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Identification of Failure Modes in DFMEA Through Application of Integrated Model of Product Functions (PF) and 7 Potential Failure Modes (7PFM)

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Abstract
Identification of potential failure modes in DFMEA is the most crucial step which often takes time. Therefore, the team conducting DFMEA should have ready reference to easily identify potential failure modes. The purpose of this study is to introduce a model to identify potential failure modes when the functions of the product are known but the product is not realized. Model proposed in this research can be utilized for complex product/system with multiple sub-systems that has to carry out multifaceted functions. Proposed new model is amalgamation of 7PFM model with Product Function (PF) relationship concept. This new model is then utilized to identify potential failure modes during DFMEA conducted for a land munition system. A new approach of numbering the causes of failure modes based on their significance is also introduced in this study. Identified causes having high importance are further treated as different risks for which corrective actions are proposed in DFMEA. Our study through implementation of integrated model in land munition system suggests that the model helps in smooth identification of failure modes, saving of time in completing DFMEA, identifying causes effectively and determining various risks to the product.

Keywords: DFMEA, Failure Modes, Product Function, C&E diagram, 7PFM.

1. Introduction

1.1 FMEA overview:

Failure Mode and Effects Analysis (FMEA) has been widely used since its inception through MIL standard, MIL-P-1629 in 1949. Although this standard was subsequently cancelled in 1998 (MIL-P-1629, 1998), the requirements and procedures for performing FMEA was adopted by various industries such as manufacturing, automobile, electronics, healthcare, aerospace etc. There are few other documents which specifically lay out the procedure and methodology of conducting FMEA that are being comprehensively used in multiple industries. Automotive Industry Action Group (AIAG, 2008) publication “Failure Modes and Effects Analysis Reference Manual” published in 2008 is the most widely used reference document in automotive industries. Similarly, Society of Automotive Engineers has also released guidance document (SAE-J-1739, 2009) and is popular document among automotive engineers. Bureau of Indian

Standards has released exclusive document titled "Failure Mode Effects Analysis" in 2005, which provides detail explanation of process and method of conducting FMEA.

As per IS 15550:2005, "FMEA is a technique to prevent problem from occurring by identifying and investigating potential failure modes and its related causes". This technique can be:

a) applied in early concept selection or design phase and then progressively refined and updated as the design evolves
b) used to recognize and evaluate the potential failure of a production process and its effect
c) helpful in identification of possible causes, including root causes in some cases, and also helpful in establishing the relationships between causes
d) used as a tool to aid in the improvement of the design of any given product or process
e) used to document the process

FMEA technique is also useful to ensure reliability and safety of the product thereby can be defined as a qualitative method, of inductive nature, that aims at identification of those failure modes in a system/component/process which could disable system operation or become initiator of accidents with significant external consequences (Zio, 2007). Many other authors have defined FMEA and highlighted benefits of FMEA in different ways. Layzell and Ledbetter have defined FMEA as a systematic and analytical quality planning tool to identify and prevent the potential problem (Layzell and Ledbetter, 1998). FMEA is a method of reliability analysis to identify failures that have important consequences affecting the system performance (Stamatis, 2003). FMEA focuses on preventing defects, enhancing safety and increasing customer satisfaction (McDermott *et al.*, 2008). FMEA can be used to identify failure modes and mitigate the effects of those failure modes using the appropriate measures in system (Raheja and Gullo, 2012).

There are four basic types of FMEA based on their use; Design FMEA, Process FMEA, Program/Project FMEA, and Machinery FMEA. This research study is focused on DFMEA, which is an inductive method carried out to perform qualitative system reliability and safety analysis and is intended to analyze the manner with which systems would fail. The effects of failures are investigated to understand or measure the risk to the main system (Muthukumar *et al.*, 2012). DFMEA is conducted during design phase to understand and prevent potential failure modes in the product. It is a systematic approach of documenting all the design issues involved and taking corrective actions so that failures do not occur with end users (Borse *et al.*, 2021).

In DFMEA, a Risk Priority Number (RPN) is identified for each cause of the failure modes and accordingly, corrective actions are recommended to reduce the risk priority number, ultimately mitigating the risks associated with the product. Risk Priority Number is the product ranked on three values, Severity (S): from 1 to 10, Occurrence (O): from 1 to 10, and Detection (D): from 1 to 10. Therefore, Risk Priority Number (RPN) is calculated by (as in conventional DFMEA):

$$RPN = S \times O \times D$$

Where, S stands for severity of failure mode; O stands for occurrence of failure mode and D stands for chances of the failure being detected. It is safely assumed that larger the RPN, more the risk to the system.

1.2 Failure modes identification methods:

DFMEA is divided into three different stages to ensure success of this technique. Determination of potential failure modes is the first stage. Second stage comprises of finding data for occurrence, detection and severity ranking. The final stage is the modification of the product design and the development of the control process based on the FMEA report (Teng and Ho, 1996). For success of DFMEA, it is pertinent that failure modes are identified correctly, however for product/system with multiple sub-systems having multifaceted functions, identification of failure modes is complex phenomenon. Therefore, Wu *et al.* in 2020 has suggested various entry points in the system to identify failure modes, namely, by product functions; function/component relationship; function/structural relationship; and component/component relationship. Product function approach of identification of failure modes for a system/product is the obvious choice and can be utilized when the system/product is at design/conceptual stage and the product is not manufactured. Once failure modes are identified, finding out causes for the failure modes is equally important for which brainstorming sessions by interdisciplinary team is often used (Wang, 2003). However, brainstorming method may lead to omission of important causes due to its unstructured approach. Same brainstorming method if used in the structured format as being utilized in Cause and Effect (C&E) diagram, leads to capturing all causes for a failure mode in a structured way.

This study is focused on DFMEA in which functions of the product is considered as the entry point for identification of potential failure modes. However, identification of potential failure modes by any entry point method is time consuming and often frustrating. Kotterman (2015) in his article has proposed 7PFM (Seven Potential Failure Modes) model for better identification of potential failure modes. This research study integrates the 7PFM model with the product function concept of entry point for identification of potential failure modes during DFMEA technique conducted for a land munition system. This research study further utilizes the C&E diagram for identification of causes for failure modes. In doing so, a new approach of numbering the causes based on their importance is introduced. Various identified causes through C&E diagrams, that have high importance are further treated as different risks for which corrective actions are proposed in the DFMEA.

Remainder of this paper will have detailed literature review describing the scope & objectives and methodology of the literature review along with findings of literature review in section-2. Section-3 proposes new model by integrating 7PFM model proposed by Kotterman with product function concept proposed by Wu *et al.* This section further utilizes C&E diagram to identify various causes of failure modes and list out causes based on importance. Section-4 lists out findings and results of implementation of integrated model on a land munition system and final section provides conclusion and future work.

2. Literature Review

2.1 Scope and Objectives:

With product functions becoming more complicated, identification of failures and its causes during design stage also becomes complicated and hence there should be a method which can immensely help in identifying failure modes and improving the reliability of the product after product's realization. This study uses a systematic literature review to understand what research has been conducted for identification of failure modes based on functionality of the product during the design stage and for implementation of C&E diagram in FMEA.

2.2 Methodology:

A systematic literature review is carried out to understand system failure mode identification and also to understand utilization of quality tools including C&E diagram in FMEA. A methodical review was conducted by using the criteria (1) FMEA & Failure Mode Identification (2) FMEA and

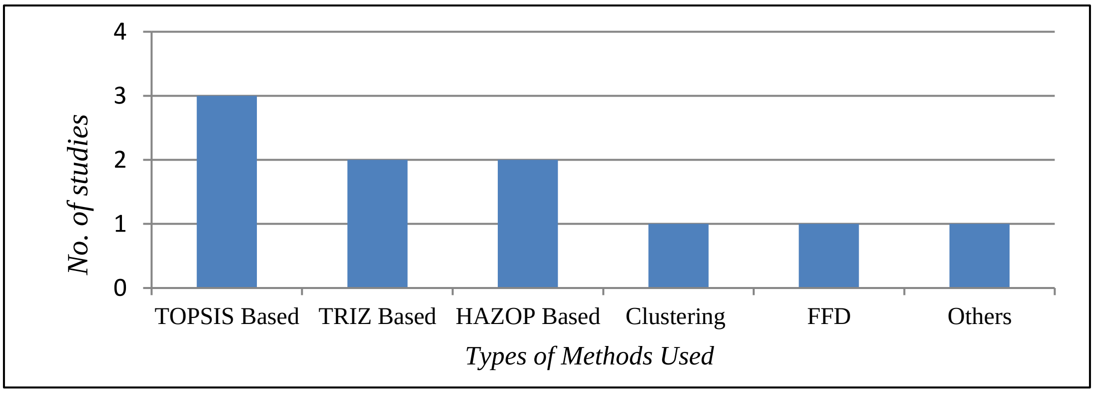
Integration/Integrated (3) FMEA and C&E (4) FMEA and Fishbone and (5) FMEA and Ishikawa. Literature search was limited to peer-reviewed journal articles available in open sources, pertaining to engineering subject area without any time limit settings.

2.3 Literature Review Findings

2.3.1 FMEA & Failure Mode Identification:

Although, we were looking for direct reference of failure mode identification with respect to functionality of the product, when research with respect to criteria 1 in section 2.2 i.e. FMEA & Failure Mode Identification was conducted, it was noticed that not many studies had direct relevance to the functionality aspects. It was also observed that many researchers have used the term risk identification rather than direct reference as failure mode identification. Sharifi *et al.* in 2022 have used the FMEA-TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method for identifying and ranking risks in dairy industry and simultaneously offering mitigation strategies for the risks. Similarly, Lo *et al.* in 2021 have used the Indifference Threshold-based Attribute Ratio Analysis (ITARA)-TOPSIS based integrated model to identify potential product and system risks. TOPSIS approach is again used by Wang *et al.* in 2021 in their research to prioritize risk of equipment failure modes in the oil and gas processing system. HAZOP (Hazard and Operability) along with FMEA was used for identification of risks in petrochemical plants by Mechhoud *et al.* in 2016. HAZOP is again used along with three other techniques, mainly FMEA, Analytical Hierarchy Process (AHP) and Supply Chain Operation Reference (SCOR) to identify and assess risks in construction supply chain (Hernadewita and Saleh, 2020).
Fault Investigator Tool (FIT) combining both TRIZ (Theory of Inventive Problem Solving) and FMEA is used as failure identification tool in the product-service system in a crane manufacturing for trucks operations by Russo *et al.* in 2016. TRIZ is again used along with Anticipatory Failure Determination (AFD) to identify all possible failure of the system and eventually to improve the reliability of the product by Mzougui and Felsoufi in 2019. Similarly, statistical clustering analysis has been used to identify potential failures in the conceptual design stage (Arunajadai *et al.*, 2004).
Tumer and Stone in 2003 have created a function-failure mode method to take advantage of the link between failure modes and functionality of components in an aerospace industry. Effective use of functional models (relational model) is utilized for identifying failure modes by Hata *et al.* in 2002. They have constructed functional relations models among components and defined two ways of component failure, which were then taken as input in FMEA. Figure 1 depicts different methods of these research studies related to failure mode identification.

Figure 1: Number of studies w.r.t different methods used for identification of failure modes



2.3.2 FMEA and Integrated/Integration:

It was pertinent to understand whether C&E diagram was utilized with other tools and techniques in conjunction with FMEA before exclusively doing search on utilization of C&E diagram with FMEA. Literature review was conducted as per criteria (2) mentioned in section 2.2 i.e. FMEA and Integrated/Integration. Scopus review resulted in 41 different research papers, however, upon careful review, it was noticed that only 20 papers had direct utilization of various tools/techniques along with FMEA. It is observed from this literature review that various tools and techniques, such as Quality Functional Deployment (QFD), 5Why, Fault Tree Analysis (FTA), Kano Model, Statistical Quality Control (SQC) tools, DEMATEL have been used in conjunction with FMEA.

Kammoun *et al.* in 2021 has used QFD along with FMEA for bettering the Hospital Sterilization Process (HSP). In 2019, Rizkya *et al.* have exploited the 5Why technique effectively to identify the problems in crude palm oil quality in Indonesia. Similarly, Tang *et al.* in 2021 have integrated Kano model with FMEA to improve the service quality of logistic centres. A well-documented literature review on integration of basic quality tools was done by Ng *et al.* in 2017, wherein they have highlighted the limitations of FMEA technique and thereby categorized the integration of other tools and techniques with respect to FMEA limitations. DMAIC (Define, Measure, Analyze, Improve & Control) process of 6Sigma has been utilized in developing Fuzzy logic of FMEA model (Godina *et al.*, 2021) and similarly, Fuzzy Analytical Hierarchy Process (FAHP) and modified Fuzzy Multi-Attribute Ideal Real Comparative Analysis (FMAIRCA) is combined with Multi-Criteria Decision Making (MCDA) method for removing drawbacks of classical FMEA to improve the risk estimation process in FMEA (Boral *et al.*, 2020). Shafiee *et al.* in 2019 have developed a modified FMEA approach in the backward integration of FTA for identification, evaluation, and prioritization of failure risks in a safety critical system. Similarly, in 2021 de Oliveira *et al.* have integrated FTA and Process Mapping technique with FMEA for reducing faults. FTA was again used in combination with FMEA for assessing risks in metal company (Wessiani and Yoshio, 2018).

QFD was integrated along with FMEA as a decision support tool for selection of manufacturing automation technologies (Alamanai *et al.*, 2008). Harikumar and Saleeshyain 2019 have used QFD with FMEA and Lean to manage risks in hospitals and Altuntas and Kansu in 2020 have utilized QFD along with SERVQUAL (service quality measurement) for service quality improvement. Pythagorean Fuzzy Dimensional Analysis (PFDA) is integrated with FMEA for assessment of risks during product design (Garcia *et al.*, 2022). Wang *et al.* in 2022 have proposed integration of Decision-Making Trial and Evaluation Laboratory (DEMATEL) method and The IekriterijumskoKOmpromisnoRangiranje(VIKOR) method with FMEA to overcome the deficiencies in analysing risks in real application of Failure Mode Effects and Criticality Analysis (FMECA). Similar model of using DEMATEL with Reality Charting and FMEA was proposed by Cheshmberah *et al.* in 2020 to understand and implement Root Cause Failure Analysis (RCFA) effectively.

FMEA is integrated with hybrid Multi-Criteria Decision Analysis (MCDA) model for evaluating the risks and prioritizing mitigations strategies over the extended lifetime of subsea facility in High Pressure High Temperature (HPHT) environment (Shafiee and Animah, 2022). FMEA is also used in conjunction with SQC tools in a tea product packaging industry (Ruchitra and Amelia, 2021). Similarly, Manurung *et al.* in 2021 have effectively utilized FMEA to analyze various work accidents occurring in production line of a paint and coating factory using SQC tools. Savelev *et al.* in 2021 have developed a special software tools to provide an opportunity to use Model Based Safety Assessment (MBSA) model while performing FMEA.

Literature review regarding integration of tools with FMEA has revealed that various tools and techniques have integrated with FMEA across various industries to generate different results, mostly to improve the existing process or to better the FMEA technique itself. Table 1 depicts details of research being done by various researchers utilizing different tools/techniques being integrated with FMEA in various domains/industries. References are also mentioned in the Table 1.

Table 1: Details of different tools/techniques integrated with FMEA

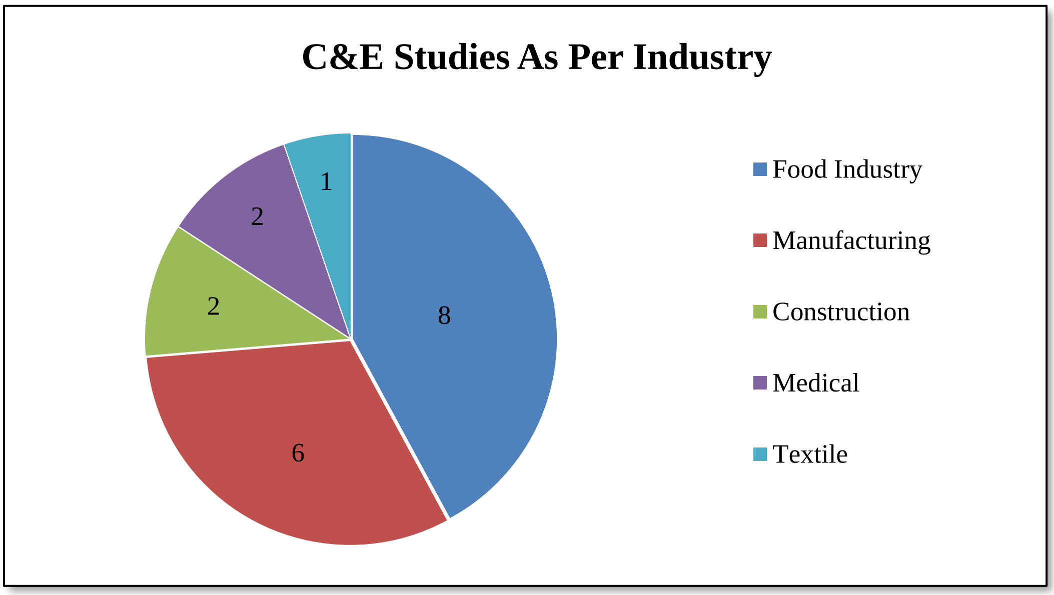
S. N.	Tools/Techniques	Application/ Domain	References
1	Fault Tree Analysis (FTA)	Healthcare Industry	Kammoun *et al.*, 2021
2	5Why	Food Processing	Rizkya *et al.*, 2019
3	Kano Model	Service	Tang *et al.*, 2021
4	Quality Tools	Literature Review	Ng *et al.*, 2017
5	• Fuzzy Logic with DMAIC • Fuzzy Logic with MCDA	Automobile General	Godina *et al.*, 2021 Boral *et al.*, 2020
6	• FTA • FTA and Process Mapping • FTA	Oil and Gas General Metal	Shafiee *et al.*, 2019 de Oliveira *et al.*, 2020 Wessiani and Yoshio, 2018
7	• QFD • QFD & Lean • QFD &Servqual	Manufacturing Hospital Service	Almannai *et al.*, 2008 Harikumar and Saleeshya, 2019 Altuntas and Kansu, 2020
8	Pythagorean Fuzzy Dimensional Analysis (PFDA)	Electronic	Garcia *et al.*, 2021
9	• DEMATEL & VIKOR • DEMATEL & Reality Charting	Wind Turbine Automobile	Wang Z *et al.*, 2022 Cheshmberah *et al.*, 2020
10	MCDA	Oil & Gas	Shafiee and Animah, 2022
11	SQC	Packaging Paint	Ruchitra and Amelia, 2021 Manurung *et al.*, 2021
12	Model Based Safety Assessment	Aviation	Savelev *et al.*, 2021

2.3.3 FMEA and C&E/Fishbone/Ishikawa:

Literature review with respect to integration of FMEA with C&E diagram/Fishbone/Ishikawa was carried out as per criteria 3, 4 and 5 mentioned in section 2.2 to understand how C&E was utilized in FMEA. Scopus review resulted in total of 25 different papers which claimed to use the C&E diagram in association with FMEA. A closer look revealed that 19 of these papers had direct relevance of C&E inclusion with FMEA. Further closer look displayed that eight out of 19 of these papers had used C&E in association with FMEA in food processing industries and were similar in nature wherein C&E diagram has been used to identify the causes of the end problem.

Remaining 11 studies were related to use of C&E diagram in various industries along with FMEA as shown in Figure 2. Nowotarski *et al.* in 2019 has used FMEA and C&E diagram for improving the quality of ground works processes while adapting the DMAIC approach of 6Sigma in construction industry. Similarly, DMAIC method is again utilized by Maryani *et al.* in 2021 for improving the quality of aluminium alloy wheels product but in manufacturing setup. Further in manufacturing industries, Bialy and Ruzbarsky in 2018 have utilized C&E diagram to understand various causes of failure of one of the components of the machine that was breaking down frequently. In this study, C&E and FMEA are utilized as a separate tool for varying purposes. Rizkya *et al.* in 2021 have also utilized both FMEA and C&E diagram effectively but separately to analyze the blow moulding machine damage in a packaging industry. FMEA was used to find out information about the factors causing loss and to determine the priority level of risk based on the RPN value and C&E diagram was used to determine causes of failure of the blow moulding machine. In the similar vein of understanding various failures and its causes of screw press machine, FMEA and C&E were utilized to improve the preventive maintenance program in a crude palm oil production environment (Hamali *et al.*, 2021). Another use of FMEA and C&E diagram in sugar mill boiler setup in manufacturing industry was successfully done by Mariajayaprakash and Senthilvelan in 2013. In this study, the authors have identified that fuel feeding system of the cogeneration boiler was failing frequently. Drum feeder is the key component of the fuel feeding system and it had several reasons for the stoppages, which were identified by C&E diagram. Out of all the causes for stoppage, most significant were identified through FMEA. Hemadewita *et al.* in 2020 have utilized C&E diagram to identify various causes for one of the defects in Seals (Gasket Connector) manufacturing. In this study, Auto Deflash, was considered for further analysis through C&E and FMEA. C&E diagram identified various causes for Auto Deflash and then these causes were put in FMEA table to understand failures due to these causes and to provide RPN values.

Figure 2: Industry wise details of Integration of C&E with FMEA



In textile industry, literature review identified one study which was conducted using FMEA and C&E diagram. FMEA has been used to identify possible failures in the weaving section of fabric production and C&E diagram was used to identify possible causes of the fabric defects (Fithri *et al.*, 2020). In construction industry, C&E have been used to find out possible root causes for delays in execution of road infrastructure project (Purwanggono and Margarette, 2017). The last two studies out of 11 studies other than food industries were in medical industry, which dealt with integration of C&E with FMEA. Prajapati *et al.* in 2020 have performed Design of Experiments (DOE) based FMEA for implementation of analytical quality by design approach in development of stability indicating assay method for estimation of Apremilast drug. C&E diagram was used for listing and categorizing failure modes. Similarly, C&E diagram, FMEA and DOE have been utilized to optimize the chromatographic purification process for Streptococcus Pneumonia Serotype 23F Capsular Polysaccharide (Ji *et al*., 2014). C&E diagram was used to identify process variables for the chromatography process in a flow through mode when the resin was chosen. These variables were put in FMEA format to identify various failure modes, their effects, causes and process control method. Subsequently, RPNs were calculated and high RPN parameters were further investigated and optimized through DOE method.

2.3.4 Findings:

Literature review has revealed that direct correlation with identification of failure modes with functions of the product is not mentioned in any of the studies. Besides, failure modes identification is not referred directly by any researcher, rather, risk identification term is used instead. Although, there is a reference of research in which functionality of the components had been utilized to link the failure modes in components (Tumer and Stone, 2003), this function-failure mode method is specific to aerospace components and products. In this study, failure modes related to basic aerospace components are determined and this generalization is applied to identify failure modes for larger family of components/systems. Similarly, Hata *et al.* have worked on relations models between components and accordingly have defined two ways of component failure. These failures were taken as input in FMEA.

It is observed from the literature review that there is a vacuum in terms of standard template for identifying failure modes and hence a simplified method of identifying failure modes during DFMEA technique has to be realized. Since DFMEA is done at the design stage, identification of the failure modes through product functions basis and then utilizing the 7PFM model would work as a standard template for the designers to identify failure modes. This integrated model when used during DFMEA can results in streamlining and identifying requisite failure modes. Use of the integrated model is further explained in next section through a case study.

3. Integrated Model

3.1 The Model:

In the integrated model, failure modes are identified by combining the product/system function analysis with 7PFM model. The 7PFM model as proposed by Kotterman reduces the near-infinite numbers of potential failures to manageable & comprehensive seven potential failure modes. It identifies the potential failure modes in three failure domains namely, quantity, variation and time and then divides these failure modes into seven PFM as shown in Table 2. Once the failure modes are identified, identification of causes of failure modes is done through C&E diagram by further categorizing the causes into various groups such as Man, Machine, Material, Mother Nature and Method (5M) by using 5Why technique, thereby concentrating the efforts to resolve the observed problem (Hafida *et al.*, 2022). All identified causes are further rated from 1 to 5 as stated in Table 3. Causes having rating from 3 to 5 are considered eligible for taking corrective actions for their elimination/reduction. These corrective actions are then mentioned in FMEA format

Table 2: 7PFM Model by Kotterman

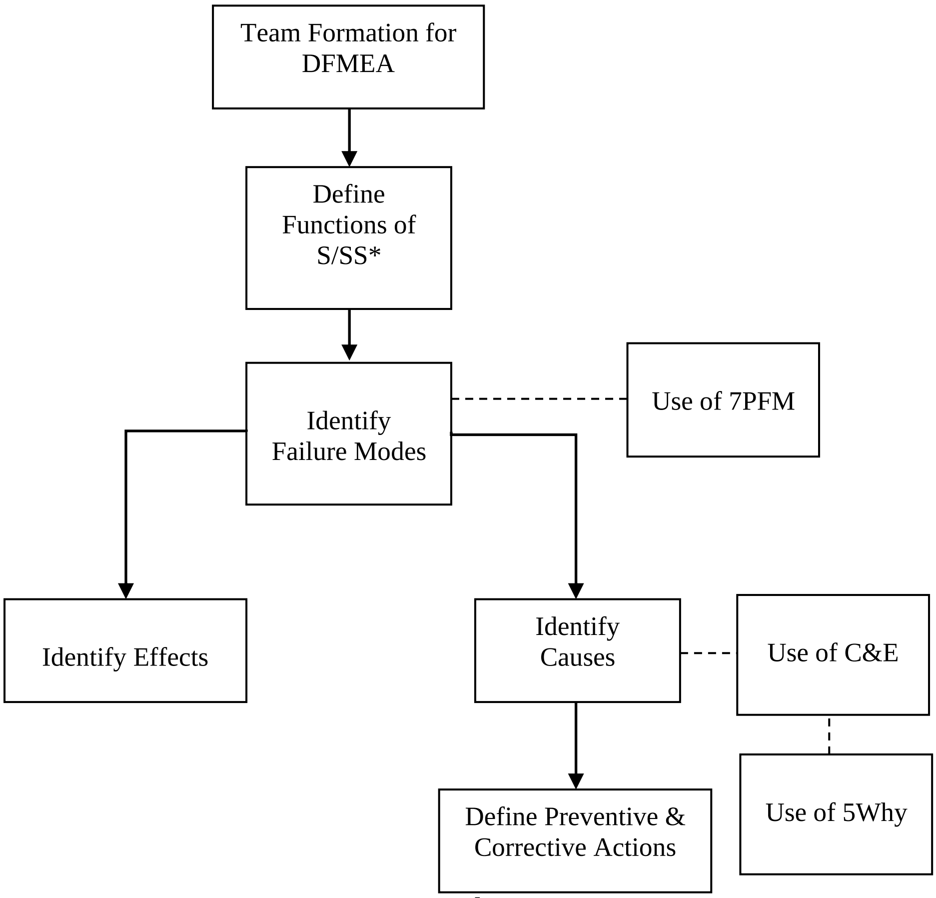
Failure Domain	PFM	Failure Description
Quantity	Did not	No action
	Too much	Excessive action
	Too little	Insufficient action
Variation	Inaccurate	Action off target
	Inconsistent	Variation in action within or between events
Time	Too fast	Action happened too quickly or too soon
	Too slow	Action happened too slowly or too late

Table 3: Rating for the causes in C&E diagram

Number	Rating
5	Very Severe; Immediate action required
4	Important; Action needed
3	Important; Action can be delayed
2	Not Important
1	No Action required

The system for which functional analysis has to be carried out is divided into various sub-systems. Each sub-system has its own function to carry out and accordingly, 7PFM model is used to understand failure modes with respect to each sub-system functioning. This approach is utilized during conduct of DFMEA for one of the munitions development in a R&D organization. A team of design engineers, quality engineer and manufacturing engineers was constituted. A facilitator with knowledge of conducting both C&E diagram and FMEA led the team. The team identified the failure modes on the basis of functions and accordingly, C&E diagrams were constructed for each failure mode to understand various causes of the failure modes. Each cause was then given proper rating as mentioned in Table 3. A flow chart giving details of sequence of events for implementation of integrated model is shown in Figure 3. A detailed study of implementation of integrated model for the munition assembly is explained in section 3.2.

Figure 3: Sequence of events for the integrated model



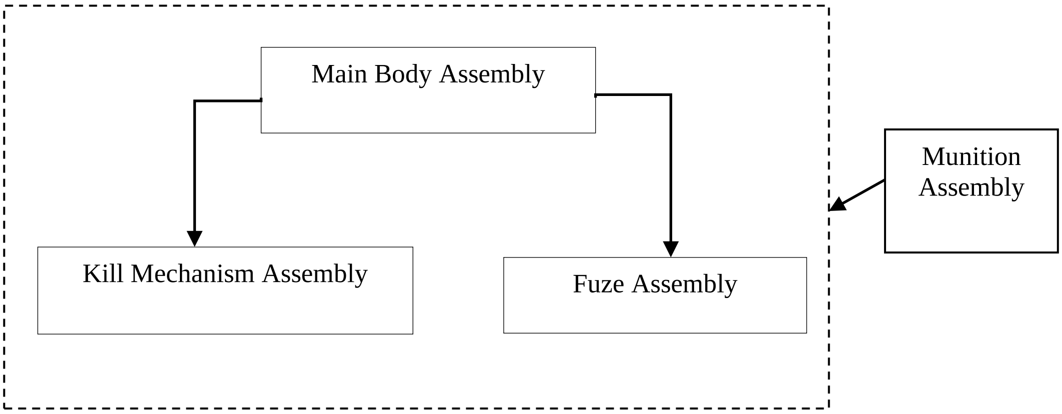
*S/SS – System/Sub-system

3.2 Implementation of new model:

Application of integrated model for identification of potential failure modes and application of C&E diagram for identification of potential causes of the failure modes for FMEA was carried out during design stage of a product having three sub-systems. A team is constituted as mentioned in section 3.1, which was responsible for conducting both DFMEA and C&E. This team was also responsible for rating various causes and further translating these causes in the FMEA format.

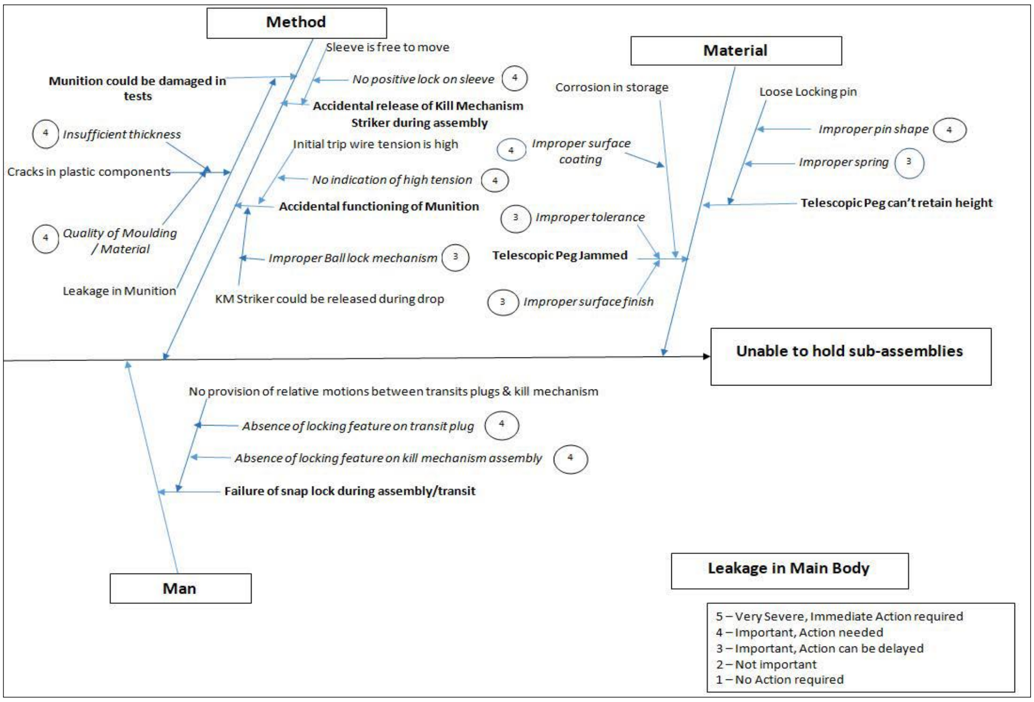
Figure 4 shows the division of munition system (assembly) into three different sub-systems. The main body assembly holds the other two assemblies i.e. kill mechanism assembly and fuze assembly. While conducting DFMEA for the munition assembly, functions of each sub-system were considered and 7PFM model was used to identify various failure modes. Once failure modes were identified, C&E diagram was utilized for finding out various causes of individual failure mode. Each failure mode was plotted as an effect on the C&E diagram. Causes were identified by segregating the causes mostly into 5M categories. While trying to identify the root cause of failure occurrence (considered as an effect), 5 Why methodology is utilized. Once all the root causes are identified, these root causes are ranked based on their significance and impact on failure mode. The team involved in conducting DFMEA and C&E diagram decided the ranking of the causes and ultimately decided on the corrective actions to eliminate/reduce the root causes.

Figure 4: Main System and sub-systems



DFMEA for the Main Body Assembly is shown in Table 4 wherein, the first function of the main body assembly, i.e. to hold the other sub-assemblies is considered and shown as an example. As per 7PFM template, two failure domains i.e. quantity and variation are considered to be best suited for the "to hold other two sub-assemblies" function. Accordingly, two failure modes of "unable to hold sub-assemblies" in quantity failure domain and "inappropriate holding of sub-assemblies" in variation failure domain were identified. Cause and effect diagram were then plotted considering each failure mode as an effect and various different causes were identified. All root causes are depicted in *Italic* and are ranked as per criteria mentioned in Table 3. Identification of root causes for the failure modes for two failures are shown in Figures 5 & 6.

Figure 5: C&E diagram for first failure mode of main body assembly



Unanimous decision of the team was to put only those root causes in the DFMEA table that has rankings of 3, 4 and 5. The team then identified existing detection methods to detect the causes and accordingly, Risk Priority Number (RPN) was calculated. The team again unanimously decided to eliminate/reduce those root causes that has RPN values more than 50 and only for those causes, corrective actions were suggested as explained in Table 4.

Figure 6: C&E diagram for second failure mode of main body assembly

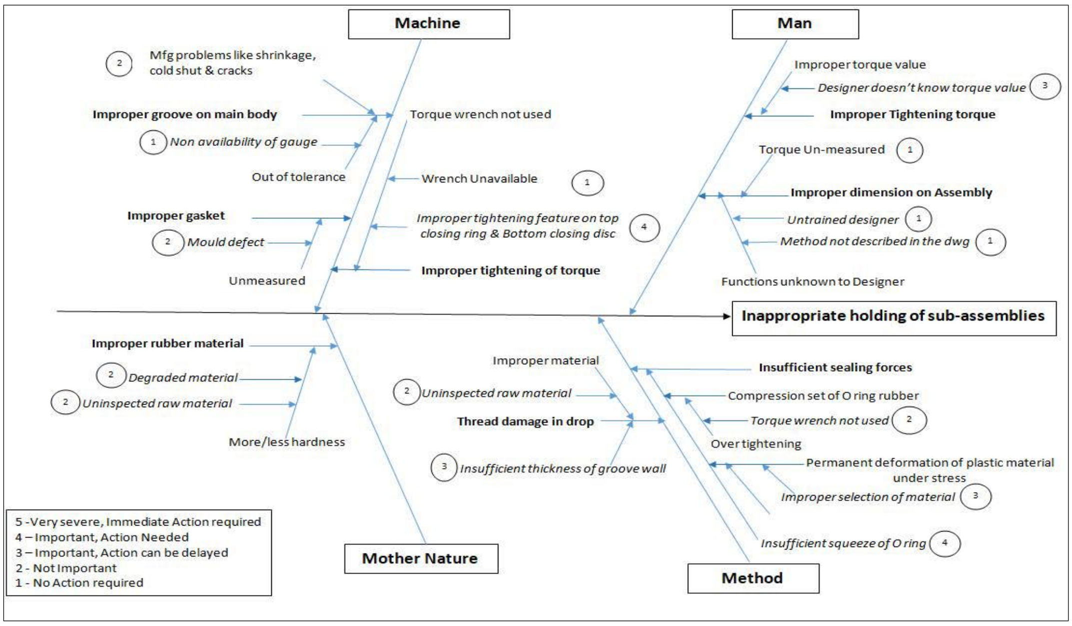


Table 4: DFMEA for the Main Body Assembly

Design Failure Mode and Effect Analysis				Main Body Assembly					
Functions (using the functional approach)	**Potential Failure Mode (using 7PFM model)**	**Potential Effect(s) of failure**	**Sev**	**Potential Causes**	**Occur**	**Detection Methods**	**Det**	**RPN**	**Corrective Actions**
To hold two other sub-assemblies (Kill Mechanism Assembly and Fuze Assembly)	Unable to hold the sub-assemblies	Safety Hazard (9), Non-functioning of system (8)	9	Insufficient thickness of main body	2	Simulations & initial drawing	3	**54**	Drop analysis should be carried out to ensure strength
				Quality of moulding\ Material	4	Initial checks of raw material	3	**108**	Manufacturing process parameter to be controlled
				No positive lock on sleeve	2	Simulations, jigs & fixtures	3	**54**	Safety lock is required to be provided
				Improper ball lock mechanism	2	Quality check	3	**54**	Indication is required for excessive tension in trip wire
				Absence of locking feature on transit plug	2	Visual	4	**72**	Locking feature is required to be provided on transit plug
				Absence of locking feature on Kill Mechanism Assembly	2	Visual	4	**72**	Locking feature is required to be provided on Kill Mechanism Assembly
				Improper Pin Shape	2	Quality check	3	**54**	Pin shape is to be controlled in the manufacturing
				Improper Coating, Surface finish & tolerance	3	Simulations & initial drawing checks	3	**81**	1. Peg can be maufatured from the stainless steel 2. Control of tolerance & Dimensions
	Inappropriate holding of the sub-assemblies	Safety Hazard (9), compromised functioning of the system (8)	9	Improper tightening feature on top closing ring & Bottom closing disc	4	Simulation and initial drawing checks	2	**72**	Additional feature required to be provided to accommodate tightening tool on bottom closing disc and top closing ring
				Insufficient squeeze of O Ring	3	Simulation studie	2	**54**	Control of tolerances and fitted part
				Designer doesn't know torque value	4	Review Mechanism-	2	**72**	Training to designer.
				Insufficient thickness of groove wall	3	Simulation studie	2	**54**	Tolerance analysis
				Improper selection of material	3	Simulation studies, quality checks	2	**54**	Material sheet to be referred for proper selection

While conducting DFMEA, the team has to deliberate on assigning Severity, Occurrence and Detection ranking as per evaluation criteria mentioned in standard for which the team referred IS 15550:2005. Another job of the team was to identify various detection methodologies for identification of failure modes and finally to deliberate on the corrective actions for the identified potential causes for nullifying the effects of the failure modes. DFMEA with standard format only for the main body assembly and fuze assembly is shown in Table 4 & 5 respectively. All the causes for various failures in fuze assembly were identified through C&E diagram and put into the DFMEA format. Corrective actions for the high RPN values were identified and implemented to reduce the overall impact of the failure mode. Similarly, DFMEA was also being done for the kill mechanism assembly wherein causes were identified by plotting the C&E diagrams.

Table 5: DFMEA for the Fuze Assembly

Design Failure Mode and Effect Analysis				Fuze Assembly					
Functions (using the functional approach)	Potential Failure Mode (using 7PFM model)	Potential Effect(s) of failure	Sev	Potential Causes	Occur	Detection Methods	Det	RPN	Corrective Actions
To ignite the propellant charge	Unable to ignite	Non-functioning of system (8)	8	Corrosion/rusting of balls of striker assembly of fuze	2	Quality checks	2	32	
				Incorrect hole feature to release striker ball in striker assembly	3	Preliminary design review	2	48	Understanding of design for manufacturability
				Improper cam profile on pull cam and pressure pad	2	Simulations studies	3	48	Design review by cross functional expert team
				Restriction of stiker assembly movement due to clash between inner and outer sleeve	4	Simulation and design review	2	64	Additional and adequate clearance to be given
				Non generation of pressure due to improper groove dimension in KM casing	2	Simulation studies	3	48	Groove dimension to be corrected
				Fuze cover not getting sheared due to improper dimension given on sheering groove	3	Simulation studies	2	48	Modification of sheering groove dimension
				Relay pallet doesn't pick up the flash due to improper assembly of NRV	2	Quality check	3	48	Checks to be provided for ensuring proper assembly of NRV
	Inconsistent ignition	Compromised functioning of the system (8)	9	Misalignment of shutter due to insufficient cavity depth on shutter for detonator	3	Simulation and initial drawing checks	3	81	* Cavity depth of the shutter to be increased * Shutter pin to be modified
				Accidental release of striker due to non-provision to constrain relative motion	3	Simulation studies	2	54	Through hole to be provided on inner and outer sleeve
				Assembly issues after environmental testing	3	Checklist for environmental tests	2	54	Work instructions for environmental testing to be made and followed
				Arming lever not able to start timer due to insufficient rotation of starter arm	3	Simulation studie	2	54	* Arming level slot to be modified. * Timer pin length to be increased
				Misalignment of lower and upper arming lever	2	Simulation studies, design review	2	36	
				Insufficient clearance of top cover with shutter & Fuze inner body	2	Simulation studies, quality checks	2	36	

4. Results/Findings:

It is important that DMFEA is initiated at the earliest development phase of the product development i.e. during the design stage to identify failure modes. An early implementation of DFMEA is crucial for reducing and/or eliminating the causes of failures thereby reducing the cost of late non-compliance identification (Paciarotti *et al.*, 2014). Therefore, it is essential that DFMEA should not take long duration to complete for garnering maximum benefits. When the product is at design stage, failure modes can be detected by identifying the functions of the product/system/sub-system as is done in the example shown in section 3. During the design phase of munition assembly as discussed in section 3.2, all the sub-systems of the munition were identified. These sub-systems are depicted in figure 3 for which failure modes were identified utilizing the functionality of each of these sub-systems. As such, identification of failure modes is always crucial while conducting FMEA and therefore a 7PFM model was utilized for easy identification of these failure modes. Once the failure modes were identified, causes of the failure modes were identified by utilizing the C&E diagram. As the failure modes and its causes are identified, rest of the exercise of identifying detection methods and then providing severity, occurrence and detection ranking becomes less cumbersome. An integrated model of 7PFM and product functions was implemented to identify failure modes in a munition assembly by a team constituted for this purpose. During the new model implementation for a munition system, the team could complete the DFMEA in short duration as identification of the failure modes and its causes were done smoothly.

It was evident from the implementation of new integrated model mentioned in section 3.2 that it immensely helped the team to conduct and complete DFMEA for the land munition assembly and most importantly to identify all potential failure modes. As the same team conducted both C&E and DFMEA, understanding of the problem statement and what is expected from the team was very clear. Since the potential causes were identified from C&E diagram, it helped the team to quickly identify the corrective actions for the failures. Timely completion of the DFMEA helped the designers to do timely course corrections and gave leeway for experimentation to make the design more robust. Suggestions from DFMEA were implemented resulting in changes in the design. Prototypes were manufactured with reference to the new design, for which improvements were immediately observed by the team as the product performed exceptionally well. It was possible to make these amendments because DFMEA was conducted on timely fashion and designers had time to implement these suggestions, which was further possible because integrated model helped the team to identify failure modes quickly. The ultimate aim of a design team is to make a robust design with low probability of failure after product is realized, which was achieved in this case as potential failures were rectified by taking appropriate corrective actions. Following advantages were derived by utilizing the integrated model and using C&E diagram for identification of causes:

- Comprehensive and smooth identification of failure modes
- Effective identification of the causes
- Availability of time to implement corrective actions
- Timely completion of DFMEA
- Availability of time to manufacture prototypes to validate improvements
- Strongly propagated simulation methods which enabled designers to purchase simulations software
- Effective risk mitigation before product realization
- Great exchange of ideas among members of cross functional team
- Advantages allowed other teams to imitate the same methodology in other products

5. Conclusion:

This paper has successfully introduced and utilized the integrated model of 7PFM model with the product function relationship concept for identification of potential failure modes during DFMEA technique conducted for a land munition system. This new model can help design engineers working in the new product development or in product design areas who wants to utilize DFMEA for early identification of failure modes. This study also utilized the C&E diagram for identification of causes for the failure modes that were derived from using integrated method, wherein a new approach of numbering the causes based on their importance is introduced. Various identified causes through C&E diagrams, that have high importance are further treated as different risks for which corrective actions are proposed in the DFMEA.

The new integrated method was implemented for a munition assembly with three sub-systems. These authors have proved that implementation of integrated model and use of C&E diagram for identification of causes certainly save time in conduct of DFMEA and also have multiple benefits. The normal way of finding potential failure modes and potential causes in DFMEA is through brainstorming sessions. However, brainstorming may be ineffective if not controlled in proper way or a systematic approach/technique/tool is not associated with brainstorming. This study has effectively utilized the same brainstorming approach in C&E diagram to identify various causes of potential failure modes. These authors have also effectively utilized the 5Why concept in C&E diagram to reach out to the root cause of the problem. A novel approach of rating the causes was used to segregate important and trivial causes in the C&E diagram. This approach has helped the team to focus on implementation of corrective actions on important causes of failures. This has further helped in reducing the time for completing the design cycle for the product and realization of prototypes.

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