# A state-of-the-art review of FMEA/FMECA including patents


## Abstract

This paper presents a critical review of Failure Modes and Effect Analysis (FMEA). Although the method is almost 70 years old, in literature there are still many researchers, both from academy and industry, devoted to improve it and overcoming unsolved and still open problems. The aim of this work consists in analysing a representative pool of scientific papers (220) and patents (109), in order to have an overview of the evolution of the method and try to understand if the efforts spent to improve it effectively answer to the several criticisms found in literature. All documents have been classified according to authors, source, and four technical classes dealing with the applicability of the method, representation of the cause and effect chain, risk analysis and integration with the problem-solving phase. A detailed analysis of the results allowed us to identify the most current problems, the improvement paths, and which other methods and tool are proposed to be integrated with FMEA.



**Keywords:** FMEA, FMECA, Risk analysis, patents


## 1. Introduction

From its introduction in 1949 by US Army to study problems that might arise from malfunctions of military systems, FMEA was modified several times and improved with standards and scientific publications. Although FMEA is a well-established method and mandatory in some sectors, it still presents important shortcomings that compromise, most of the time, its use as a design method but as a check the proof of what has been designed with other methods and approaches.

The starting hypothesis is that many, academics and companies, have tried to improve it but in an uncoordinated manner by working on specific issues without a whole vision. Even if FMEA has been successfully accepted in many different fields, there are still many doubts about the methodology. According to Prince et al. (2002), it cannot be applied in the industrial practice of every day since the required work is too demanding. Kmenta et al. (1998) highlighted its subjectivity that depends on the users' experience; moreover, its application is too boring and not creative. A software tool, which automatizes FMEA, may help, but not when the user is called to actively contribute, for example during problem solving. In addition, the traditional FMEA does not support the conceptual design phase since it is used to improve an existing product and not a prototype, where the problem solving phase can be surely more helpful and effectiveness, having, at this time, margins of modification.

The aim of this work is to trace the history of these modifications, by extracting from scientific and patent literature problems and answers provided by academic researchers and companies.

Firstly, a pool of scientific papers published in the last sixty years has been selected focusing on those providing classifications of FMEA methods and tools. For example, Bouti and Kadi (1994), presented a state of the art about the critical issues of FMEA, with the aim to comprehend how the analysis has been specifically used till 1994 in product design and manufacturing.

Sutrisno and Lee (2011) studied service reliability assessment using FMEA, analysing scientific papers published from 1994 to 2010, in order to update the previous analyses by overcoming the temporal gap till 2010, and by enlarging the focus on the analysis of service sectors.

Tixier et al. (2002) reviewed 62 Risk Analysis techniques and classified the methodologies according to input and output data, while Hu et al. (2013) reviewed 75 FMEA papers, evaluating the research trends and the popularity of the proposed approaches in term of citation. Both the surveys focused their attention on risk evaluation approaches in FMEA.

Differently from mentioned surveys and with the aim of highlighting the technical contributions provided by industry, we extended the analysis to patents filed from 1978 to 2016 and related to different areas of application (i.e. design, manufacturing, risk analysis, problem solving, etc.).

Then, the survey has been used to comprehend if there are differences between academia and industry with regard to: traditional FMEA approach, how scientific literature and patents try to provide answers to FMEA problems and if all the problems have been considered or some are still open. In addition, we wanted to determine if it is possible to identify specific trends of development during last years. The final result is a couple of infographics for better understanding the state of the art of FMEA problems and solutions, and two timeline diagrams for identify trends and scientific research directions. This work can be useful for all researchers working in FMEA improvement, for matching most important needs and focus all efforts to face still open problems.

The paper is organised as follows. Section 2 describes how the relevant journal publications and patents have been identified and selected. Section 3 summarises the results of the survey in terms of FMEA problems and shortcomings, while Section 4 proposes the state of the art of FMEA improvements. Finally, Section 5 draws conclusions.

## 2. Research methodology

FMEA literature is dispersed in heterogeneous way in form of periodicals, book chapters, conference proceedings, patents, normative, and company reports. According to our goal, we carried out a wide search in scientific literature and patents, databases spanning from 1978 and 2016.

We mainly focused the attention on international journals and conference proceedings rather than other sources since they assure a more scientific content and can guarantee a rigorous revision process.

The selection of scientific journals was based on the editor's notoriety (Wiley, Elsevier, Springer, etc.), journals maturity, impact factor, matching to the scope of the journal and preferring those indexed by international repositories such as Scopus index. For what concern the conferences we selected only the international ones, explicitly dedicated to this topic and with a long lasting and adequate referee processes guaranteed for instance by ASME, IEEE and ASCE.

Figure 1 summarises the most relevant selected international journals.

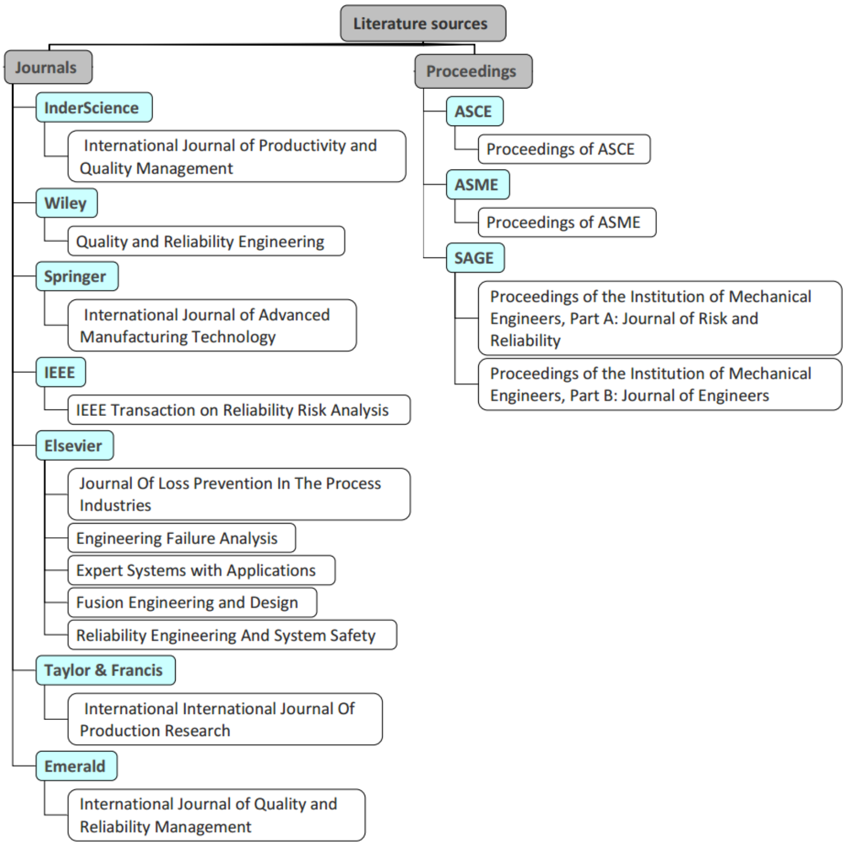



*Figure 1: Selected international journals.*

For patent search Espacenet worldwide service has been used. It can be universally considered the most diffused and complete collection of patent documents, recording more than 90 million among patent applications, grants and utility models. This database covers the most important patent offices and contains bibliographic data from more than 100 authorities and documents in English or machine translated from other languages.

A combination of terms like "FMEA, FMECA, DFMEA, AFMEA, RFMEA, Failure Modes and Effects Analysis, Risk Analysis, Failure Analysis" was used to set the search query both for patent and non-patent literature. In particular, for the patent search the query was launched only in Title and abstract.

The most critical activity has been the manual classification of the documents for excluding contributions describing mere applications without suggesting any methodological improvements and documents with too few quotes compared to the years of publication.

Finally, both papers and patents have been classified according to the authors (academia or industry), and source (scientific literature or patents).

The final set counts 329 documents, 220 scientific papers (203 from academia and 17 from industry) and 109 patents (23 from academia and 86 from industry). Distributing these documents according to a temporal axis (Figure 2), it is easy to note that the number of patents is increasing (except for 2014-2016 that does not include all potential patents since they are not disclosed for the first 18 months), while there is a decrease in publishing papers in journals and conferences.

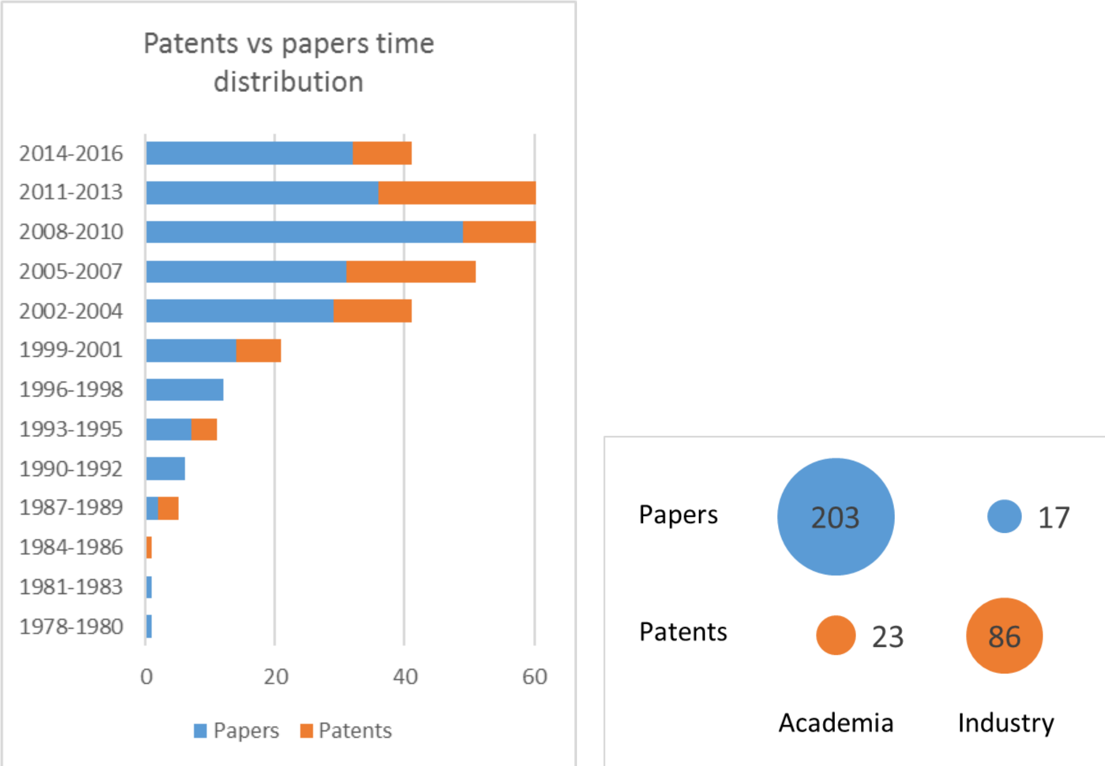



*Figure 2: (on the left) Time distribution (taking into account only priority date) of the collected documents and (on the right) the global distribution composition of the final set according to papers vs patents and academia vs industry.*

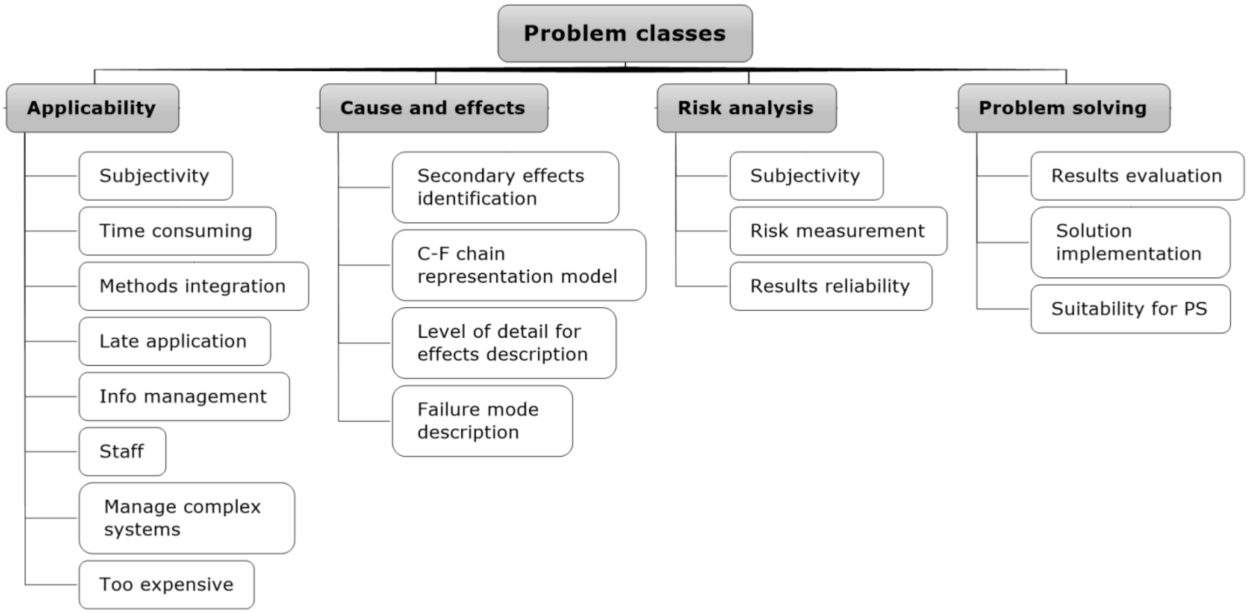
# 3. Literature classification

In this section, we introduce the main problems affecting FMEA, taking into account only those explicitly declared by authors in the considered documents. All problems have been classified according to a two levels hierarchical classification, and distributed on a temporal axis to identify potential trends.

The first level of the classification includes four generic **classes**: i) "applicability", difficulties in applying the method; ii) "*cause-effect*", problems in representing causes and effects; iii) "*risk analysis*", problems related to the analysis of the risks; iv) "*problem solving*", limitations of the outputs provided during the phases of problem solving and decision making.

Figure 3 summarizes the proposed classification in classes for the problems.

*Figure 3: Proposed classification for the problems with classes (column 1) and problems (column 2).*




In the following paragraphs a brief description of each class is presented.

## 3.1. Applicability

*Applicability* group is the wider and more heterogeneous class of problems. It concerns repeatability of the procedure, time investment when applied in different context of application, subjectivity of the results when users have different levels of expertise, the difficulty to manage large bill of materials that mutually interact each others and the limitations of anticipating FMEA in the early phases of the product lifecycle: during the design rather than manufacturing phase.

Another important issue deals with management of information, which takes into account all difficulties in managing data from complex assemblies, when it is not clear how to fix the right level of decomposition into single parts, and prioritize components. In addition, when FMEA is integrated with other methods or database and tools, there are problems of obsolescence and updating. In many cases FMEA is perceived as time-consuming, boring and expensive.

Finally, there are problems related to the cooperation among team members, especially when they have different personal backgrounds (creative vs analytical people) and come from different business functions, because of FMEA rigid structure.

Table 1 summarises problems related to FMEA applicability.

*Table 1: Problems related to applicability ordered by number of citations in papers/patents*

| *Applicability problems* | Number of citations in papers/patents | | |
|---|---|---|---|
| | Academia | Industry | Total |
| **Subjectivity:** Excessive subjectivity of the method related to users' expertise in different domain of application (Bell, 1992) | 18 | 3 | 21 |
| **Time consuming** (Price et al., 1995) | 11 | 5 | 16 |
| **Methods integration:** Lack of Integration with database of physical effects and PLM software (Lee, 2001) | 12 | 3 | 15 |

| | | | |
|---|---|---|---|
| **Late application:** Limited results caused by the wrong time of application of the methodology, typically too late (Price et al., 1995) | 6 | 3 | 9 |
| **Info management:** Missing information for BoM selection (level of detail), e.g. how to choose assemblies and single components (Carlson, 2012) | 5 | 4 | 9 |
| **Staff:** Low level of preparation of team members, lack of involvement of team members, lack of staff communication (Liu et al., 2010) | 3 | 4 | 7 |
| **Manage complex systems:** Difficulty to manage complex systems with several components that mutually interact in complex systems, by using FMEA templates (Bell, 1992) | 4 | 1 | 5 |
| **Too expensive:** The project can be too expensive in term of involved resources (humans and methods of management) (Ormsby et al., 1991) | 3 | 1 | 4 |
| ***Total*** | **62** | **24** | **86** |

## 3.2. Cause and Effect

This class concerns the FMEA ability to support the user during the determination of failure modes, failure effects and failure causes, their description and modelling. More in detail, shortcomings related to failure determination regard the number of identified failures and their typology, i.e. the primary failures affecting the product and the secondary effects affecting the user and the environment. Regarding failure description, main issues are due the difficulty in distinguishing the kinds of failures and choosing the right level of detail or the best suitable model of representation.

Table 2 summarises the identified problems.

*Table 2: Problems related to cause and effect ordered by number of citations in papers/patents*

| ***Cause and effect problems*** | **Number of citations in papers/patents** | | |
|---|---|---|---|
| | **Academia** | **Industry** | **Total** |
| **Secondary Effects identification:** Difficult identification of secondary effects in cause effect chains, especially for environment and health effects (Augustine et al., 2012) | 12 | 4 | 16 |
| **C-F chain representation models:** Lack of proper models (e.g. Multi-physics) to describe cause and effects chain (Augustine et al., 2012) | 8 | 2 | 10 |
| **Level of detail for effects description:** Effects description at too high level of detail (Abbas and Vachtsevanos 2009) | 3 | 3 | 6 |
| **Failure mode description:** Lack of guidelines to distinguish between failure modes and effects (Bluvbnd and Grabov, 2009) | 5 | 1 | 6 |
| ***Total*** | **28** | **10** | **38** |

## 3.3. Risk analysis

This class contains problems related to the evaluation of the risks connected to the identified failures, from their identification to the determined results. These shortcomings refer to ambiguous and too limited suggestions and objective evaluation criteria, and the inconsistency of the provided results for the successive activities.

Table 3 summarises critical issues for Risk analysis.

*Table 3: Problems related to risk analysis ordered by number of citations in papers/patents*

| *Risk analysis problems* | Number of citations in papers/patents | | |
|---|---|---|---|
| | **Academia** | **Industry** | **Total** |
| **Subjectivity:** Ambiguous definitions leading to subjectivity during risk evaluation (Rhee and Ishii, 2002) | 23 | 4 | 27 |
| **Risk measurement:** Lack of specific criteria and quantification of the risk (e.g. economic criteria) (Bluvband and Grabov 2009) | 10 | 0 | 10 |
| **Results reliability:** Risk evaluation inconsistent for decision making and problem solving (Sachdeva et al., 2009) | 8 | 0 | 8 |
| ***Total*** | **41** | **4** | **45** |

## 3.4. Problem solving

This class regards the capability to provide results suitable for decision making, by quantifying them through reliable and accepted parameters or tests and by providing preliminary evaluations about their feasibility. It also considers problems concerning lack of well-defined problems with specific goals, clearly defined solution paths, and clear expected solutions.

Table 4 summarises problems about FMEA and problem solving.

*Table 4: Problems related to problem solving ordered by number of citations in papers/patents*

| *Problem solving problems* | Number of citations in papers/patents | | |
|---|---|---|---|
| | **Academia** | **Industry** | **Total** |
| **Results evaluation:** Difficult decision making: lack or weak quantitative parameters or tests on the results (Liu et al., 2014) | 7 | 3 | 10 |
| **Solution implementation:** Difficult decision making: few or missing evaluations about the implementation of the solutions (Bluvband and Grabov 2009) | 8 | 0 | 8 |
| **Suitable for PS:** Final FMEA framework not suitable for problem solving (Liu et al., 2014) | 2 | 2 | 4 |
| ***Total*** | **17** | **5** | **22** |

## 3.5. Summary of problem identification

Figure 4 depicts the comparison of identified problems between academia and industry.

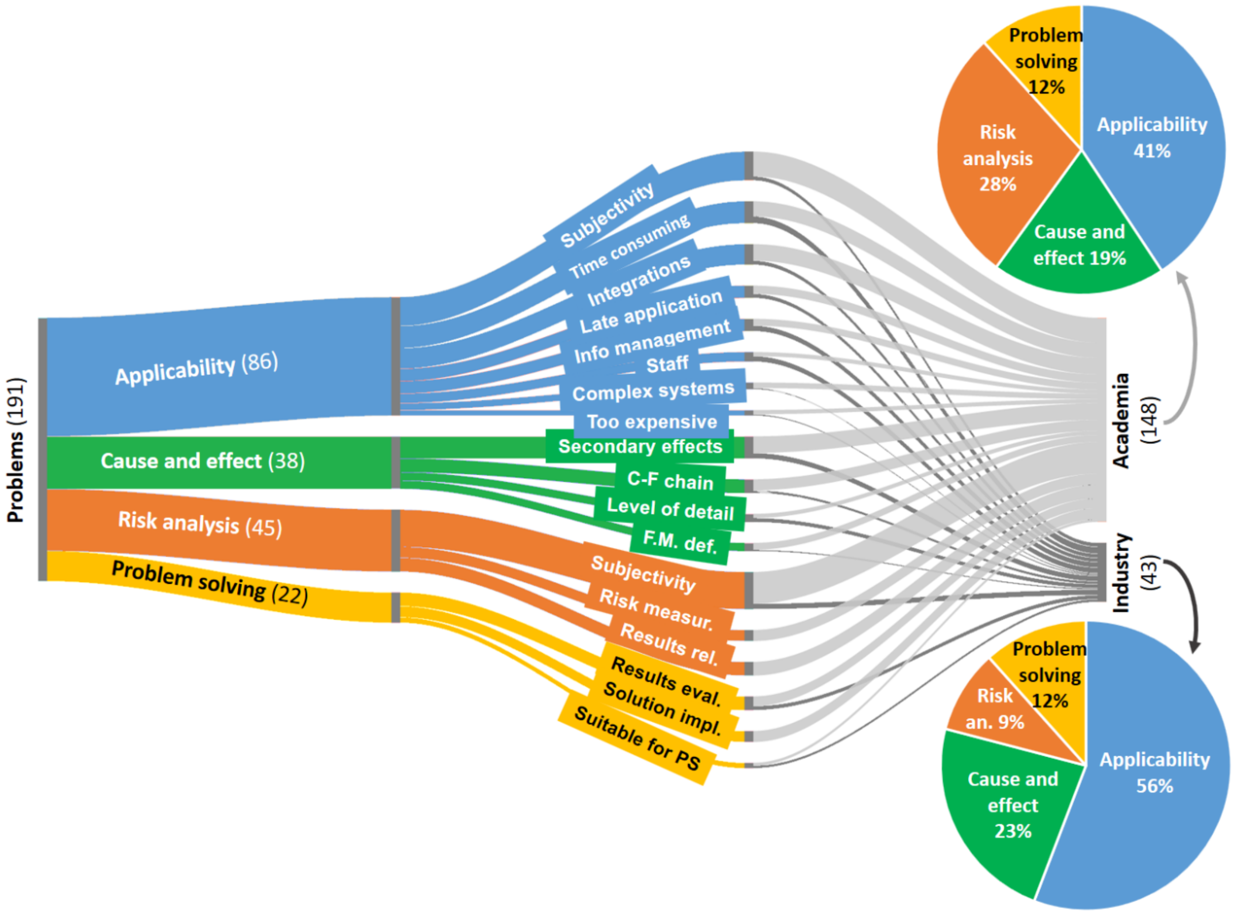



*Figure 4: Distribution of the problems and shortcomings for academia and industry.*

Analysing figure 4, we can identify the meaningful problems for each class as described in the following:

- Applicability: the main problems are related to the subjectivity and the time consuming for both academia and industry.
- Cause effect: there is a lack of secondary effects modelling, especially for academia, and it is difficult to choice the right level of detail in describing effects (mainly for industry).
- Risk analysis: there is too subjectivity during risk evaluation; in general, most of criticisms comes from academia.
- Problem solving: academia claim a lack in evaluating the implementation of a solution, while both academia and industry would like to better decide where to start with problem solving and ameliorate the representation of results.

We can also observe that academia is more interested in risk analysis (28% of the cases) compared to industry that is more focused on the applicability; while there are many similarities for the other categories.

The following chart (Figure 5) shows the time distribution of problems reported in papers and patents and classified according to the four mentioned classes (e.g., Applicability, Cause and Effect, Risk Analysis and Solving) and document authors (Academia or Industry).

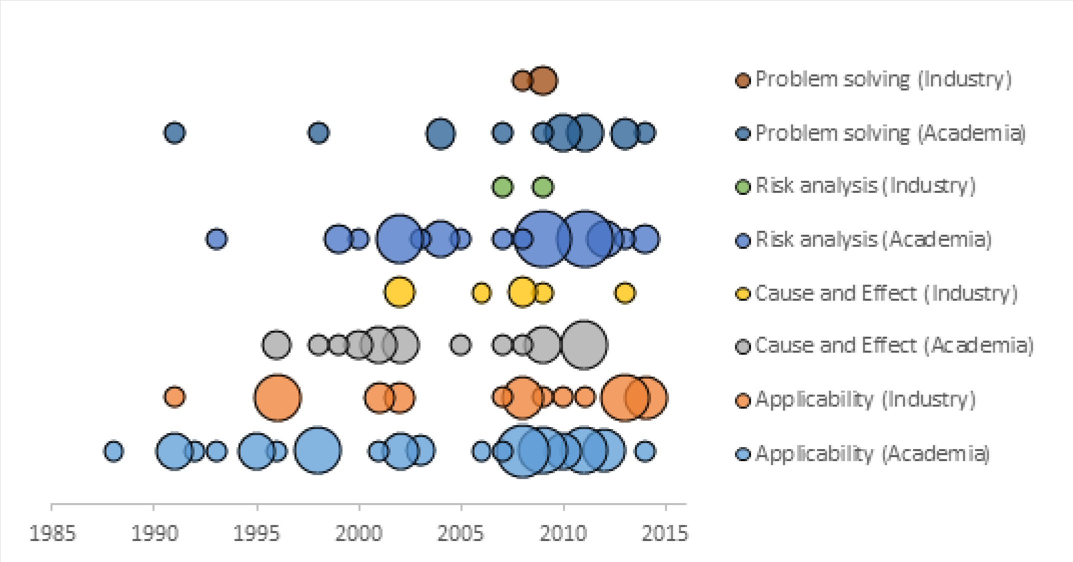



*Figure 5: Trend extrapolation.*

Analysing Figure 5, we can observe that Industry generally follows academia with a delay of few years. Probably, this relies on the fact that academia is more used to write scientific publications, while industry generally publishes at the end of a project, or preferring longtime publications as patent literature. This trend is also confirmed by time distribution of patents, generally produced by industry as we can see in Figure 2. In addition, the average of publications per year in the last 5 years increases of more than 200% respect the average in the previous 25 years (1985-2010). The trend is valid for both academia and industry and this is mainly due to the high increase of Chinese publications, especially patents. Finally, compared to the absolute distribution of the publications in the considered period, in the last 5 years the distribution of the problems in the four categories is not constant and both academia and industry focused the attention mainly on the application of the method.

# 4. Suggestions for ameliorating FMEA

Since its introduction, FMEA has been continuously modified and implemented according to two main research fields: development of the traditional FMEA and its modification. The first one, with standards and scientific papers, contributes to improve the comprehension of the traditional methodology and its application in several fields maintaining the original structure. The second one includes modified methods and the traditional structure of FMEA is changed as well the sequence of the steps.

Using the same pool of papers and patents, we have identified the solutions/improvements (Tables 2-5) proposed to solve problem categories described in section 4. Then, for each problem category, we have identified methods and tools to solve it.

## 4.1. FMEA Improvements

In the following we summarise the solutions identified to solve/improve mentioned problems.

**Applicability** of the methodology has been improved by modifying it in different ways, but without directly radically modify the operational sequence. FMEA has also been automated, to reduce or exclude the human intervention. The management of information has been improved through the introduction of more structured templates (e.g., tables and graphical representations), sometimes with the purpose of improving the user's interface, proposing new guidelines in order to explain the path to be followed during the analysis, and the introduction of specific steps and criteria to apply the analysis to complex systems by considering all the items or by simplifying them.

**Cause and effects representation** has been improved with the purpose of increasing the efficiency in failures detection and description. Some authors explained how to determine more Failure Modes, Failure Effects and Failure Causes, including root causes, proposing the integrations with specific methods and tools. Others provide new models to analyse the relations among different effects occurring at the same time and the consequences they arise.

**Risk analysis** has been improved by introducing many evaluation criteria, both qualitatively (based on the evaluation of the judgments of expert people) and quantitatively. These latter are based on statistical evaluation (i.e., probability distributions of the fault), cost-based approaches that provide economic quantification of the faults, history-based methods that consider historical data about faults, and requirements related approaches that consider the user's satisfaction about the product following the manifestation of the damage.

**Problem solving** has been improved through suggestions about the reformulation of the identified problems in a more suitable way (e.g., through a couple VERB: Negative action + OBJ: Damaged entity) and their modality of presentation (e.g. through sketches, graphs, simulations) in order to favour decision-making and problem solving phase. In addition, some authors showed how to apply FMEA not only for failure investigation but also for robust design by making it an integral part of the conceptual design process.

Table 5 summarises the solutions identified to solve FMEA problems and the number of citations in papers and patents.

*Table 5: Problems and solutions for ameliorating FMEA (where Accad: academia and Ind:industry).*

| *Problems* | *Solutions* | **Number of citations in papers/patents** | | |
|---|---|---|---|---|
| | | **Accad.** | **Ind.** | **Total** |
| **Applicability** | **Anticipate the analysis:** Integrate FMEA with design methods in order to anticipate it during design phase (Liu et al. 2011) | 54 | 18 | 72 |
| | **More automation** (Price and Taylor, 2002) | 34 | 19 | 53 |
| | **Info management:** Improve management of the information through matrix and graphical representations | 38 | 10 | 48 |
| | **Guidelines:** Introduce new guidelines to explain the sequence of application and the single steps. | 28 | 12 | 40 |
| | **Complex systems:** Introduce criteria to approach complex systems by analysing all the components. | 16 | 5 | 21 |
| | **User interface:** Ameliorate user interface by providing data filing template (Price, 1996) | 10 | 9 | 19 |
| | **New criteria:** Introduce criteria to approach complex systems by reduce the number of ITEMS to be analysed (Regazzoni and Russo, 2011) | 3 | 2 | 5 |
| **Cause and effects representa-** | **New methods for Failure Modes** identification (Lee, 2001) | 35 | 30 | 65 |
| | **New methods for Failure Effects:** increase the number of determined Failure Effects (Xiao et al., 2011) | 30 | 13 | 43 |

| | | | | |
|---|---|---|---|---|
| **tion** | **Combine multiple Failures Effects**, studying the result and the possible synergies (Price and Taylor, 1998) | 18 | 8 | 26 |
| | **New methods for Failure Causes:** Increase the number of the determined Failure Cause, including root causes (Yang et al., 2010) | 10 | 5 | 15 |
| **Risk analysis** | **Statistical methods:** quantify statistically and logically the probability of the faults (Xu et al., 2002) | 68 | 10 | 78 |
| | **Requirements-based criteria:** New measure to evaluate the risks based on the analysis of the requirements | 25 | 6 | 31 |
| | **Economic criteria:** quantify the potential faults according to economic criteria (Rhee and Ishii, 2003) | 13 | 3 | 16 |
| | **Historical data:** quantify the potential faults according to historical data (Garcia and Gilabert, 2011) | 9 | 5 | 14 |
| | **Qualitative criteria:** Analyse qualitatively the risk, using personal judgments and impressions instead of aseptic measurements and numerical ratings (Kara-Zaitri et al. 1991) | 1 | 4 | 5 |
| **Problem solving** | **Results representation:** Improve presentation of the results by changing the interface of presentation. | 27 | 7 | 34 |
| | **New methods** to be integrated into FMEA (TRIZ, Maintenance management tools, etc.) (Lee et al., 2001; Liu et al. 2011) | 19 | 10 | 29 |
| | **Use FMEA for other purposes** (i.e. robust design) | 3 | 5 | 8 |
| ***Total*** | | 441 | 181 | 622 |

Figure 6 shows the comparison betweeen Academia and Industry with regards to solutions to overcome FMEA problems.

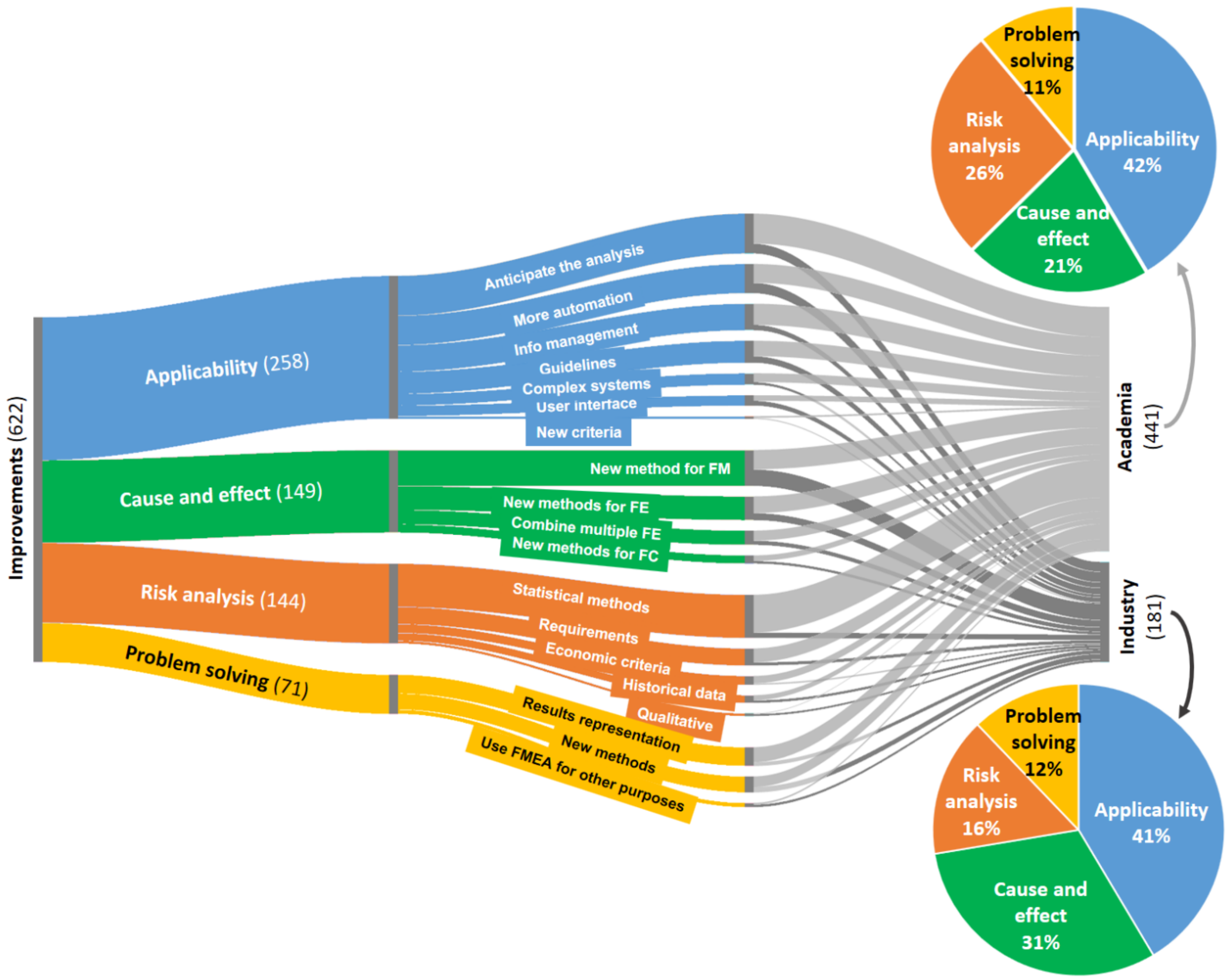



*Figure 6: Main solutions proposed by academia and industry.*

Figure 7 portrays the time distribution of the four categories of improvements divided into academia and industry.

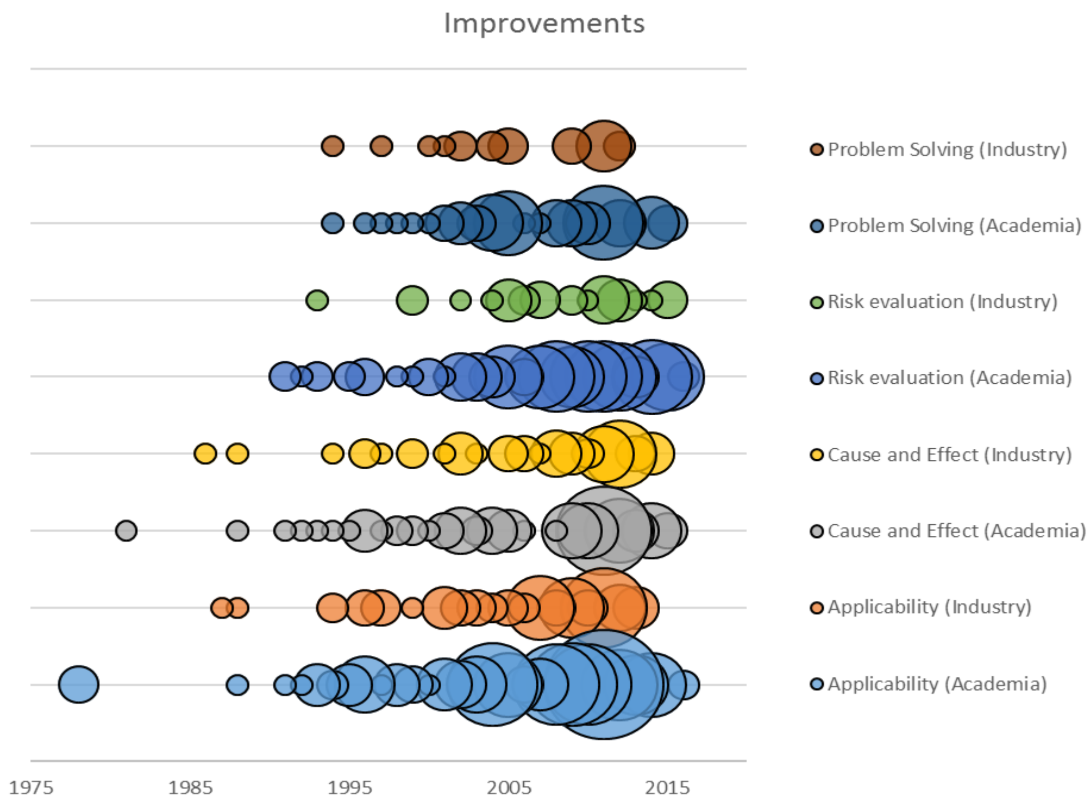



*Figure 7: Trends extrapolation of FMEA improvements*

Analysing the whole results, we can observe that the most criticized problems seem to be also the most considered for improvements. In general, there many solutions for each declared problem.

In addition, academia proposes more methods than industry, about 3 times more. From a statistical point of view, we can observe that the most numerous suggestions regard “anticipate FMEA analysis” (both for academia and industry) and “quantify statistically and logically the probability of the faults” (only for academy). More in general, a great effort has been spent to automatize the method and manage the information with the goal to make the method quicker, less subjective, with less error probability, with few choices for the user and with a more limited use of resources.

Only in few cases, the declared needs remain unsatisfied: solutions for team building management are missing and there is only one solution to adapt FMEA structure for problem solving.

In general, academia and industry operate in a similar way, even if in some cases we can identify some peculiarities. To improve applicability, academy focuses on the management of information, especially for complex system, while industry offers fewer solutions. Industry on the contrary worked on the automation and the amelioration of the user’s interface. To improve cause effect representation, industry expressed a great interest in new methods for failure modes identification. To improve risk analysis, industry suggests much less solutions than academy. For problem solving, with regard to the high request of solutions representation, we found a very high offer of academic methods against a limited industrial activity. On the contrary, many solutions based on the integration with other methods have been collected, especially from industry with regard to maintenance.

## 4.2. Methods and tools

Several authors suggested integrating FMEA with other methods and tools to improve it. We classified methods and tools in the same categories previously considered depending on their aim as described in the following.

**Applicability** has been improved through the introduction of: i) infographics (i.e. Kara-Zaitri et al., 1991) to represent the results and the relations among the identified failures, and ii) ontologies (Ebrahimipour et al., 2010) to provide the rules for a common representation of the results. Moreover, it is quite common the use of databases to automate FMEA, (Montgomery, 1996 and Lee, 2001).

**Cause and effect representation** has been supported by integrating databases (Lee, 2001) and physical modelling (Price and Taylor, 2002) to determine a great number of failures, especially Failure Modes. The Scenario representation (Kmenta and Ishii, 2000) resulted the most common method to map the cause-effect chain by including also the secondary effects affecting user and environment and their relations.

**Risk analysis** has been improved by suggesting in most cases the integration with mathematical and statistical methods (e.g. Fuzzy logic, Bowles and Peláez, 1995) in order to provide a method of evaluation, while the introduction of specific criteria of comparison has been mainly operated through the analysis of the requirements (i.e. the integration with Quality Function Deployment, Gonzales Bosch and Tamayo Enríquez, 2005) and economic considerations based on costs databases (Rhee and Ishii, 2003).

**Problem solving** phase has been almost exclusively improved by introducing TRIZ tools in FMEA (Regazzoni and Russo, 2010) in order to reformulate the failures and to analyse them.

Methods have been grouped in different categories: database, statistical, mathematic and logic. Table 7 summarises methods and tools proposed for each problem category.

Table 7: Problem categories vs Methods and Tools (where A=Acedamia, I=Industry, *= *Topsis, Izonote, AHP, Graph theory*, **=*Kano, Hazop, Project management, Optimisation models*).

| ***Categories of methods*** | ***Methods/tools*** | **Applicability** | | **Cause and effect** | | **Risk Analysis** | | **Solving** | | **Total** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **A** | **I** | **A** | **I** | **A** | **I** | **A** | **I** | **A** | **I** |
| **Databases** | Physical effects | 0 | 0 | 8 | 5 | 0 | 0 | 0 | 0 | **8** | **5** |
| | Historical data | 1 | 0 | 12 | 11 | 3 | 0 | 0 | 0 | **16** | **11** |
| | Costs DB | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | **1** | **1** |
| | Others DB | 10 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | **10** | **6** |
| | **Subtotal** | **11** | **6** | **20** | **16** | **4** | **1** | **0** | **0** | 35 | 23 |
| **Mathematical, logic and statistical** | Fuzzy | 0 | 0 | 0 | 0 | 51 | 4 | 0 | 0 | **51** | **4** |
| | Bayesian network | 3 | 1 | 3 | 0 | 4 | 0 | 0 | 0 | **10** | **1** |
| | Petri net | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | **2** | **0** |
| | Statistical (analysis of mean and variance) | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 0 | 6 | 0 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Others* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0** | **0** |
| | **Subtotal** | **3** | **1** | **5** | **0** | **61** | **4** | **0** | **0** | **69** | **5** |
| **Problem solving** | QFD | 0 | 1 | 0 | 0 | 15 | 1 | 0 | 0 | **15** | **2** |
| | TRIZ | 0 | 0 | 0 | 0 | 0 | 0 | 13 | 0 | **13** | **0** |
| | Methods for maintenance planning | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 9 | **3** | **9** |
| | Brainstorming | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | **0** | **1** |
| | **Subtotal** | **0** | **1** | **0** | **0** | **15** | **2** | **16** | **9** | **31** | **12** |
| **Prototyping** | Simulation | 0 | 0 | 7 | 5 | 0 | 0 | 0 | 0 | **7** | **5** |
| | Test | 0 | 0 | 1 | 4 | 0 | 0 | 0 | 0 | **1** | **4** |
| | **Subtotal** | **0** | **0** | **8** | **9** | **0** | **0** | **0** | **0** | **8** | **9** |
| **Others** | Infographics | 5 | 4 | 0 | 2 | 0 | 0 | 0 | 0 | **5** | **6** |
| | Functional Analysis | 0 | 0 | 8 | 11 | 0 | 0 | 0 | 0 | **8** | **11** |
| | Ontologies | 7 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | **7** | **4** |
| | FTA (Fault Tree Analysis) | 0 | 0 | 11 | 4 | 0 | 0 | 0 | 0 | **11** | **4** |
| | Scenario | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | **3** | **0** |
| | Others** | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 1 | **3** | **1** |
| | **Subtotal** | **12** | **8** | **22** | **17** | **0** | **0** | **3** | **1** | **37** | **26** |
| ***Total*** | | **26** | **16** | **55** | **42** | **80** | **7** | **19** | **10** | **180** | **75** |

Analysing Table 8, we can observe that regarding applicability and cause and effect chain, academia and industry have generally adopted the same number of methods and tools. In addition, academia proposed many methods for risk analysis; while industry seems to be satisfied by the traditional FMEA tools. The most popular method is Fuzzy, even if it is clearly related to academia. Historical data DB and Functional analysis follow and are equally distributed between academia and industry. Quality Function Deployment and TRIZ are used respectively for improving risk analysis and problem solving, and they are generally linked to FMEA almost exclusively in academia. On the other hand, methods for maintenance planning are mainly prosed by industry. Finally, to improve cause and effect chain analysis both academia and industry mostly use historical-data DB, Functional Analysis, FTA (Fault Tree Analysis) and Simulation.

## 4.3. Final Considerations

The results of this survey have been compared with those described in a previous survey (Sutrisno and Lee, 2011). The introduction of patents offered a clearer understanding of the industry perspective on FMEA. The previous survey does not highlight as ours the importance of integrating FMEA with data coming from product life management (such as data collected in other FMEA activities or costs) or databases of physical effects that can systematize and speed up the application of the method. Also prototyping, functional analysis and ontologies have been identified as critical topics to improve FMEA, with a significant number of publications both from academia and industry.

As the previous survey, our analysis shows how mathematical and logic methods (Fuzzy, Bayesian network, Petri net) are the most integrated methods with FMEA, however almost exclusively by academia, while they are practically the least considered by industry.

In addition, this work clearly reveals that both academy and Industry ask for methods to better communicate and represent results (i.e., ontologies and infographics).

Figure 8 summarises the results of the comparison.

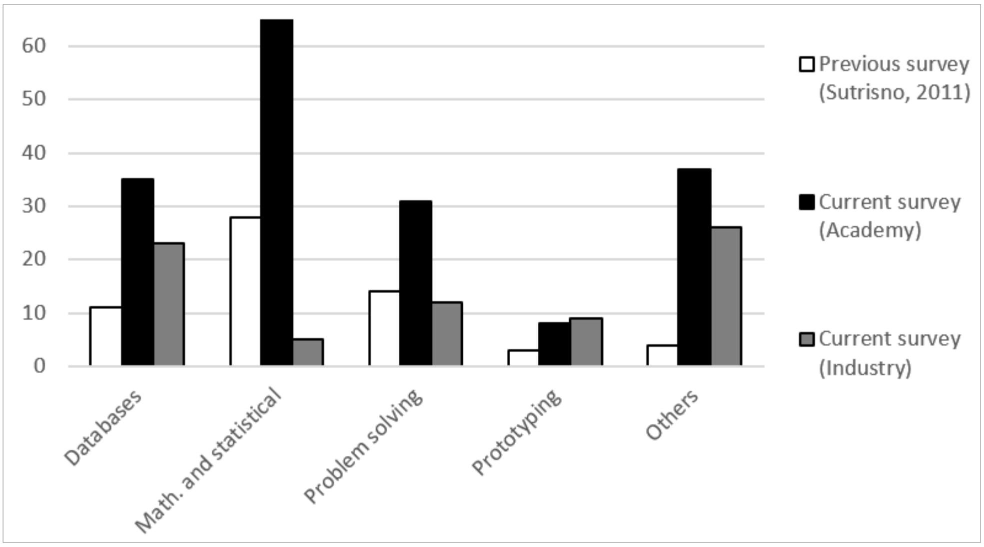



*Figure 8: Comparison with the previous survey of Sutrisno and Lee (2011)*

# 5 Conclusions

In this paper, a survey about 40 years of FMEA publications has been proposed in order to identify trends, open issues, research areas of improvement and integrations with other methods. A pool of over 300 documents has been selected from international journals, conference proceedings and international patents since 1978.

Each document has been manually analysed extracting problems and solutions. Only those ones clearly showing problems and/or solutions were considered for the following classification tasks.

The main output of this work is summarized in two infographics based on Sankey diagram style. The first one shows the whole set of FMEA problems, classified in 4 main classes and 18 different sub-problems; the second one about FMEA solutions/improvements, classified by the same 4 categories and 19 types of solutions.

Organising selected documents by date in a timeline diagram, it has been possible to visualize trends and identify the most actual research directions and still open issues. Classification process has been conducted always taking into account the document source (patent or scientific literature) and the background of authors (academia or industry).

From this analysis emerges that criticisms to FMEA are the same for both academia and industry, with very little discrepancy as for example for risk analysis and problem solving integration, more cared by academics.

The analysis of the methodological proposals, reflects quite closely the framework emerged by the problems, except for: (i) a slight overabundance of risk quantification solutions compared to the demand, with a specific peak about works on Fuzzy integration, carried out almost exclusively by academia; (ii) a misalignment of problem solving proposals, which are partially inferior to the demand and (iii) a lack of solutions to team building problems to which industry is more sensitive than academia.

Finally, it was noticed that almost all works offer incremental solutions, useful to answer narrowed and specific problems but unable to transversally face the more general problems such as time consuming or the boredom of the application. No solutions were found to radically modify the operational sequence or for ranking intervention on elements from the bill of materials.

Lastly, there are so many attempts to create more rigorous definitions about failure mode, failure effect and cause but nevertheless there is not yet a proper ontology that could transversally solve many different classes of problems.

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