The integration of FMEA with other problem solving tools: A review of enhancement opportunities

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Abstract. Failure Mode Effect Analysis (FMEA) is one of the most effective and accepted problem solving (PS) tools for most of the companies in the world. Since FMEA was first introduced in 1949, practitioners have implemented FMEA in various industries for their quality improvement initiatives. However, studies have shown that there are drawbacks that hinder the effectiveness of FMEA for continuous quality improvement from product design to manufacturing. Therefore, FMEA is integrated with other PS tools such as inventive problem solving methodology (TRIZ), Quality Function Deployment (QFD), Root Cause Analysis (RCA) and seven basic tools of quality to address the drawbacks. This study begins by identifying the drawbacks in FMEA. A comprehensive literature review on the integration of FMEA with other tools is carried out to categorise the integrations based on the drawbacks identified. The three categories are inefficiency of failure analysis, psychological inertia and neglect of customers’ perspective. This study concludes by discussing the gaps and opportunities in the integration for future research.

1. Introduction
Profitability has always been the main motivation of most companies. However, the pressure from the increasingly competitive market today has motivated the companies not only to be cost-driven, but also to be quality-driven [1]. In order to remain competitive in the market and gain customers’ loyalty on the product, the companies have to pay much attention on the continuous improvement in quality [2]. In order to maintain high quality of products and services, companies had implemented numerous problem solving (PS) methodologies such as Failure Mode Effect Analysis (FMEA).

FMEA is a step-by-step approach for evaluating a process to identify all possible failures and to assess the relative impact of different failures to identify the parts of the process that require change [3]. According to Stamatis [5], there are four types of FMEA, namely, system, design, process and service. The system-FMEA is the highest-level system analysis, which is made up of various subsystems [4]. Design-FMEA focuses on the design of the product. Process-FMEA emphasises on the manufacturing or assembly process that focuses on the quality of the products manufactured. Lastly, service-FMEA is responsible to analyse the service before it reaches the customers [5].

Traditionally, FMEA was used to perform risk analysis via Risk Priority Number (RPN) that is derived from the combination of Occurrence (O), Severity (S) and Detection (D) [3]. The RPN will identify the critical failure modes from the system, design, process and/or service, and prioritize for actions. However, extensive review done by Liu [6] found out that RPN shows some weakness in FMEA.
Actually, RPN is not the only drawback of FMEA. Therefore, the first objective of this paper is to extend the review done by Liu [6] by identifying the other drawbacks of FMEA. The second objective is to categorise the integration of FMEA with other PS tools based on the drawbacks identified. The third objective of this study is to identify the gaps and opportunities from the literature review on the integration of FMEA with other tools.

The rest of this paper is organised as follows. Section 2 discussed the opportunities for FMEA enhancement. Section 3 reviewed the integration of FMEA with other PS tools. The gaps and opportunities of FMEA integration are discussed in Section 4. Conclusions are drawn in the last section.

2. Opportunities for FMEA Enhancement
FMEA has proven to be one of the most important and relevant failure preventive techniques in many fields such as manufacturing, medical, civil engineering and automotive. However, traditional FMEA has drawbacks that need to be addressed for further enhancement. Besides RPN, there are also other drawbacks in FMEA. Firstly, one of the pitfalls of FMEA is the missing failure modes [7]. At the beginning of the FMEA procedure, practitioners are required to identify the failure modes. The missing failure modes hinder the efficiency of failure analysis in FMEA.

Secondly, brainstorming is required to determine the problems, causes and solutions in FMEA and the risk assessment for the failure modes [8]. Brainstorming involves a group of experienced and knowledgeable people. However, they may face the limitation of brainstorming which is known as psychological inertia [9]. Psychological inertia means the resistance to change as it prevents the human mind from reaching full potential, limits innovation and creativity during PS [10]. This happens because boundaries and restrictions tend to happen in the person’s mind when the person has a set of rules and regulation in mind [11].

Last but not least, according to Koomsap [12], FMEA has been conducted based on the manufacturers’ perspective without considering the customers’ perspective. As a matter of fact, customers’ perspective is important in defining the quality of the products and services because customers will be directly affected by failure. As indicated by Shahin [13], customers may perceive the failure modes differently compared to the manufacturers.

3. Integrated approaches of FMEA
FMEA need to be integrated with other methodologies in order to address the drawbacks of FMEA [14]. Not only that, these integrations are able to enhance FMEA’s risk analysis and failure prevention. This section presents the literature on tools in overcoming the three categories of drawbacks such as inefficiency of failure analysis, psychological inertia and neglect of customers’ perspective. The summary of the literature is depicted in table 1.

3.1. Inefficiency of Failure Analysis
As indicated by Russell [1], high demand on high quality products and services have driven the companies to implement quality improvement initiatives. To curb the demand of high quality products and services, a complete and extensive failure analysis is needed. Numerous tools such as the seven basic tools of quality, Root Cause Analysis (RCA) and Fault Tree Analysis (FTA) have been integrated into FMEA to improve the risk analysis of FMEA. The seven basic tools of quality are Ishikawa diagram, check sheet, control chart, histogram, Pareto chart, scatter diagram and stratification. These tools are famous for the set of graphical techniques that are able to assist practitioners troubleshoot quality related problem [15]. To effectively identify all possible failures and causes, the knowledge base of the process need to be established clearly. Therefore, recent studies had integrated RCA in FMEA to establish a strong knowledge base in process for risk analysis. FTA is a top-down failure analysis which uses Boolean logic to analyse an undesired state of a system [16].
### Table 1. Classification of tools.

| Categories                  | Author                  | Sector                     | Types of FMEA | Tools integrated                  |
|-----------------------------|-------------------------|----------------------------|----------------|-----------------------------------|
| Inefficiency of Failure Analysis | Mariajayaprakash [13] | Manufacturing              | Process        | Ishikawa diagram                  |
|                             | Ji [18]                 | Health                     | Process        | Ishikawa diagram                  |
|                             | Can [19]                | Civil engineering          | Design         | Pareto analysis                   |
|                             | Adar [20]               | Environmental chemical     | System         | Ishikawa diagram                  |
|                             | Sharma [21]             | Mechanical                 | Process        | RCA, NHPPP                         |
|                             | Sharma [22]             | Mechanical                 | Process        | RCA, Fuzzy method                 |
|                             | Panchal [23]            | Water Treatment            | System         | RCA                               |
|                             | Held [24]               | Manufacturing              | Design         | FTA                               |
| Psychological Inertia       | Regazzoni [14]          | Manufacturing              | Design         | IP, CM                            |
|                             | Awad [27]               | Automotive                 | Process        | IP, CM                            |
|                             | Thurnes [28]            | Manufacturing              | Design         | AFD                               |
|                             | Russo [30]              | Manufacturing              | Design         | IP, CM                            |
| Neglect of customers’ perspective | Almannai [33]      | Manufacturing              | Process        | QFD                               |
|                             | Hassan [34]             | Manufacturing              | Design         | QFD, ABC                          |
|                             | Korayem [35]            | Manufacturing              | Design         | QFD                               |
|                             | Chen [36]               | Manufacturing              | Design         | Fuzzy QFD                         |
|                             | Shahin [13]             | Tourism                    | Service        | Kano model                        |
|                             | Koomsap [12]            | Aerospace                  | Service        | Kano model                        |

In the manufacturing sector, Mariajayaprakash [17] integrated process-FMEA and Ishikawa diagram in the cogeneration process in the sugar industry. The objectives of their study were to identify the failures in the cogeneration process in sugar mills and to minimize the failures. Ishikawa diagram was adopted to identify all the parameters and process-FMEA was adopted to identify the most significant parameters. In the health sector, Ji [18] proposed an alternative chromatographic process to eliminate the toxic organic solutions that were utilised in the traditional vaccine purification process. Ji [18] integrated Ishikawa diagram and process-FMEA. Ishikawa diagram managed to identify the critical factors of chromatography. RPN from the process-FMEA identified four parameters under the loading phase have significant impact on the process.

In the civil engineering sector, Can [19] applied the integration of design-FMEA and Pareto analysis at the beginning of the design process to determine the risk of aerial photography in the mapping activities for landslide movements. In the environmental chemical sector, Adar [20] proposed the integration of system-FMEA and Ishikawa diagram to identify the problems which occurred in the supercritical water gasification system used in the sewage sludge treatment.

In the mechanical sector, Sharma [21] introduced an integrated framework of RCA, FMEA and Non-homogeneous Poisson point process (NHPPP) to improve the reliability and maintenance of the paper machine system. In the paper machine system case study, Sharma [22] simultaneously adopted three methodologies such as RCA, FMEA and fuzzy methodology.

In the case study of a real water treatment plant of a coal fired thermal power plant, Panchal [23] proposed three phases integrated framework that consists of quantitative and qualitative approaches. The first phase was the data collection from various sources via maintenance logbook and report. For the second phase, Petri net approach was initiated to evaluate the reliability of the system. At the third stage, RCA was adopted to identify the subsystems. Thereafter, system-FMEA was used to identify the important components in the system.

An experiment that consists of FTA and FMEA was conducted by Held [24] to analyse the behaviour of a cell’s internal short circuit and its effects towards the battery and vehicle. The top down approach of FTA provides an in-depth analysis of the cell system that effectively overcome the drawback of
FMEA in identifying the combination of failure and effects directly. This integration helped to overcome the failure mode of the cell that caused a fire on the vehicle.

In summary, these studies outline a significant role of seven basic tools of quality in the integration of FMEA. Ishikawa diagram enhances the risk analysis of FMEA while Pareto chart prioritises action for process improvement. In addition, RCA enhances the risk analysis of FMEA by providing a strong knowledge base of the process, while FTA provides in-depth analysis of the processes.

3.2 Psychological Inertia
As described in Section 2, psychological inertia often occurs during the brainstorming session. Therefore, TRIZ is useful in overcoming psychological inertia because it drives systematic brainstorming whereby generic solutions will be provided for the problems [9], [11]. Inventive problem solving methodology (TRIZ) is a PS methodology that is based on logic, data and research without using intuition [25].

Yen [26] proposed an approach that integrates the concept of green design with FMEA in an eco-innovative product design tool. The study focused on the design-FMEA of a vacuum cleaner. The RPN used in the study was different from the traditional RPN because environment impact (E), customer perspective (C), and regulation compliance (R) were taken into consideration. TRIZ Inventive Principles (IP) and Contradiction Matrix (CM) have been adopted to provide recommendation actions.

Regazzoni [14] integrated design-FMEA with TRIZ to enhance the risk management for product design. The objectives are to build an improved risk management model for product design and to reduce the failure occurrence by using the enhanced capability of the problems and technical solutions anticipation. Functions analysis and substance-fields models are among the TRIZ tools applied in the case study of a hairdryer.

Awad [27] proposed a methodology that integrates web-based FMEA and TRIZ for part of the welding process in an automobile company in Malaysia. Their objective is to solve the problems effectively and promptly via converting the conventional process-FMEA into an open architecture process-FMEA web-based system and integrate TRIZ into the web-based system. IP and CM are TRIZ tools that were adopted in the study.

Thurnes [28] proposed the Failure Mode and Effects Anticipation and Analysis (FMEAA), a hybridization of FMEA and Anticipatory Failure Determination (AFD) in a case study of door lock. AFD is one of the TRIZ tools. Thurnes [28] suggested that AFD provides creative and inventive systematic approach in locating possible and future failures.

In the automotive industry, high performance, high quality, safe product, and low cost of components are the upmost important element in Original Equipment Manufacturer (OEM). Therefore, Daniel [29] applied TRIZ in the design-FMEA to improve the prevention and detection actions in the development stage of the product. IP and CM were used to verify whether the defined actions are technically feasible and secure from the quality perspective.

Russo [30] proposed a tool known as Fault Investigator Tool (FIT) that helps the users to identify the cause of failure of the crane through a series of questions about the behavior of the malfunctioning crane. FIT is an after sale service tool that consists of an integration of function analysis and AFD from TRIZ, and service-FMEA. FIT mapped and organised about 1500 failure modes of crane failures to be filtered by 150 questions.

In summary, the outcome of the studies shows that TRIZ is able to overcome the limitation of brainstorming, which highly required in determining the problems, causes and solutions in FMEA and calculation of RPN for prioritization of action. In addition, the structured inventive solutions provided by TRIZ are able to assist practitioners in solving the problem more effectively compared to the typical PS methods such as trial and error, brainstorming and experience [11].

3.3 Neglect of Customers’ Perspective
Besides manufacturers or service providers, customers also play a crucial role in overcoming the drawbacks. Customers’ needs and requirements are considered very important elements in defining the quality of the product [31]. Quality Function Deployment (QFD) is a systematic customer-driven product development tool. House of Quality is one of the important product/service tools in QFD, which helps developers to make decisions, by taking into account customer needs or requirements. This can avoid hasty quality improvement decisions which cause failure to the product [32].

QFD and FMEA was integrated by Almannai [33] and Hassan [34] to support the decision-making process. Almannai [33] proposed an integrated decision tool where QFD identifies the best manufacturing automation alternative from customers’ perspective, process-FMEA to identifies the associated risks for the alternative. This decision-making tool was able to strengthen between the degree of importance of technology, organisation and people. Hassan [34] introduced a quality/cost-based conceptual process planning (QCCPP) by integrating the House of Quality from QFD, process-FMEA and activity-based costing (ABC) method to assist the decision-making process of the company. The purpose of QCCPP is to determine key process resources by taking into account the manufacturing costs and risks. The implementation of QCCPP approach is illustrated in the case study of the auxiliary shaft cover of a car engine.

Korayem [35] and Chen [36] integrated QFD and design-FMEA to improve the design and development of new products. Design-FMEA was adopted by Korayem [35] to identify the critical failure modes of two robots, namely 3P and 6R. QFD was adopted to improve the quality of the robots in accordance with customers’ requirement. For new product development, identifying the design requirements and parts characteristics fulfilment levels are important during QFD activity processes. According to Chen [36], most of the studies focused on the phase one of QFD. Therefore, Chen and Ko (2009) emphasises on phases one and two of QFD by proposing fuzzy linear programming models that comprises of the fuzzy approach of QFD’s house of quality and fuzzy design-FMEA. Fuzzy approaches are adopted in the study to overcome the drawbacks of diversified and imprecise problems between customers’ requirements and design requirements and among the design requirements.

Shahin [13] and Koomsap [12] integrated FMEA with Kano model to improve the conventional service-FMEA based on the customers’ perspective. Shahin [13] proposed a new index known as correction ratio to evaluate the corrective action in FMEA. Kano model has bridged the gaps between management’s point of view and customers’ point of view. Similarly, Koomsap [12] introduced a new customer-oriented RPN that involved customers’ perspective. They found out that the integrated approach is able to address the risk more effectively because customers’ point of view takes into consideration.

In summary, QFD and Kano model are able to complete the risk analysis of FMEA by providing information based on the customers’ perspective. These integrations enable manufacturers and customers to perform a comprehensive improvement initiative on the parts of the processes that require improvement.

4. Gaps and Opportunities

The drawbacks of FMEA have motivated researchers to propose many improvement initiatives aiming at accurate and robust risk evaluation. The review in Section 3 reveals numerous tools have been integrated with FMEA to overcome the drawbacks of FMEA, which are inefficiency of failure analysis, psychological inertia and neglect of customers’ perspective. Therefore, this section will discuss on the gaps and opportunities identified from the review of case studies.

The integration of seven basic tools of quality with FMEA not only enhances the failure analysis of FMEA but also assists the prioritisation of actions. Based on the literature review, recent studies only focus on the integration of Ishikawa diagram and Pareto chart with FMEA. Therefore, the integration of FMEA and other basic tools of quality such as check sheet, control chart, histogram, scatter diagram and stratification remain unexplored.

In addition to the seven basic tools of quality, the 7 new tools for improvement were introduced to focus on group processes and decision making [16]. The 7 new tools for improvement consists of affinity
diagram, interrelationship diagram, matrix diagram, tree diagram, prioritisation matrices, process decision program chart and activity network diagram. Tools such as affinity diagram, tree diagram, interrelationship diagram and matrix diagram could improve the FMEA failure analysis of the failure modes. Tools such as prioritisation matrices, process decision program chart and activity network diagram could assist the prioritisation of improvement action for the failure modes.

There are 27 tools available in TRIZ [11], [37]. From the review of the integration of FMEA and TRIZ, a great deal of researches focused only on CM, IP, function analysis, AFD and substance-fields model in order to overcome the psychological inertia. However, according to Yeoh [11] and Yeoh [37], TRIZ tools are able to contribute beyond generating inventive solutions. TRIZ are able to assist in problem and root cause identification, new product introduction and solution robustness. In addressing inefficiency of failure analysis, TRIZ tools such as process analysis and physical contradiction could be integrated into FMEA.

In addition, TRIZ tools such as ARIZ, Clone Problem Application and Scientific effects can be integrated into FMEA to address the psychological inertia. In improving FMEA solutions’ robustness, tools such as function oriented search and super-effect analysis could be integrated into FMEA. Yeoh [37] suggested that TRIZ tools are able to assist in tackling people related problems. Perception mapping under the people category can address the neglect of customers’ perspective in FMEA.

In a nutshell, the gaps and opportunities identified via this study suggest the future work in the improvement of FMEA. FMEA can become very useful and an effective PS tool across industries once the drawbacks are addressed. Non-engineering sectors like management, marketing and finance can capitalise the effectiveness of FMEA in the improvement processes.

5. Conclusion
FMEA has proven to be one of the most established and effective PS tools widely used across sectors. However, numerous studies have been carried out to criticize and overcome the drawbacks of FMEA. In this paper, a comprehensive literature review is carried out to (1) identify the drawbacks in FMEA, (2) categorise the integration of FMEA with other PS tools and (3) identify the gaps and opportunities. This paper extends the review conducted by Liu [6] and identifies other drawbacks of FMEA such as inefficiency of failure analysis, psychological inertia and neglect of customers’ perspective. The integration of FMEA with some of the seven basic tools of quality, TRIZ tools, and QFD have been categorised based on the drawbacks identified. Our study proposes future researches via identified gaps and opportunities such as integration of FMEA and the 7 new tools for improvement, integration of FMEA and other TRIZ tools include process analysis, physical contradiction, function oriented search, super effect analysis and perception mapping. In addition, this paper suggests that the integration of TRIZ tools with FMEA are able to address all the three drawbacks of FMEA.

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