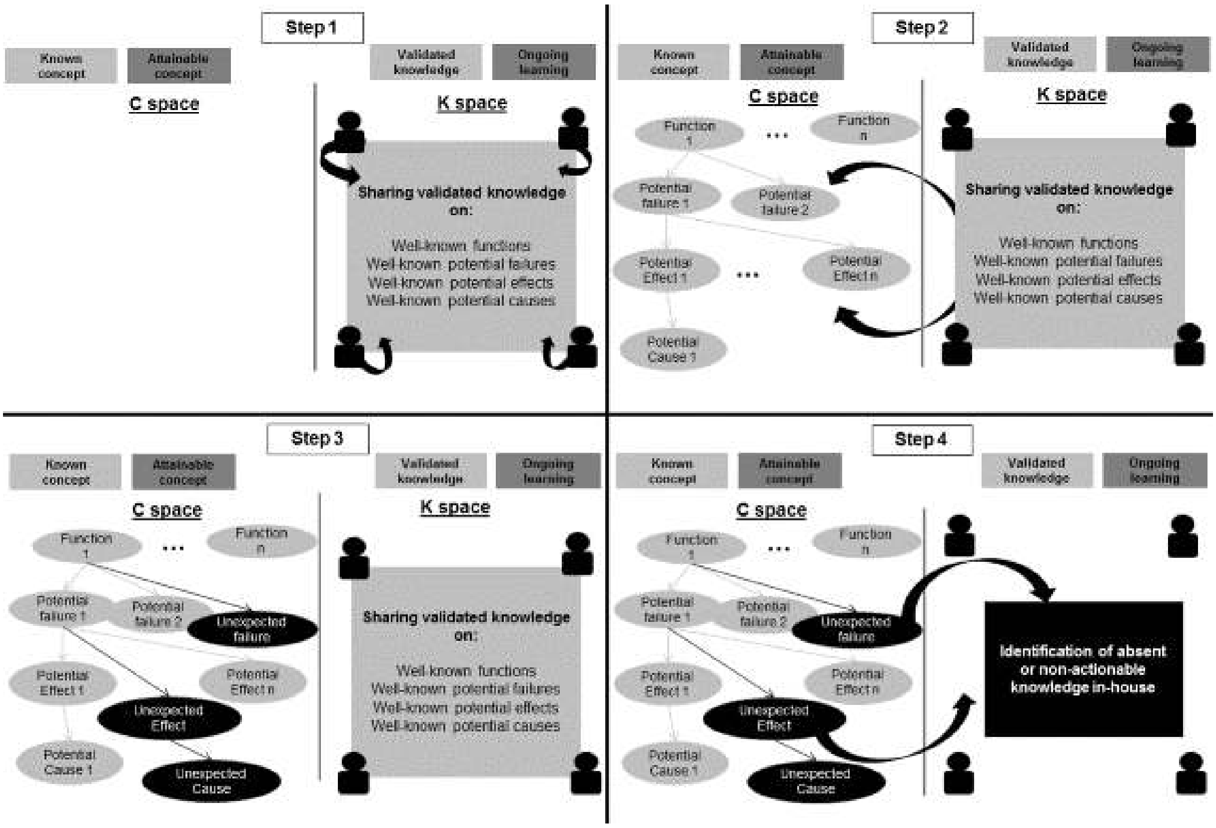

Figure 6. FMEA design process with the C-K framework

4.4.3. Stage 3: Generating unexpected concepts from collective learning at the interface of different types of FMEA.

Stage 2 was based on the production of concepts of potential failures, effects and causes in a specific type of FMEA (e.g. design FMEA or process FMEA). Stage 3 focused on the generation of unexpected concepts from collective learning at the interface of different types of FMEA. As we highlighted in the literature review and the presentation of the case study, the uncertain relationship between the different types of FMEA is also a source of unexpected issues. To identify these issues, we conducted collective learning at the interface of different types of FMEA. Based on the fact that causes in design FMEA should become failures in process FMEA, we used the C-K framework to model interactions between different types of FMEA (Figure 7). We merged two teams of FMEA designers concerning the same system – a team specializing in process FMEA and a team specializing in design FMEA - and proceeded as follows.

- First, we organized the collaboration of the two teams based on the potential causes identified in design FMEA. We used identified causes in design FMEA as a new knowledge base in process FMEA (A.1 in the figure below). Based on this new knowledge base, we tried to identify and confirm potential failures already identified in process FMEA (A.2). If this was not possible, we engaged collective reflection to generate a new unexpected potential failure (A.3).
- In the same way, we used failures identified in process FMEA as a new knowledge base in design FMEA (B.1 in the figure below). We sought to identify existing causes in design FMEA (B.2) or to generate an unexpected cause following an already identified effect (B.3). In a few cases, we also discovered that we had to imagine new potential effects and failures (B.4).

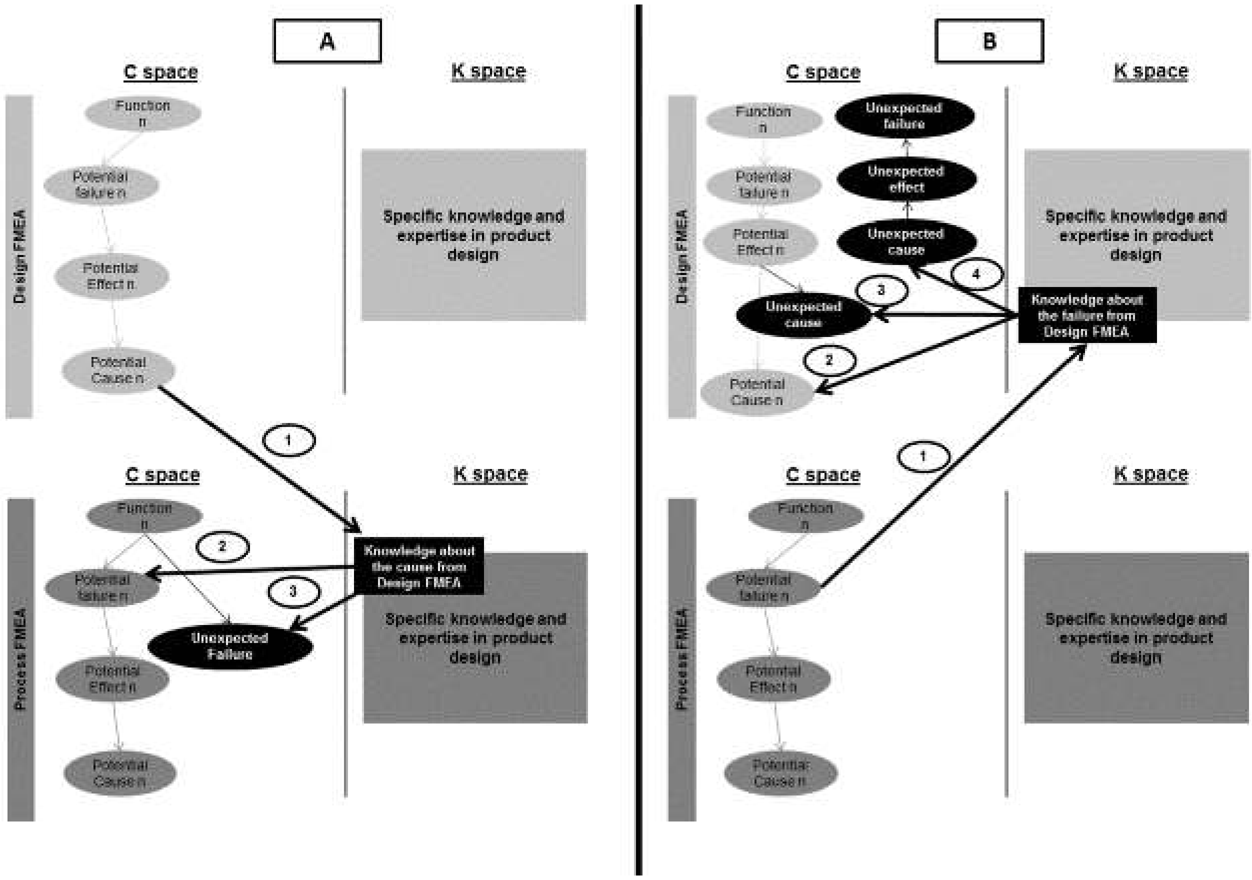

Figure 7. Management of FMEA interfaces through C-K design theory

To illustrate this process, we now propose a quick example. During our experiment, we are interested in the development of FMEA on the topic of semiconductor-manufacturing recipes. We observed that experts in design FMEA have identified only one root-cause failure concerning the function "auto wafer placement": "not match with the target 1 & 2" (potential failure), "loss of yield" (potential effect), "low pressure" (potential cause). However, we also observed other experts in process FMEA have identified that a wrong temperature could be also a source of potential failure. Based on the CK-FMEA process, we engaged a collaboration between the two teams (design FMEA team and process FMEA team) in order to evaluate the effect of temperature in design FMEA. This collaboration, based on C-K design theory, concluded that a high temperature could also be a cause of the loss of yield. As a result, the design FMEA team has reconsidered the potential failure previously identified. The team highlighted two unexpected new potential failures by splitting target 1 and target 2. They found that by decoupling target 1 and target 2 (e.g. target 1 OK and target 2 no OK) it was possible to discover new potential failures whose causes had never been previously identified (temperature problem). (Figure 8).

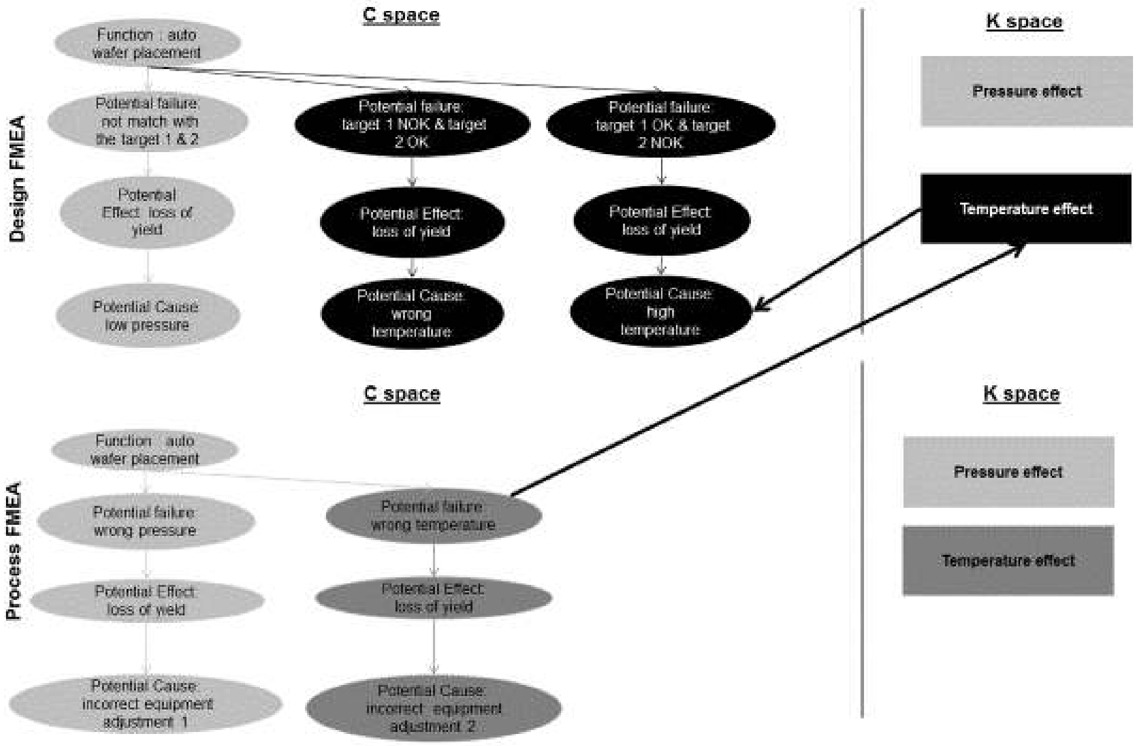

Figure 8. Example of the management of FMEA interface through C-K design theory

4.4.4. Stage 4: detection analysis and improvement actions

The two previous stages allowed the identification of potential failures, effects and causes through a robust and creative-oriented analysis. It also allowed the generation of a relevant knowledge structure to prevent problems and drive design and process improvements. Stage 4 focused on the classic FMEA approach based on the tabular method of presenting data. The aim was to visually display information in a series of worksheet rows and columns for each type of FMEA. Figure 9 presents STMicroelectronics FMEA tables before and after the C-K design workshop.

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STMicroelectronics FMEAs BEFORE C-K design workshop

	Function		Potential Failure Mode	Potential Effect(s) of Failure	Potential Cause(s) of Failure
Design FMEA	**Item:** Auto Wafer Placement	**Function:** Way to place wafers on the heater: True or False	Process results not @ target 1& target 2	Yield loss	Wafer sliding due to move to process position when not at base pressure
Process FMEA	**Item:** Auto Wafer Placement	**Function:** Way to place wafers on the heater: True or False	WT1 alarm (pressure not reached before WT1) except PROS3	Equipment fault	Time to reach a pressure of 50mT > max time (system constant)
			WT1 alarm (pressure not reached before WT1) on PROS3	Equipment fault	Time to reach a pressure of 50mT > max time (system constant)
			WT1 time not at 5s on PROS3	Hillhock on PROS3 / Nitride chambers	Increase of thermal budget. Copper diffusion. SCRAP
Equipment FMEA	**Item:** Auto Wafer Placement	**Function:** Way to place wafers on the heater: True or False	N/A	N/A	N/A

STMicroelectronics FMEAs AFTER C-K design workshop

	Function		Potential Failure Mode	Potential Effect(s) of Failure	Potential Cause(s) of Failure
Design FMEA	**Item:** Auto Wafer Placement	**Function:** Way to place wafers on the heater: True or False	Process results not @ target 1& target 2	Yield loss	Wafer sliding due to move to process position when not at base pressure
			Process results target 1NOK & target 2 OK	Yield loss	Temperature on wafer not at target,wafer placement done on step 1 & 2 in the recipe
			Process results target 1 OK & target 2 NOK	Yield loss	Temperature on wafer not at target, heat up of wafer done with spacing at 1350 mils in step 2 of the recipe and not with system constant for auto wafer placement
Process FMEA	**Item:** Auto Wafer Placement	**Function:** Way to place wafers on the heater: True or False	Wong pressure	Yield loss	Incorrect equipmet ajustment 1
			Wrong temperature	Yield loss	Incorrect equipmet ajustment 2
			WT1 alarm (pressure not reached before WT1) except PROS3	Equipment fault	Time to reach a pressure of 50mT > max time (system constant)
			WT1 alarm (pressure not reached before WT1) on PROS3	Equipment fault	Time to reach a pressure of 50mT > max time (system constant)
			WT1 time not at 5s on PROS3	Hillhock on PROS3 / Nitride chambers	Increase of thermal budget. Copper diffusion. SCRAP
Equipment FMEA	**Item:** Auto Wafer Placement	**Function:** Way to place wafers on the heater: True or False	N/A	N/A	N/A

Figure 9. STMicroelectronics FMEA before and after the C-K design theory workshop

Based on these tables, each team had to identify prevention and detection controls and elaborate improvement actions to reduce the overall risk and likelihood that failure modes would occur. This step was based on classic FMEA recommendations (AIAG 2008; Ford Motor Company 2011; AIAG and VDA 2019).

4.4.5. Stage 5: Evaluation of the FMEA methodology based on C-K design theory

At the end of the experiment, we conducted several interviews to analyze the advantages and disadvantages of the CK-FMEA methodology. We asked participants to describe the strengths and weaknesses of the proposed approach. We also encouraged them to propose future improvements. Participants noted that this new method provides clear guidelines for the identification of potential failures, effects and causes. It also provides general guidance for the practical implementation of FMEA. They stressed that the C-K design framework is a powerful systematic approach that combines creativity as well as feasibility and robustness issues. They highlighted that, unlike classic brainstorming, C-K design theory provides a clear framework that allows the generation of expertise-oriented creative ideas. Stage 2 (identifying common knowledge and generating unexpected concept in each FMEA project) was considered useful for structuring the discussion and for eliciting and aligning the available knowledge on the system under consideration. Another point that was emphasized was collaboration in a multidisciplinary environment. People recognized that the C-K framework is a relevant tool that allows coordination between different FMEA teams. They appreciated the structured approach that promotes knowledge sharing and the definition of a shared problem understanding. According to them, the C-K approach brought them to the same level of knowledge in a participatory way.

On the other hand, the pinpointed disadvantages mainly concerned significant investment of time and resources. Participants noted that the C-K approach involved specific training to be able to use the method and required a very long time to conduct the analysis of potential failures, effects and causes. However, they recognized that this time was likely necessary to engage in relevant and effective learning that improves the quality of evaluation.

We also conducted interactive debates with STMicroelectronics senior experts in operations engineering to evaluate the new methodology. We evaluated the method based on previously identified STMicroelectronics challenges: consistency of FMEA reports, unexpected issues, linkages between FMEA, and learning devices. First, we found that the C-K workshop stimulated the sharing and creation of knowledge to improve the consistency of FMEA reports. It also made the report writing process less dependent on the people involved in the process. Second, we found that C-K workshops allow the identification of new failure modes, effects, and causes that were unexpected before the workshop. Third, we found that this CK-oriented method works as a collaborative learning device and allows multidisciplinary collaboration. It allows the management of FMEA interfaces and promotes reliability analysis from a global point of view rather than only system by system. It brings together experts who are not used to working together. We also found that this approach is fully compatible with the latest international FMEA standard (AIAG and VDA 2019). CK-FMEA does not replace the 7-step approach proposed by the recent AIAG and VDA handbook (2019), but complements and enhances the 4th step "failure analysis" (Figure 10).

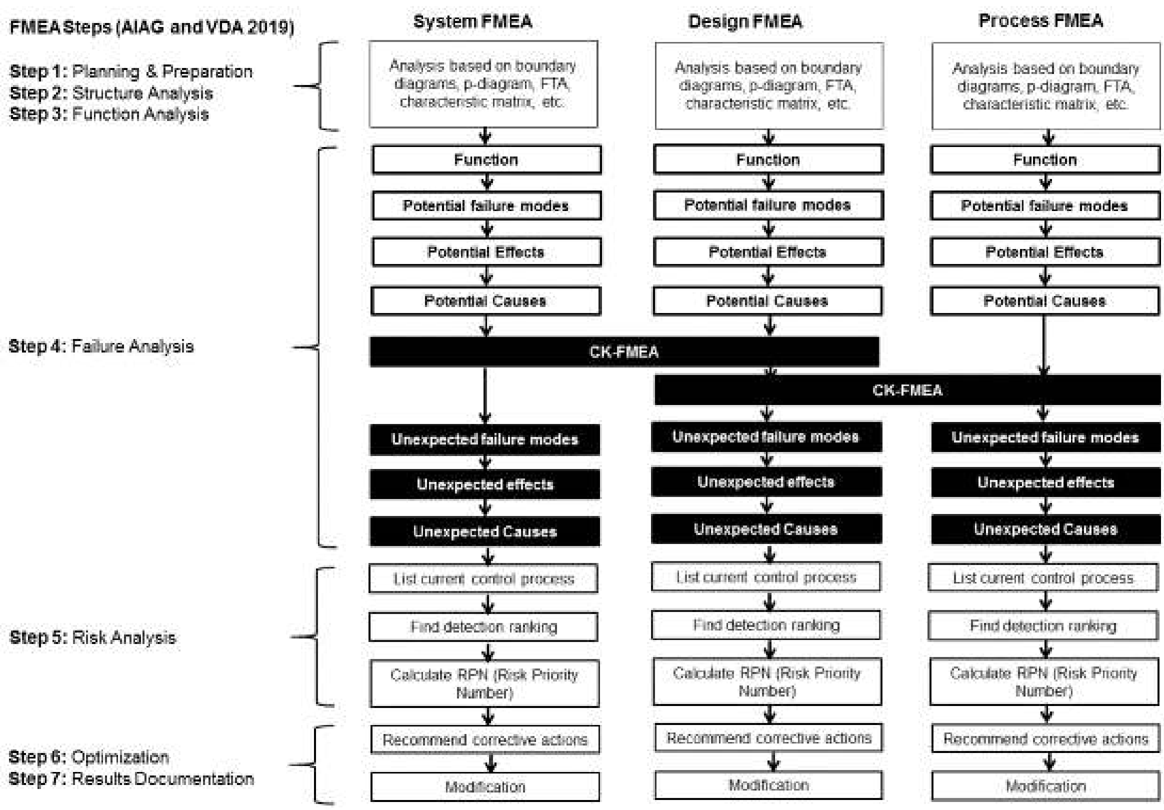

Figure 20. FMEA 7-step approach and CK-FMEA

Finally, we concluded that the C-K approach offers a true collective learning space that goes beyond the simple collection of existing information. We also discussed the point that this new procedure could save time or, on the contrary, was too complex to set up in organization. We recognized that there was a risk of wasting too much time in applying the C-K method. However, we concluded that it was better to take time to prevent risks and potential problems instead of spending time resolving complex future problems.

Based on these encouraging results, STMicroelectronics experts decided to begin a gradual deployment of the method in the company and to evaluate the results obtained on a monthly basis. For some specific STMicroelectronics processes, we have already observed an increase of more than 50% in FMEA accuracy, resulting in significant gains in overall equipment efficiency (OEE gain >15%) and reduced maintenance costs (the maintenance cost of power generation equipment decreased by 50% due to improved reliability). Although these results are satisfactory and encouraging, further analysis should be conducted to ensure the validity of these data. From a conceptual point of view, this study allowed us to redefine reliability management using FMEA at STMicroelectronics. STMicroelectronics has moved from a classic approach based on a hierarchical and linear model of reliability to a new CK-oriented approach based on a chain-linked model of reliability (Figure 11).

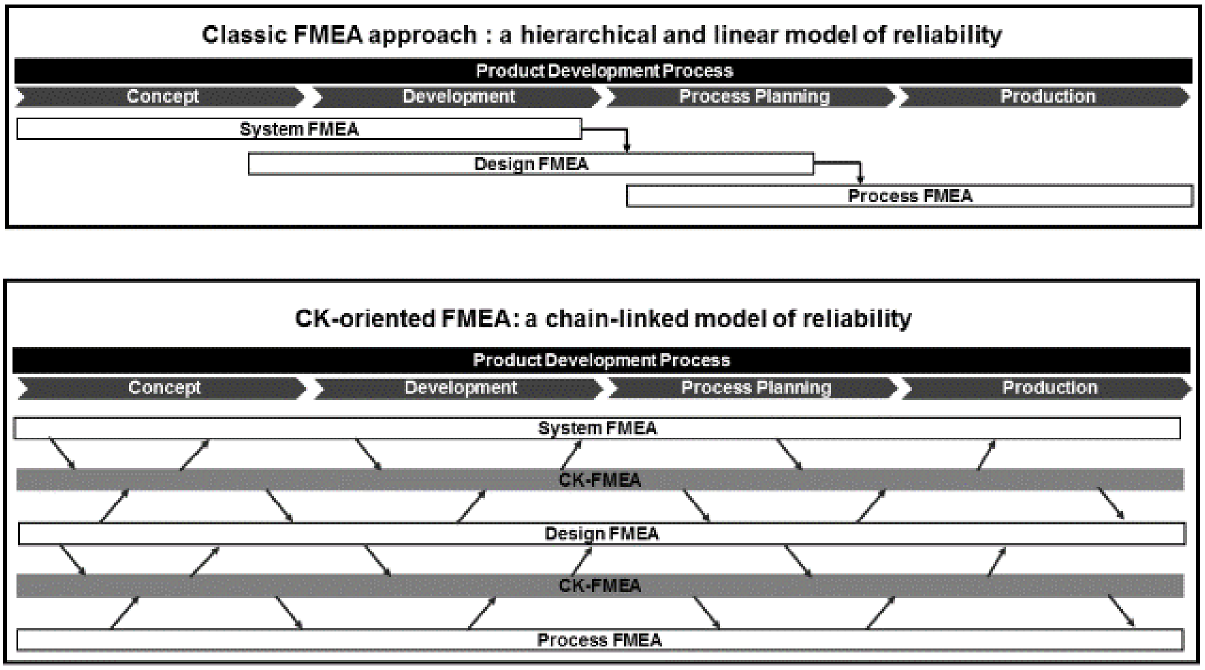

Figure 11. Classic FMEA approach vs. CK-oriented FMEA approach

5. Discussion

5.1. CK-FMEA as a creative and collective method to identify cognitive bias and fixation effects in failure analysis

From a methodological point of view, the C-K design theory framework offers a formal approach to conduct FMEA projects that combine both creativity and robustness in the analysis. Unlike the brainstorming method, C-K theory provides a systematic framework in which knowledge sharing and structuring, the learning process and creative thinking are not external phenomena but are the central core of the process itself. The CK-FMEA approach improves both organizational and cognitive issues. The method provides a framework to structure collaborative learning and clear guidelines to support coordination between different FMEA teams. From a cognitive point of view, the C-K framework helps to identify fixation effects (Agogué et al. 2014c, Pluchinotta et al. 2019) and a lack of knowledge that limits the capability to generate unexpected concepts of failures, effects and causes. According to Agogué et al. (2014b), fixation effects are cognitive biases that constrain the generation of new solutions. Fixation effects convey the fact that designers can be trapped by existing or obvious solutions (or knowledge) that constrain the generation of alternative solutions. Therefore, CK-FMEA promotes two main phases. The first is based on knowledge sharing and structuring to identify common knowledge and potential sources of fixation effects. The second is based on the generation of unexpected potential failures as a starting point for the unfixation process.

5.2. CK-FMEA as a boundary object to ensure learning and collaboration in a multidisciplinary environment

CK-FMEA can be interpreted as a boundary object (Star and Griesemer 1989). This is an artifact shared by several different technical communities that is both malleable enough to adapt to specific requirements of the several parties that employ it and robust enough to maintain coherence and a common identity across all stakeholders. Boundary objects allow coordination without consensus; they permit an actor's local understanding to be reframed in the context of a wider collective activity (Kimble et al. 2010). According to Fox (2011), boundary objects allow different groups to share meaning and to learn about each other's perspectives. We think that CK-FMEA could play a role in the evaluation of new ideas and in the adoption of new reliability practices within organizations and across technical communities. CK-FMEA ensures cohesion and collaboration through a visualization device that can highlight potential concepts and knowledge areas for which there is common interest to explore together. In a way, the collaborative identification of unexpected potential failure modes can also be a pretext to trigger original collaborations and to create new connections between different types of actors involved in reliability analysis processes. As a boundary object, CK-FMEA increases joint action and stimulates congruence (i.e., strategies are aligned and oriented towards achieving a jointly desired outcome). It also allows for incongruence and disagreement, which can help actors learn about their differences across specific boundaries (Klerkx et al. 2012).

5.3. From FMEA as a problem-solving approach to a design-oriented approach

It seems relevant to analyze our study in relation to the debates on the nature of ill-structured problems and the problem-solving paradigm (Simon 1973, 1996; Dorst 1997, 2006). The problem-solving paradigm, based on *"bounded rationality"* introduced by Simon (1973, 1996), remains a dominant paradigm for design models and methods. However, according to Dorst (2006), this approach has been subject to several criticisms. Among them, Hatchuel (2001) sought to renew the problem-solving paradigm through the concept of *"expandable rationality"*. For the author, design includes problem solving, but it cannot be reduced to problem solving. To illustrate this argument, Hatchuel (2001) proposes two examples. The first is considered a problem-solving situation: *"looking for a good movie in town"*. The second is considered a design situation: *"have a nice party"*. Hatchuel (2001) explains that there are three important differences between these situations:

- The first difference is that in the second example (*"have a nice party"*), there is no dominant design for what a *"good party"* should be. Hence, there is something more: *"unexpected designs of what a party is can emerge from the process"* (Hatchuel 2001). Finally, if unexpected expansions of the initial concepts are integral to a design process, the design situation cannot be reduced to problem solving.
- The second difference concerns collective learning. In example 1, collective learning results from the exploration of already recognized knowledge areas (films, theaters, member preferences, etc.). However, in case 2, collective learning determines the generation of problems and must be considered a design area. Hatchuel (2001) uses the term *"learning devices"*, a sort of subprocess that helps designers *"learn about what has to be learned or should be learned"*.
- Social interaction is not just a design resource, as in case 1. In design situations, social interaction is a design resource and a designable area. Thus, the understanding and design of social interactions is part of the design itself (Dorst 2006).

According to Hatchuel (2001), this conveys a new perspective on rationality: *"what does rational behavior mean in infinitely expandable and non-countable sets of actions?"* Hatchuel (2001) proposed the concept of *"expandable rationality"* to highlight the "*designer's ability to manipulate (individually and collectively) infinitely expandable concepts"*. Based on this work, we suggest that the classic FMEA approach is based on the problem-solving paradigm but should not be reduced to problem-solving. The use of the C-K design framework in the FMEA design process allows us to move toward a full design activity, including the generation of unexpected concepts, collective learning and the design of social interactions. The CK-FMEA methodology highlighted in this paper allows for the inclusion of the following points:

- The generation of unexpected concepts is an integral part of the design process.

- Collective learning determines the generation of problems and must be considered a design area.
- Social interaction is a design resource and a designable area.

6. Conclusion

This paper presents a new form of the FMEA procedure called CK-FMEA. CK-FMEA is a methodology that formalizes the FMEA design process based on C-K design theory. It supports knowledge sharing and structuring to identify common knowledge on defect prevention and the reliability of systems. It combines creativity and robust analysis to support the generation of unexpected potential failures, effects and causes. It connects different technical communities and teams within the entire FMEA process by building a collective understanding of the problem and collaborative learning.

This research was conducted empirically within STMicroelectronics. It brings new insights to conducting FMEA in science-based organizations. The experimentation of the new methodology shows positive results and significant improvements in the management of reliability and risk prevention at STMicroelectronics.

From a theoretical perspective, we provide insights to explain the weaknesses of the FMEA methodology. We analyzed these weaknesses, explained the causes and proposed recommendations. We highlighted the limits of the usage of brainstorming for FMEA, and we showed that design theory allows us to significantly improve existing operations management processes. We showed how to use C-K design theory as a reverse engineering process to study existing issues and as a framework to transform FMEA into a boundary object allowing new collective learning, better social cohesion and strong coordination between FMEA teams. These contributions allow FMEA to be extended from a problem-solving approach to a design-oriented approach. From a managerial perspective, we provide important operational solutions to conduct FMEA and to improve the management of reliability. These findings are based on a single case study. Therefore, more empirical research is needed to generalize and refine CK-FMEA. For example, further research should be conducted to ensure the validity of the proposed approach in semiconductor industries and in other industrial contexts.

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