CRANFIELD UNIVERSITY

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Enhancing product quality control through applications of FMEA

SCHOOL OF APPLIED SCIENCES

MSc by Research Thesis

Academic Year: 2010 - 2011

Academic Supervisor: Dr. Ahmed Al-Ashaab

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ABSTRACT

Product quality is the most vital factor for manufacturers' survival. As an effective quality control technique, FMEA (Failure Mode Effect Analysis) has been put into widespread use. However, improper, unsystematic and isolated FMEA applications in product design and manufacturing process design have lowered its effectiveness greatly.

This research aims to develop an integrated FMEA framework which can guide correct FMEA applications. The focus of the research is to interrelate and provide traceability of the potential failures of functions of product design and the manufacturing processes. The objectives are to: (1) synthesise the best practices of FMEA applications through a comprehensive literature review; (2) identify the gap between FMEA application performances and best practices through document research, staff interviews and questionnaire in an aerospace company; (3) develop an integrated FMEA framework designed to interrelate and provide traceability of potential failures of functions of product design and manufacturing processes; (4) validate the framework through expert judgement in collaboration with the aerospace company.

This research has proposed an integrated FMEA framework. It has five parts, which mean 5 stages for applying FMEA. To guarantee enough management support and required resources, it is first necessary to establish management awareness and commitment; then the system for mandatory, systematic and correct FMEA applications must be established; subsequently, staff training to develop a sound understanding of FMEA applications, FMEA implementation for risk assessment and elimination and auditing process for continuous improvement are proposed sequentially. According to the expert judgement, the framework can guide correct and systematic FMEA applications in the collaborative aerospace company, focusing more attention on defect elimination and thereby enhancing product quality control.

Keywords: quality control, defect traceability, potential failures, functions, product design, manufacturing processes, best practices, gap, framework.

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1. Introduction

1.1. Background

With the world economic globalisation and development of technology, manufacturing companies are experiencing more discerning customers as well as fierce competition in producing products with less expense, instant delivery, better quality, etc. However, product quality is the most vital factor for manufacturers to survive (Tang, 2007 and UNIDO, 2006).

High product quality is always required during aerospace product development. The traditional method of quality control is to plan and inspect the product against relative specifications. However, sometimes defects cannot be found easily through in-process inspection, even though the production process of airplanes is required to be monitored and recorded rigorously. Whenever these defects are found afterward, especially at the final stage of production, solutions can just be employed merely to remedy the defects, which might reduce the life duration or inter-changeability of the product. Even worse, the part or component has to be discarded, which means loss of time and money.

Researches implemented on product quality and reliability management have revealed that 75 percent of product defects, a significant proportion, derive from the development and planning phase; approximately 80 percent of deficiencies remain embedded in the product until the final tests or until the product being delivered to customers (Vassilakis and Besseris, 2009). Hence, to enhance the product quality control, it is crucial to eliminate the defects at the planning stage.

According to Onodera (1997), FMEA has been proved to be one of the most effective preventive quality control techniques for potential failure assessment and prevention and continuous quality improvement. It has been used broadly in industries, including the aerospace industry. However，most companies do not apply this technique correctly and efficiently, due to the limitations of the technique itself as well as the lack of systematic guidance in those companies.

1.2. Research motivation and problem definition

According to Scribd (2010) and Dyadem Press (2003), the benefits of effective FMEA applications are as follows:

(1) Improvement of the product quality and reliability;

(2) Less resource waste caused by afterward modifications;

(3) Emphasis on problem prevention in advance;

(4) Accumulation of knowledge and experience;

(5) Defect and root cause traceability through FMEA documentation system;

All the benefits listed above are crucial for producing and developing even simple products with high quality, let alone the aerospace product with high complexity. However, incorrect and improper applications of FMEA have cut down its effectiveness. This research focuses on the development of an integrated FMEA framework, which can guide correct and systematic FMEA applications, preventing the risks and defects in the planning stages and thereby enhancing the product quality control and defect traceability.

1.3. Brief introduction of the collaborative company

This research involves an aerospace company as the collaborative company. The following information indicates the scale and product nature of this company:

(1) It mainly concerns the civil airplane design and manufacturing: one being a regional airplane with fewer than 100 seats; the other a 150 seats, single-aisle airplane.

(2) It is also a subcontract supplier of other aerospace companies, including Airbus and Boeing.

(3) The number of employees exceeds 6000.

During the development of its regional airplane, this company has discovered limitations of its traditional quality control method. The company is now seeking for a preventive quality control technique for its new airplane development in addition to defect elimination and continuous quality improvement of its regional airplane.

The company has employed the preventive quality control concept of FMEA for many years. However, the applications of FMEA depend on the engineers' experiences and their sense of responsibility rather than the mandatory requirement of the quality control process. The effectiveness of FMEA differs from one individual to another without consistency. Sometimes, major problems, especially those in the interfaces are missed. It is difficult to deal with these problems during the assembly or flight test stage. Therefore, the company urgently needs sound guidance in the use of correct and systematic FMEA application, preventing major problems in advance, thereby enhancing product quality control.

1.4. Aim and objectives

The aim of this research is to develop an integrated FMEA framework for the collaborative aerospace company. This is to interrelate and provide the traceability of the potential failures of the functions of product design and manufacturing processes that will be used to fabricate the product and produce the required functions; then, more attention can be paid to defect assessment and elimination, enhancing the product quality control.

In order to achieve the project aim, the following objectives are designed to be followed:

(1) Synthesis the best practices of FMEA applications through a comprehensive literature review.

(2) Identify the gap between AS-IS quality control process in the collaborative aerospace company and the synthesised best practices of FMEA applications through document research, staff interviews and questionnaire.

(3) Develop an integrated FMEA framework designed to interrelate and provide the traceability of potential failures of functions of product design and manufacturing processes.

(4) Validate the integrated FMEA framework through expert judgement within the collaborative aerospace company.

1.5. Thesis structure

The project is presented in 7 chapters, summarised as follows.

Chapter 1 – Introduction

This chapter initially describes the background to the project; moving on to project motivation and problem definition, a brief introduction to the collaborative aerospace company; afterwards, the project aim and objectives are elaborated; the structure of the thesis is then presented. The information presented in this chapter provides an overview of the whole project;

Chapter 2 – State of art on FMEA

A comprehensive literature review on FMEA is carried out in this chapter. This helps to lay out a solid theoretical foundation for the whole project; FMEA applications in industries are identified; then, best practices of FMEA applications are synthesized and categorized; finally, a research gap is proposed.

Chapter 3 – Research Methodology

This chapter focuses on the steps followed in the project as well as deliverables in each stage to ensure that the research approach is correct. A timescale is also provided to illustrate the progress of the work.

Chapter 4 – AS-IS quality control process and gap identification

This chapter provides an introduction to quality system in the collaborative aerospace company; following that, the AS-IS product based quality control

process is identified through document research and staff interviews; a questionnaire is designed carefully, based on the identified quality control process and synthesized best practices, and performed to collect information about the current FMEA performances and staff views on FMEA application; finally, the gap between the AS-IS quality control process and the synthesized best practices is identified through data analysis.

Chapter 5 – FMEA framework development

In this chapter, the interrelationships between DFMEA and PFMEA are presented; then, a case study involving an aerospace flange is carried out with the purpose of illustrating the interrelationships of DFMEA and PFMEA; then the method to develop the integrated FMEA framework is elaborated; finally, an integrated FMEA framework is developed to guide correct FMEA applications in the collaborative aerospace company, involving the interrelationships of DFMEA and PFMEA. This is designed to interrelate and provide traceability of the potential failures of functions of product design and manufacturing processes.

Chapter 6 – FMEA framework validation

In this chapter, the FMEA framework developed in chapter 5 is validated through expert judgement within the collaborative aerospace company.

Chapter 7 – Conclusions and recommendations

This chapter mainly focuses on discussion of the methodology, research work and achievements, conclusions. The contribution to knowledge, research limitations and the recommendations for future work are also presented.

2. State of art on FMEA

2.1. Introduction

The purpose of this chapter is firstly to carry out a literature review on FMEA, including defining DFMEA and PFMEA, outlining FMEA templates in wide use and FMEA applications in various industries. The best practices of FMEA applications are then synthesized in order to provide a baseline for gap analysis and support for the FMEA framework development. Finally, a research gap analysis is proposed based on the comprehensive literature review.

2.2. State of the art on FMEA

2.2.1. Definition of FMEA

FMEA (Failure Mode Effect Analysis) is a team-based, systematic, risk preventive technique. It is used for managing the known or potential quality risks by identifying all the possible failure modes, evaluating their effects, occurrences and detectability, identifying their root causes, finding effective solutions and finally taking actions to eliminate the risks before their occurrences. The whole process is required to be documented, reflecting the current status of product design, manufacturing processes design, and the potential defects, root causes and solutions to potential defects elimination. The documentation system allows the tracing of defects of product design and manufacturing process design. At the same time, the valuable knowledge and experiences of product design, manufacturing process design and defect prevention methods are accumulated in the FMEA format (McDermott, 1996, Dale, 1999 and SAE J1739, 2002).

2.2.2. DFMEA and PFMEA

Even though some FMEA derivatives have been developed, such as machinery FMEA, application FMEA and service FMEA, FMEA can be mainly categorized into two types: DFMEA (Design FMEA) and PFMEA (Process FMEA). They are

applied during product design evaluation and manufacturing process assessment separately (Chow, 2003, McDermott, 1996, Pantazopoulos and Tsinopoulos, 2005).

DFMEA is usually implemented by the responsible product designer for product design evaluation, based on customer requirements and relative product specifications. In the process, the functions of product design are analysed, identifying the potential design defects which could make product malfunction against customer requirements and relative specifications. The process also serves the purpose of ranking the effects, occurrence and detection, and finding solutions to eliminate the potential design defects (Dyadem Press, 2003, Chow, 2003, Ford Motor, 2004).

PFMEA is usually employed by the responsible manufacturing engineer for the manufacturing process design assessment. It is used for identifying the latent failure risks which can cause manufacturing processes to fail to manufacture the product and produce the functions of product design, ranking the failures and making improvements to prevent their occurrences. PFMEA cannot rely on the design changes to solve the potential process defects, but design factors should be taken into the PFMEA process, for the manufacturing processes are designed to produce the functions of product design (Chow, 2003, Dale, 1999, and Ford Motor, 1995).

It can be seen that DFMEA and PFMEA are mainly concerned with defect prevention and quality improvement. It is actually a way of using criticism in the product design and manufacturing process design, with the purpose of seeking all latent approaches which might cause product or processes fail, and then eliminating these potential defects in advance.

According to Dyadem Press (2003), this technique is critical to the product quality control in its development stage, as approximately 76 percent of design changes are caused by design deficiencies. This assessment and ranking process can help to prioritize the efforts and resources to deal with these issues.

2.2.3. FMEA procedures

Both DFMEA and PFMEA have similar technical analysis procedures. The whole technical FMEA analysis process can be divided into three main stages, illustrated in Figure 2.1 (Teng and Ho, 1996, Chow, 2003, McDermott, 1996).

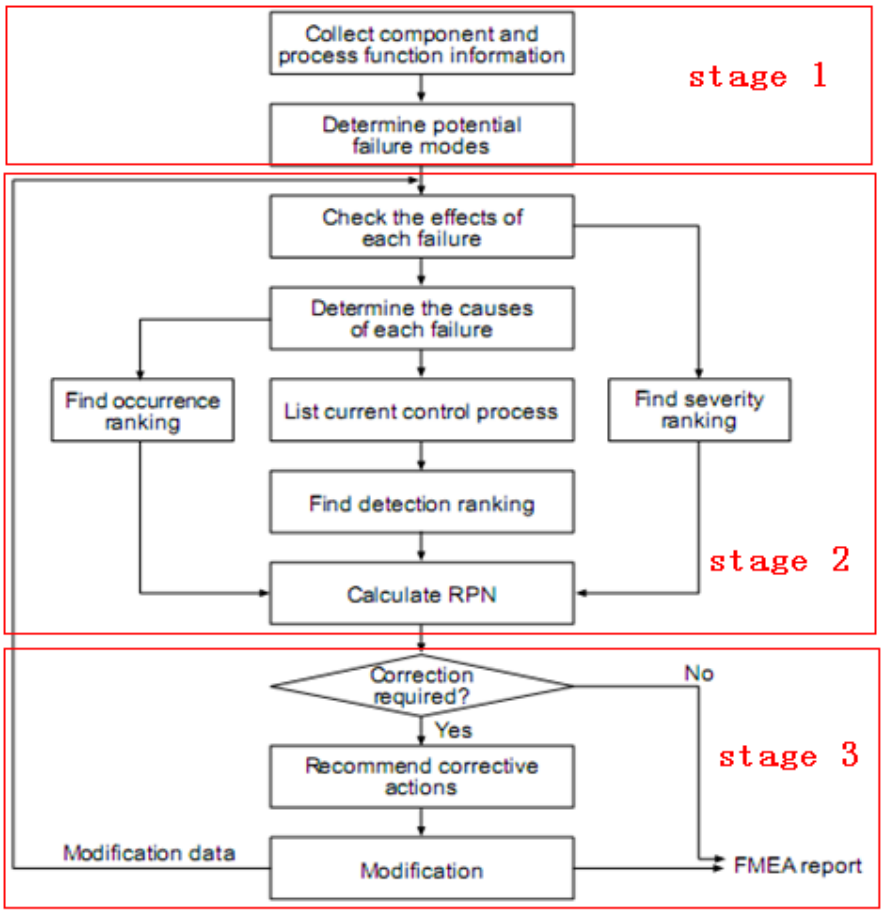

Figure 2.1 Technical analysis procedures (Teng and Ho, 1996)

(1) The first stage: item function and failure mode identification

The major task in stage one is to identify the product functions or process functions and all the potential failures. The product design or manufacturing process design should be reviewed thoroughly; product functions or manufacturing process functions should be listed correctly; the latent failure modes in the product design or manufacturing process design should be identified extensively. The identified failure mode might be the cause of the

failure of top level system or the effect of the failure of the sub-component. For DFMEA, product design is assessed against the customer requirements and relative specifications, capturing the latent failures which can make the design fail to meet customer requirements and relative specifications; the design deficiencies which will cause operation or service failure should also be listed; For PFMEA, manufacturing processes are evaluated to find the potential failures in order to achieve the designed functions and quality standards.

The work in this phase is a process of failure mode collection from all the FMEA team members who are representatives of different areas with high levels of experience of the reviewed product or similar products.

(2) The second stage mainly focuses on the risk evaluation and ranking.

Firstly, list all the effects of each failure, including the impact on the product itself，the internal customers and external customers;

Secondly, examine the severity (S) of each effect, the failure occurrence (O) and detection (D) and assign a reasonable ranking level (from 1 to 10, low to high) to these three measurements;

Finally, calculate the Risk Priority Number RPN (RPN=S×O×P) and rank the RPN as item prioritization for improvement.

In this phase, the root cause of each failure mode should also be analysed thoroughly and listed in the format which can be used for identifying effective solutions to eliminate the potential failures.

(3) The third stage is design modification for improvement.

Effective solutions should be identified based on the root causes listed in the second stage. Then, the recommended actions should be implemented in order to modify the product design or manufacturing process design, with the purpose of eliminating the failures.

In the first and second stages, all the team members should have the same understanding of the customer requirements, product functions, manufacturing process functions and evaluation rules. Thus, internal conflicts and deviations can be avoided throughout the process. Extensive collection of failure modes and ranking of measurements from team members is also crucial, because the experienced team members will have different perspectives. In the third stage, corrective actions should be taken rigorously to eliminate the root causes or mitigate the severity of effect. Accompanying the FMEA process, the FMEA format should be filled out as a collection and repository of FMEA data (Teng and Ho, 1996 and McDermott, 1996).

2.2.4. FMEA templates in widespread applications

The most popular templates for DFMEA and PFMEA are shown in Figure 2.2 and 2.3 separately (Sourced from SAE J1739, 2002, Ford Motor, 2004 and Ford Motor, 1995).

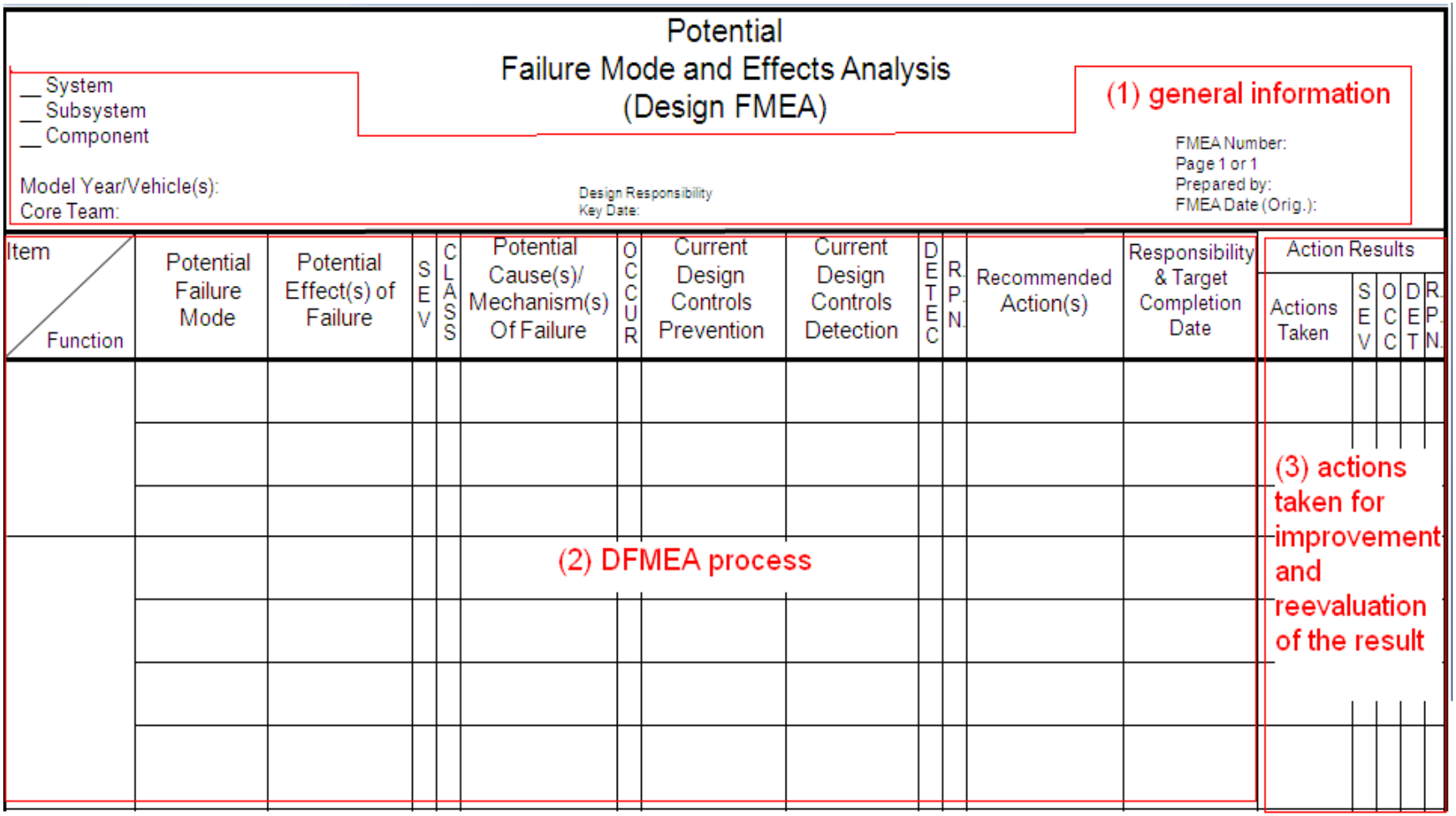

Figure 2.2 DFMEA format

(Sourced from SAE J1739, 2002, Ford Motor, 2004 and Ford Motor, 1995)

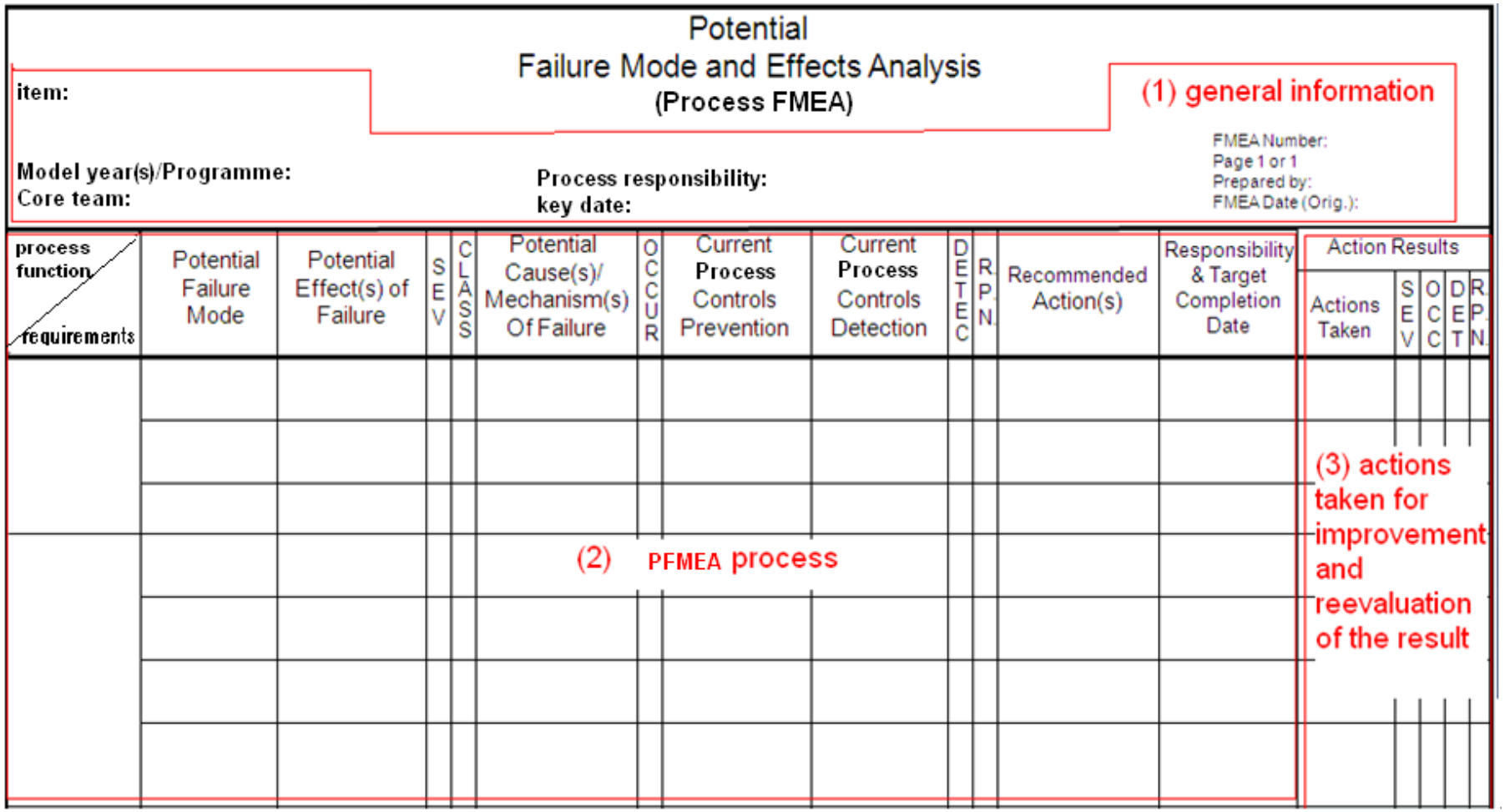

Figure 2.3 PFMEA format

(Sourced from SAE J1739, 2002, Ford Motor, 2004 and Ford Motor, 1995)

(1) DFMEA format

Before introducing the content of the DFMEA format, the customer of DFMEA should be defined clearly. The customers of DFMEA do not only include the ultimate users, but also the responsible design engineers who will use the DFMEA data to improve the product design, the manufacturing engineers as well as service engineers (McDermott, 1996, Ford Motor, 2004 and Ford Motor, 1995).

As shown in Figure 2.2, the information in this format can be divided into three parts: the general information, DFMEA analysis information and re-evaluation of the item after being improved. Usually, the general information is filled out by the product engineer, including the information about the reviewed product, team, designer, date to finish, FMEA No. for tracing and so on; contents for other columns are collected from the team members' contribution. The key terminologies in the format are explained as follows.

a) Item and function: the name, number and concise function description of the item being analysed.
b) Potential failure mode: the manners in which the item can potentially fail to meet the customer requirements and relative specifications.
c) Potential failure effect: all the effects of failure on functions which the customers (include internal as well as external customers) may experience.
d) Severity: the level of impact on the high level component, manufacturing or ultimate users, this being a relative ranking measurement.
e) Classification: used for identifying critical characteristics of product design, which need special control or inspection to ensure safety functions as well as the need to conform to specifications.
f) Potential causes: direct causes of failure.
g) Occurrence: probabilities that the root cause might happen.
h) Current control and detection: identify the method to prevent root causes or reduce the occurrence or detect the root cause or detect the failure modes in design. The detection ranking is lower, when it is easy to detect the failure mode or root cause; and vice versa.

i) Recommended actions: special attention should be paid to items with high RPN or high severity as well as items with critical characteristics, based on the root cause analysis.

j) Actions result: re-evaluate the three measurements and RPN to check if the goals have been achieved after implementing the recommended actions. If yes, the DFMEA report should be documented. Otherwise the FMEA process should be repeated until the primary goal has been achieved.

The recommended severity, occurrence and detection ranking criteria for DFMEA are shown in table 2.1, 2.2 and 2.3 separately.

Effect	Rank	Criteria
None	1	No effect
Very slight	2	Negligible effect on product performance. User not affected.
Slight	3	Slight effect on product performance. Non-vital faults will be noticed most of the time.
Minor	4	Minor effect on product performance. User slightly dissatisfied.
Moderate	5	Reduced performance with gradual performance degradation. User dissatisfied.
Severe	6	Product operable and safe but performance degraded. User dissatisfied
High severity	7	Product performance severely affected. User very dissatisfied.
Very high severity	8	Product inoperable but safe. User very dissatisfied
Extreme severity	9	Product failure resulting in highly probable hazardous effects. Compliance with government regulations in jeopardy.
Maximum severity	10	Product failure resulting in hazardous effects almost certain. Non-compliance with government regulations.

Table 2.1 Recommended severity ranking for DFMEA
(1–10 qualitative scale) (Dyadem press, 2003)

Occurrence	Rank	Criteria
Extremely	1	Failure highly unlikely.
Remote Likelihood	2	Rare number of failures likely.
Very Low Likelihood	3	Very few failures likely.
Low Likelihood	4	Few failures likely.
Moderately Low Likelihood	5	Occasional failures likely.
Medium Likelihood	6	Medium number of failures likely.
Moderately High Likelihood	7	Moderately high number of failures likely
High Likelihood	8	High number of failures likely.
Very High Likelihood	9	Very high number of failures likely.
Extremely Likely	10	Failure almost certain.

Table 2.2 Recommended occurrence ranking for DFMEA

(1–10 qualitative scale) (Dyadem press, 2003)

Detection	Rank	Criteria
Extremely Likely	1	Can be corrected prior to engineering prototype.
Very High Likelihood	2	Can be detected and corrected prior to engineering design release.
High Likelihood	3	Has high effectiveness.
Moderately High Likelihood	4	Has moderately high effectiveness.
Medium Likelihood	5	Has medium effectiveness.
Moderately Low Likelihood	6	Has moderately low effectiveness.
Low Likelihood	7	Has low effectiveness.
Very Low Likelihood	8	Has lowest effectiveness in each applicable category.
Remote Likelihood	9	Is unproven, unreliable or unknown.
Extreme unlikely	10	No design technique available or known, and/or none is planned

Table 2.3 Recommended detection ranking for DFMEA

(1–10 qualitative scale) (Dyadem press, 2003)

(2) PFMEA format

Customers of PFMEA are normally defined as the ultimate users, but downstream affected operators in the production, such as maintenance staff should also be involved.

Similar to the DFMEA format, the information in the PFMEA format illustrated in Figure 2.3 can also be divided into three parts: the general information, PFMEA process information and re-evaluation of the item after its improvement. The relative terminologies are similar to those in the DFMEA format. The general information and the re-evaluation items are almost the same. The distinct and important ones are explained as follows (McDermott, 1996, Ford Motor, 2004 and Ford Motor, 1995).

a) Process function/requirements: simple and concise description of the process and process function being analysed in a measurable manner.
   Note: process function contains both the design and manufacturing process characteristics.
b) Potential failure mode: the manners in which the process can potentially fail to achieve the process function or/and design intent.
c) Potential failure effect: all the failure effects on products, downstream operators, maintenance staff, service staff etc.
d) Severity: the level of effect seriousness on downstream operation or ultimate users.
e) Classification: used for identifying critical characteristics of the process. .
f) Current control and detection: identify the method to prevent root causes, reduce the occurrence or detect the root cause or detect the failure modes in the manufacturing process. The detection ranking of preventive methods is low, whilst the detection method of the failure cause or failure mode is effective.

The recommended severity, occurrence and detection ranking criteria for PFMEA are shown in table 2.4, 2.5 and 2.6 separately.

Effect	Rank	Criteria
None	1	Might be noticeable by the operator (Process). Improbable/not noticeable by the user (Product).
Very slight	2	No downstream effect (Process). Insignificant/negligible effect (Product).
Slight	3	User will probably notice the effect but the effect is slight (Process and product).
Minor	4	Local and/or downstream processes might be affected (Process). User will experience minor negative impact on the product (Product).
Moderate	5	Impacts will be noticeable throughout operations (Process). Reduced performance with gradual performance degradation.
Severe	6	Disruption to downstream process (Process). Product operable and safe but performance degraded. User dissatisfied (Product).
High severity	7	Significant downtime (Process). Product performance severely affected. User very dissatisfied (Product).
Very high severity	8	Significant downtime and major financial impacts (Process). Product inoperable but safe. User very dissatisfied (Product).
Extreme severity	9	Failure resulting in hazardous effects highly probable. Safety and regulatory concerns (Process and Product).
Maximum severity	10	Failure resulting in hazardous effects almost certain. Non- Injury or harm to operating personnel (Process). Compliance with government regulations (Product).

Table 2.4 Recommended severity ranking for PFMEA

(1–10 qualitative scale) (Dyadem press, 2003)

Occurrence	Rank	Criteria
Extremely	1	Failure highly unlikely.
Remote Likelihood	2	Rare number of failures likely.
Very Low Likelihood	3	Very few failures likely.
Low Likelihood	4	Few failures likely.
Moderately Low Likelihood	5	Occasional failures likely.
Medium Likelihood	6	Medium number of failures likely.
Moderately High Likelihood	7	Moderately high number of failures like
High Likelihood	8	High number of failures likely.
Very High Likelihood	9	Very high number of failures likely.
Extremely Likely	10	Failure almost certain.

Table 2.5 Recommended occurrence ranking for PFMEA

(1–10 qualitative scale) (Dyadem press, 2003)

Detection	Rank	Criteria
Extremely Likely	1	Controls will almost certainly detect the existence of the defect.
Very High Likelihood	2	Controls have a very high probability of detecting the existence of failure.
High Likelihood	3	Has high effectiveness for detection.
Moderately High Likelihood	4	Has moderately high effectiveness for detection.
Medium Likelihood	5	Has medium effectiveness for detection.
Moderately Low Likelihood	6	Has moderately low effectiveness for detection.
Low Likelihood	7	Has low effectiveness for detection.
Very Low Likelihood	8	Has lowest effectiveness in each applicable category.
Remote Likelihood	9	Controls have a very low probability of detecting the existence of a defect.
Extreme unlikely	10	Controls will almost certainly not detect the existence of a defect.

Table 2.6 Recommended detection ranking for PFMEA

(1–10 qualitative scale) (Dyadem press, 2003)

The two formats shown in Figure 2.2 and Figure 2.3 are the normal ways to document the FMEA data; one of the most important purposes of FMEA documentation is the reuse of the accumulated information. However, according to Teoh and Case (2004), with the accumulation FMEA data or because of the complexity of the product or process, the number of hardcopies will increase dramatically. Then, it becomes very difficult to find the required information from so many hardcopies. The engineers are usually not willing to spend much time on searching for the useful information from so many hardcopies (Teoh and Case 2004).

However, at the initial stage of the knowledge accumulation, the hard copy formats can be used conveniently and effectively for team-building and knowledge accumulation.

2.2.5. FMEA applications in industries

Historically, FMEA was first developed in the aerospace and defence industry during the 1960s, with the purpose of identifying the defects within the specific system of aerospace products. However, it became known widely after its implementation in the automotive industry in the 1970s. During the 1970s and 1990s, various military and professional society standards, such as Mil-Std 1629 (for ships), SAE J1739 and ARP5580, started to involve the definition of FMEA in their standards. Nowadays, FMEA has been extensively used in various industries, including automotive, food processing, machining, pharmacy, aerospace and others (Bowles, 1998 and Gilchrist, 1993).

FMEA has been proved to be one of the most effective techniques for the continuous enhancement of the product, process or service quality in various industries, particularly in the automotive industry. Correct and full applications of FMEA can benefit the company with the excellent quality and reliability payback, including less frequent design modification, authentic product or service reliability and sustainable improvement with lower manufacturing or service costs, which means more profit (Onodera, 1997, Teng and Ho, 2010, and Palady 1998).

FMEA has been widely employed in the automotive industry for continuous product improvement and to reduce the risk of product recalls. Three major automotive companies (Ford Motors, Chrysler and General Motors Corporation) compile and provide the FMEA reference manual to their suppliers for mandatory FMEA implementation. In the automotive industry, it is demanded that most parts designed are evaluated through FMEA during the product and manufacturing process design. An FMEA report is usually required to accompany the assembly or part design, which will help the engineers to build a sound understanding of the product design and manufacturing processes; then more attention is paid to quality control of critical issues, with great success in incorporating them in the actual product (Ford motors, Chrysler and General Motors Corporation, 1995, Teng and Ho, 1996 and 2006).

FMEA also helps to reduce the risks in medical applications by focusing on patient safety. According to the research of Ookalkar and Joshiand (2009), suitably recommended actions in FMEA analysis can be implemented to reduce the risk occurrence and to improve the controls, thereby reducing risk in the haemodialysis process. Reiling, Knutzen and Stoecklein (2003) also gave a positive comment on FMEA's value in healthcare facility design. It is said that despite of being an effort-consuming and time-consuming risk preventive technique, FMEA is still a valuable method that focuses on patient safety in the facility design process, arousing all relevant people's awareness on patients' safety. ASHRM also applied FMEA for medical risk assessment and elimination (Ookalkar and Joshiand 2009, Reiling, Knutzen and Stoecklein 2003 and ASHRM, 2002).

FMEA is also implemented for risk assessment and prevention in food processing systems as well as the tracing systems. Arvanitoyannis and Varzakas (2009) revealed in their research that FMEA is so useful in the quantitative risk assessment, in prioritizing the risks and taking actions to reduce RPN that the FMEA analysis integration into the ISO 22000 system of the snail production industry is considerably demanded. Bertolini, Bevilacqua, and Massini (2006) found that the integration of FMECA, one derivate of FMEA, into the traceability system analysis in the food supply chain enables the examination and ranking of failures and effects in the traceability system in a quantitative manner which helps to improve the tracing system (Arvanitoyannis and Varzakas, 2009, Ookalkar and Joshiand 2009).

In the aerospace industry, a large amount of researches on FMEA application are also implemented for risk assessment and failure prevention. Hajda (2010) employed FMEA and FMECA for fighter vulnerability assessment; Hasson and Crotty (1997) applied FMEA for commercial airplane functional safety assessment in new designs; Sun carried out FMEA application for aileron control system and All-Flying Tail Control System of a light aircraft in 2001 and 2000 separately; the author regarded FMEA as having considerable effect on product reliability analysis at the early stage of product design; then, the system

reliability can be built into the product after the preventive actions are taken. FMEA was also used to analyse the most serious failures of Legacy Aircraft Wiring and Interconnects by Moffat and Abraham (2008), classifying the failures with highest severity (Hajda, 2010, Hasson and Crotty, 1997, Sun, 2000 and Moffat and Abraham, 2008).

2.3. Best practices of FMEA applications

2.3.1. FMEA best practices identification

Best practice is the technique or method or process designed to achieve the specific goal with high effectiveness and efficiency as well as integrating the concept of continuous improvement whenever there is the possibility for it.

A matrix shown in Table 2.7 is designed to assist identification of the best practices of FMEA applications. This matrix table includes 12 references. Ticks in the table indicate where the relative items are suggested in the listed references.

From the matrix, 7 references of the 12 mentioned timeliness of FMEA applications; while 9 of the references suggested integration of DFMEA and PFMEA or integration of FMEA and quality control plan or system; the importance of proper team members and effective team work were indicated in 11 references; 7 references proposed the importance of sufficient management support in FMEA applications; 8 references emphasised efficient documentation system; 4 papers recommend the supplier involvement; while 5 sixths of the references indicate the thorough analysis in FMEA applications, including product or manufacturing process analysis, reasonable ranking system, rigorous follow-up action implementation and so on; only 2 references make mention of audit functions for FMEA performance improvement.

The following paragraphs will present each of the captured best practices in the matrix for FMEA best practices identification which have been extracted from the references listed in the table.

Best practices / References	Implement FMEA timely	Integrate DFMEA, PFMEA and quality control plan effectively	Assemble proper team members	Effective team work	Sufficient management support	Efficient documentation system	Effective supplier involvement	Through FMEA analysis	Rigorous FMEA auditing
Ford motor, 1995	√	√	√	√	√	√	√	√	
McDermott, 1996	√	√	√	√	√	√		√	√
Teng and Ho, 1996	√	√	√	√				√	
Dale, 1999	√		√	√	√	√		√	
SAE J1739, 2002,	√	√	√	√		√		√	
Chow, 2003		√	√	√		√			
Johnson and Khan, 2003			√	√	√			√	
Dyadem Press, 2003		√	√	√	√	√		√	
Ford motors, 2004	√	√	√	√	√	√	√	√	
IEEE, 2006,	√	√	√	√	√	√	√	√	√
Teng and Ho, 2006							√		
Teng and Ho, 2010		√	√	√				√	
In total	7	9	11	11	7	8	4	10	2

Table 2.7 Matrix table for FMEA best practices identification

(1) Implement FMEA timely

Regarding the timeliness characteristic, the FMEA should be implemented as early as possible in product design and manufacturing process design. It should be finished before the failures of product design or the manufacturing processes have been brought into the field production rather than afterward implementation. The best practice is that the DFMEA should be completed before the final freeze of product design; PFMEA should be finished before the start of the field production.

(2) Integrate DFMEA, PFMEA and quality control plan effectively

DFMEA, PFMEA and quality control should be integrated into the whole quality control system; then, attention can be paid on both product design and manufacturing process design; hence the quality of both product design and manufacturing process design can be controlled properly, the quality of the product itself can be guaranteed; the quality engineer can also ensure that all the potential failures listed in FMEA reports are addressed in the quality control plan, allowing greater control over those potential failures.

(3) Assemble proper team members

FMEA is a team based technique which should assemble a team of knowledgeable individuals, involving different perspectives in the FMEA analysis. Therefore, the appropriate knowledgeable team members should be involved throughout the whole analysis, contributing actively to the FMEA project. It is recommended to have from 4 to 6 engineers covering different areas (e.g. manufacturing, design, service, product, quality, etc.) in the team. The recommended team members for DFMEA and PFMEA should involve but not be limited to those shown in Figure 2.4 and 2.5.

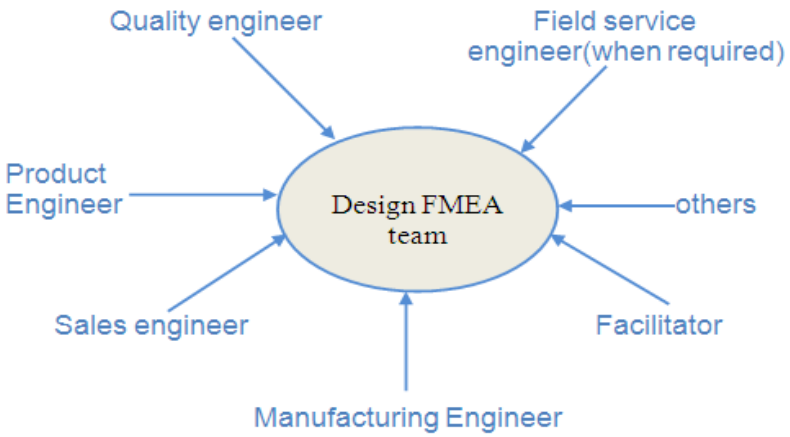

Figure 2.4 Recommended DFMEA team (Dale, 1991)

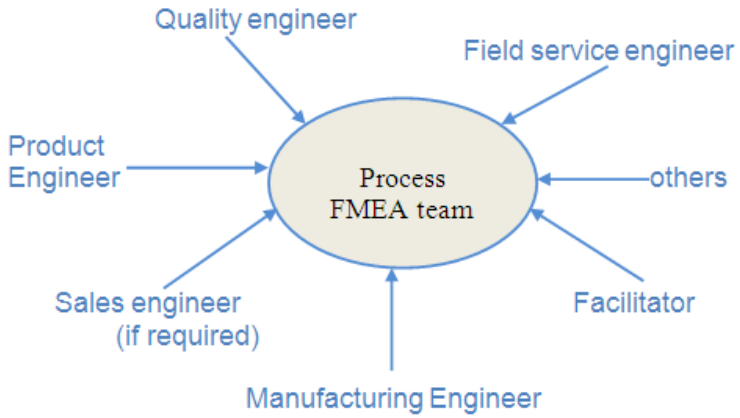

Figure 2.5 Recommended PFMEA team (Dale, 1991)

(4) Effective team work

The effectiveness of the FMEA team work organization is also important to its success. The trained facilitator should have the organisation skills of encouraging participation, discussion control, time management, and so on. Usually, the product engineer is in charge of the DFMEA, whilst the manufacturing engineer is responsible for PFMEA.

(5) Sufficient management support

Should the FMEA team be responsible for recommending correct actions? Should the FMEA team be responsible for monitoring the improving process? Such boundaries as these as well as the roles of members should be

defined and clarified by the management at the beginning of the FMEA project, avoiding deviations and conflicts in analysis afterwards.

Management should also assign the responsible engineer to have the authority to access relevant information or documents, guaranteeing the reasonable required time, resources, expense, etc. for FMEA work.

(6) Efficient documentation system

Documenting the whole process of FMEA provides traceability of the product design, the manufacturing process design and their defects. This allows the staff and management to trace the defects effectively and to pay more attention to defect elimination. At the same time, knowledge and experiences can be accumulated within the organization. However, all product design or manufacturing process design modifications should be monitored afterwards to ensure that FMEA reports reflect the latest situations and thereby trace the design defects and the designs themselves.

(7) Effective supplier involvement

For companies who have their own part or component or system suppliers, the reliability of suppliers' products should be guaranteed to avoid later deficiencies caused by them. Therefore, OEM (Original Equipment Manufacturers) should involve its suppliers in FMEA as an integrated part of its FMEA process system. The principles below should be followed for successful FMEA implementation in supply chain quality management.

a) Consistency of product analysis and ranking rules

All the product parts or systems should be involved in OEM's (Original Equipment Manufacturers) FMEA reports or those of their suppliers. Missing analysis of interfaces may mean missing significant failure prevention. Therefore, the consistency concept in FMEA applications is crucial in the supply chain environment, especially for interface components and systems.

Another important aspect is the consistency of scaling rules for severity, occurrence and detection in the whole FMEA process. Inconsistency of scaling rules will result in different RPN for the same component or system, which will mislead or delay the modification work; hence, the efficiency of FMEA would be much lower.

b) Information share

All the relative information about the products should be shared between the OEMS and suppliers. The FMEA reports should be part of the design packages (drawings, specifications, test requirements etc.) for suppliers. This will aid the understanding of key items which can be integrated into the suppliers' production.

c) Specific and clear language

Languages used in the FMEA report should be detailed rather than vague or too general, ensuring that all affected suppliers can understand the information in the FMEA report correctly. Specific actions can then be implemented at the proper site of production.

(8) Thorough FMEA analysis

Even though FMEA seems to be simple and the procedures in different industries seem to be the same, it cannot be used in a general way. Each step of the FMEA process should be tailored to the specific project.

a) Defining the product or process as well as the scope of FMEA clearly and precisely;

According to IEEE (2006), empirical survey shows that at least 50% of the problems in field production are related to interfaces. To avoid missing the interfaces, it is recommended to include the interfaces in the design diagram blocks or process flow chart. Fully understanding the product or process as well as the scope can avoid deviation from the straight road to the final goal. When defining the product or process, all the parts, components and

systems, especially the interfaces among assemblies or sub-systems should not be missed.

b) Reviewing the functions of product or process thoroughly;

It is crucial to review and describe the product or process functions as concisely and thoroughly as possible, which can ensure that all the team members have the same understanding of the product design or manufacturing processes.

c) Collecting information about failure modes and effects extensively and specifically;

It is important to collect enough information from brainstorming of all team members for DFMEA or PFMEA with the purpose of not missing out any failure modes and effects. The information consists of experiences of similar products and field experience as well as customer expectations.

d) Analysing and scaling severity, occurrence and detection reasonably and consistently, then calculate RPN;

Before doing this work, appropriate rating scales should be established and used consistently throughout the whole project.

e) Identifying the root cause of each failure mode correctly, concisely and specifically;

List the root causes or mechanisms of each failure mode extensively and then identify the major contributor to the failures by analysis or experiment(s). It is crucial to describe the root cause in a specific way without any ambiguous phrases such as ‘operator error’, ‘machine problem’, etc.

f) Taking effective actions on items with high severity or high RPN;

Special attention is needed for items with high RPN or high severity. The purpose of taking the correct actions is to reduce the ranking of any or all of

the three measurements to an acceptable level. This step is crucial to the successful FMEA implementation. Without this step, the FMEA work will be useless.

g) Follow-up monitoring timely

The process of implementing recommended actions should be monitored to ensure that everything goes smoothly. After completion, the RPN re-evaluation is needed to identify whether any further action is needed. The FMEA should always be the reflection of latest situation of the product design or manufacturing process design. Any change of product or process design should be integrated into the FMEA process.

If any of the 7 steps discussed above fails, the efficiency and effectiveness of FMEA in eliminating or mitigating the crucial and significant failures would be much lower.

(9) Rigorous FMEA auditing

Even though only 2 papers mentioned the auditing system, the best practice includes the characteristic of continuous improvement whenever possible. Hence, the auditing system should also be integrated into best practices.

The FMEA process should be checked regularly or randomly by surveying or interviews. The main efforts of audit work should focus on the improvement of the FMEA process. When any improper performance or specification is identified in the audit process, feedback should be provided for improvement. The following aspects should be included.

a) If the current FMEA implementation can improve product design or manufacturing process design effectively;
b) If all the high RPN failure modes are identified correctly;
c) If all the interfaces are included in FMEA process;
d) If the team involves the appropriate members and the team work organisation is efficient and effective;

e) If the FMEA starts timely;
f) If the FMEA process and analysis are all documented properly;
g) If resources and support for the FMEA implementation are easily obtained;

2.3.2. Categorisation of the FMEA best practices

The best practices of FMEA applications identified in this section can be categorised as the follows:

(1) Management awareness and commitment: It is clarified in best practice (4) that sufficient management support should be ensured.

(2) General requirements of FMEA applications: This include when to start, when to finish, who should prepare FMEA, who should be involved, FMEA in quality control system, supplier involvement, standards for ranking, etc. The timely FMEA application, integration of DFMEA, PFMEA and quality control plan, teamwork, as well as supplier involvement are present in the best practice (1), (2), (3) , (4)and (7) separately.

(3) Technical FMEA procedures: The 7 steps for FMEA technical applications are clarified in best practice (8)

(4) Documentation system for easy defect tracing and knowledge accumulation: This part is clarified in best practice (6);

(5) FMEA Audit system for continuous FMEA performance and specification improvement: This is presented in best practice (9).

2.4. Research gap analysis

From the extensive literature review, it can be identified that:

(1) FMEA has been developed for many years and a great deal of researches has been carried out for its effective applications.

(2) Nearly all companies implement DFMEA and PFMEA in an isolated way, focusing on product design and manufacturing process separately.

(3) Several integrated FMEA models are generated, but Teng and Ho (1996) paid more attention to the integration of FMEA within the product quality control system; while Zheng (2010) focused on the integration of the intelligence techniques and knowledge database in FMEA applications.

From the literature review, it seems that no research paper has been published currently supporting the integration of DFMEA and PFMEA, based on the interrelationships of potential failures of product functions and manufacturing processes which are used to produce the functions of product design.

Hence, this project will lead to an integrated FMEA framework which is to inter-relate the potential failures of functions of product design and manufacturing processes. The framework will offer guidance for correct FMEA applications, enhancing product quality control and defect traceability.

3. Research methodology

3.1. Introduction

This chapter focuses on the research methodology, which will be followed step by step to complete the whole project “enhancing product quality control through applications of FMEA”.

3.2. Proposed research methodology

As shown in figure 3.1, the project is divided into 4 phases, with specific tasks and deliverables for each phase.

Phase	Key tasks	Deliverables
1 State of art on FMEA	1.1 Perform literature review to formalize theory foundation. 1.2 Perform research on FMEA applications in industries. 1.3 Synthesise the best practices of FMEA application. 1.4 Research gap analysis	Best practices of FMEA application
2 Field study and gap identification	2.1 Identify the AS-IS product based quality control workflow in the collaborative aerospace company. 2.2 Questionnaire design and application for data collection. 2.3 Data analysis and gap identification.	Identified gap
3 FMEA framework development	3.1 Clarify the interrelations between DFMEA and PFMEA. 3.2 Develop an integrated FMEA framework which ensures the interrelations between DFMEA and PFMEA, enhancing quality control and defect traceability.	Integrated FMEA Framework
4 FMEA framework validation	4.1 Validate the integrated FMEA framework through expert judgement in the collaborative aerospace company	Validated FMEA framework

Figure 3.1 Research Methodology

Phase 1: State of art on FMEA

(1) Develop a sound understanding of the necessity, benefits and theory of FMEA through an extensive literature review of journal papers, conference

papers, books and web articles; thereby establishing a solid theory foundation for the whole project.

(2) Perform research to identify the status of FMEA applications in industries through journal papers and conference papers.

(3) Synthesise the best practices of FMEA based on theory foundation, research on industrial FMEA applications, with the assistance of a matrix table.

(4) The research gap analysis is carried out based on a sound understanding of the relations of quality, product design and manufacturing process design.

Phase 2: Field study and gap identification

(1) Identify the AS-IS quality control process in the collaborative aerospace company through document research and staff interviews.

(2) Design and carry out a questionnaire for data collection, with the purpose of identifying the current FMEA performance and staff views on FMEA applications.

(3) Data analysis for gap identification. This is carried out against the synthesised best practices.

Phase 3: FMEA framework development

Develop an integrated FMEA framework for the collaborative aerospace company, based on the sound understanding of interrelationships between DFMEA and PFMEA, the synthesised best practices of FMEA applications and the gap identified. This framework is to inter-relate the potential failures of functions of product design and manufacturing processes, enhancing the product quality control and traceability of defects and bridging the gap identified in phase 2.

Phase 4: FMEA framework validation

Validate the integrated FMEA framework through the expert judgement within the collaborative aerospace company.

3.3. Time scale

Figure 3.2 illustrates the estimated timescale of the whole project, which can be used to check if the project goes well and each phase is finished on time.

Task Name	Duration	Start
MSc Project	**186 days**	**17 May '10**
Research undestanding and Brief	**16 days**	**17 May '10**
research understanding	9 days	17 May '10
Project aim & objectives	7 days	28 May '10
Literature Review	**37 days**	**08 Jun '10**
Resource search	8 days	08 Jun '10
Literature filter & reading	7 days	17 Jun '10
Draft of literature review	15 days	24 Jun '10
Modification of literature review	7 days	14 Jul '10
AS-IS model in the aerospace company and gap examination	**39 days**	**23 Jul '10**
Collect relative documents in the company	5 days	23 Jul '10
Document research and staff interviews	10 days	30 Jul '10
Identify the AS-IS Model in the company	14 days	11 Aug '10
Gap examination	10 days	31 Aug '10
Framework developmet	**20 days**	**14 Sep '10**
Integrated FMEA framework development	20 days	14 Sep '10
Framework validation	**18 days**	**12 Oct '10**
send the framework to experts in the collabortive company	1 day	12 Oct '10
Explain the framework to experts	2 days	13 Oct '10
Framework discussion and feedback	10 days	22 Oct '10
Thesis writing and presubmission	**42 days**	**05 Nov '10**
Thesis writing	20 days	05 Nov '10
Thesis pre-submission	2 days	03 Dec '10
Thesis modification	20 days	07 Dec '10
Thesis submission	**14 days**	**04 Jan '11**
Viva preparation	12 days	04 Jan '11
Final thesis submission	2 days	20 Jan '11

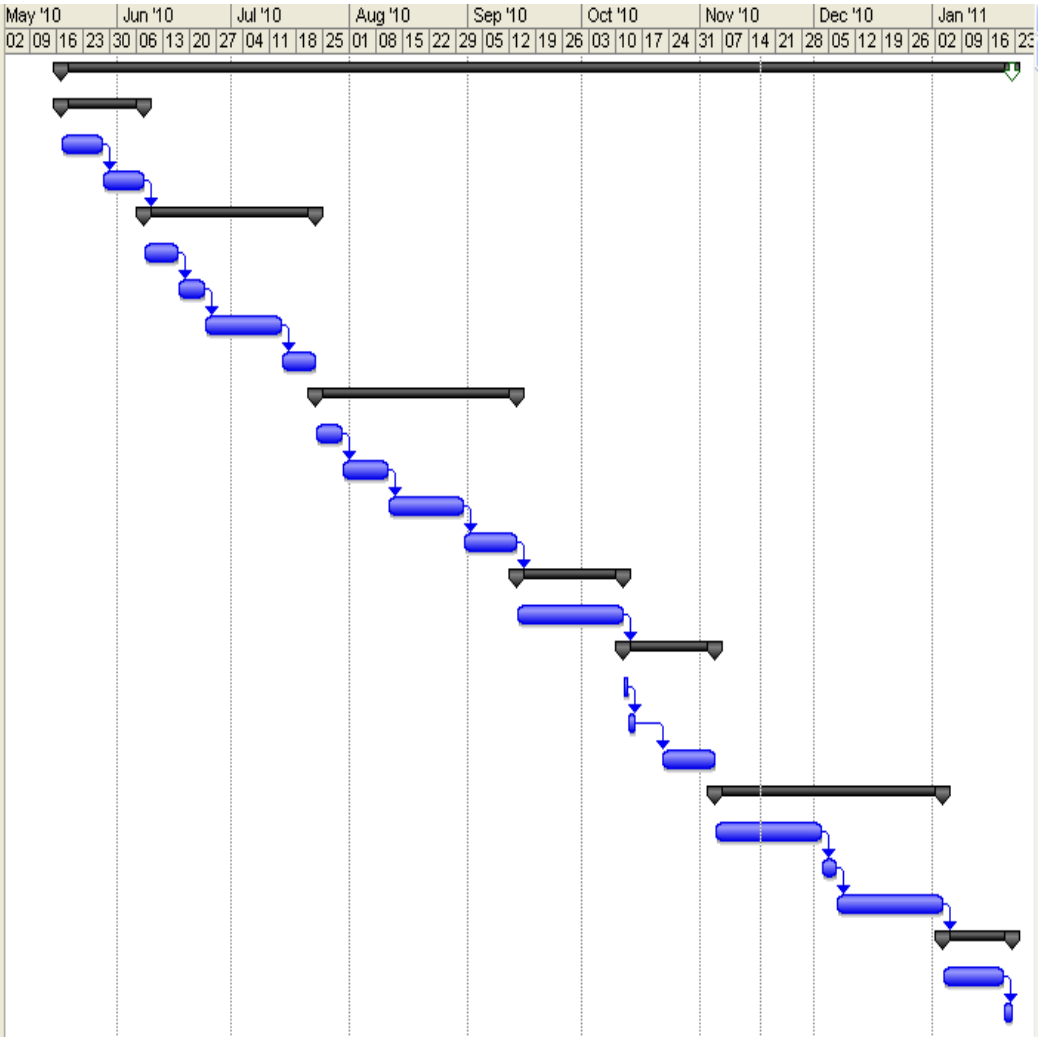

Figure 3.2 Timescale of the project

4. The AS-IS quality control process and gap identification

4.1. Introduction

Firstly, this chapter briefly introduces the quality system in the collaborative aerospace company; it then focuses on document research and staff interviews in the aerospace company, identifying its AS-IS quality control process; a questionnaire is then designed for data collection, based on the AS-IS quality control process, AS-IS quality control process analysis and the synthesised best practices; the questionnaire focuses on identifying the current FMEA application performances; finally, the data analysis is carried out to identify the gap between the AS-IS quality control process and the synthesised best practices of FMEA for afterward improvement.

4.2. Introduction of the quality system of the collaborative company

The quality system is usually based on the scale and the product nature of the company. Information about the scale and product nature is presented in section 1.3.

The current quality system has been in existence in the company for more than ten years. It is mainly based on the AS 9100 (Aerospace Quality Standard) and experience learned from overseas subcontract production. The company has also integrated its product nature, the scale of the company as well as the relative requirements of airworthiness laws into its quality system.

In this company, two quality managers are directly responsible for the general manager regarding product quality in product design and manufacturing systems separately. The quality manager in the manufacturing system is responsible for the quality of product manufacturing; while the quality manager in the design system takes responsibility for the quality of product design.

4.3. The AS-IS product based quality control process and gap identification

Based on the document research and staff interviews in the collaborative aerospace company, the AS-IS product based quality control process from the product design to field production is identified, as illustrated in Figure 4.1.

Before product design is started, the customer requirements should be identified and provided by sales engineers. The customer requirements and relative specifications are transferred to the product designers, with the purpose of enabling the designers to clearly understand the goal of product design.

Product design stage

Whenever the initial product design concepts are determined, the concepts should be reviewed for design feasibility analysis. With the development of the product design, several internal reviews are usually carried out for defect identification, involving the internal experts' experience in defect and solution identification. If there is any defect, the design should be improved, according to the recommended actions documented in the product design review meeting notes. If there seems no defect, the formal product design will be released to manufacturing system for design review and signing.

Manufacturing stage

If any defect is found during the design reviews by the manufacturing engineer, feedback should be provided to the designers for improvement. Otherwise, the manufacturing engineer should sign the design in the computer system for product design release.

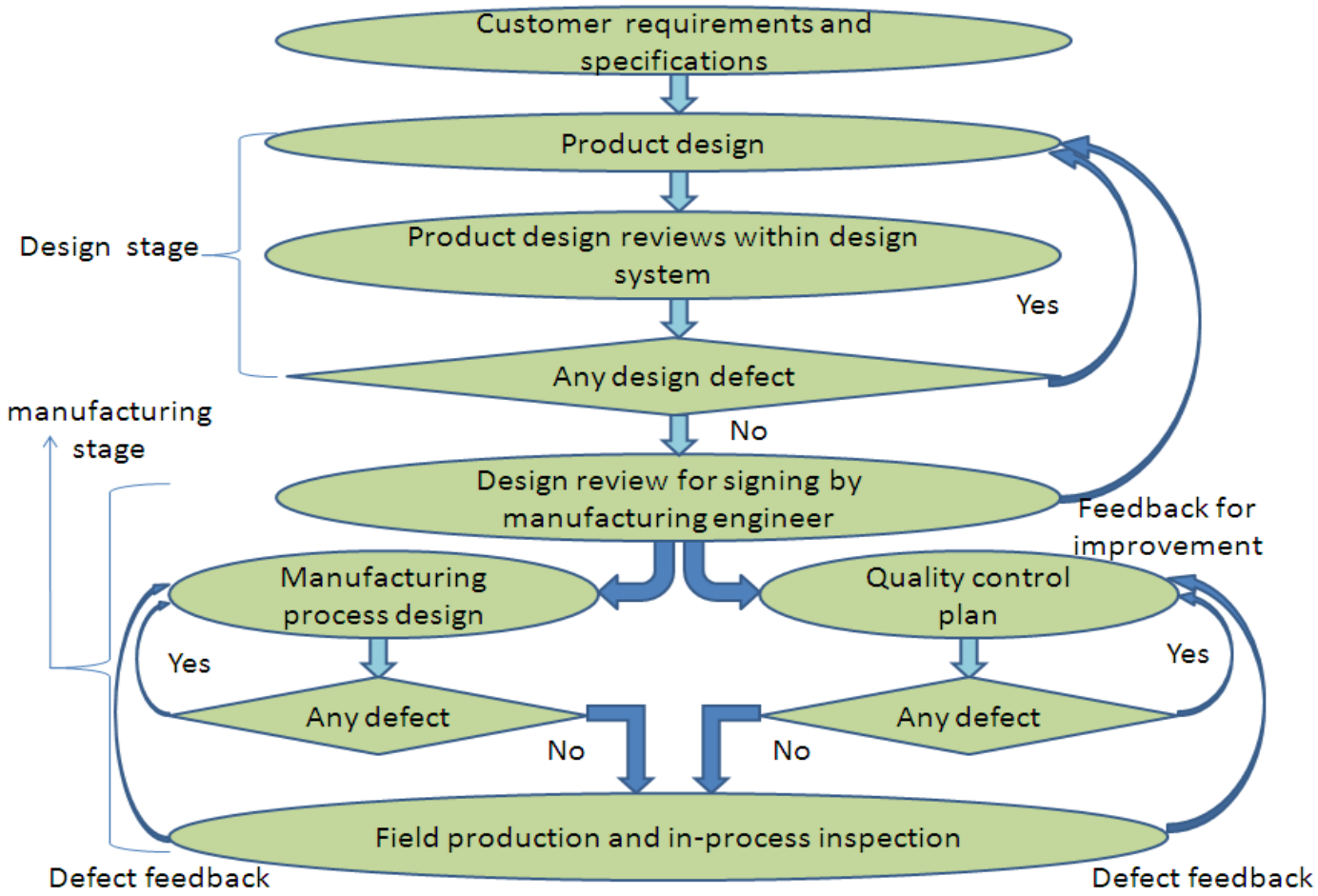

Figure 4.1 The AS-IS product based quality control process

Note: Figure 4.1 is drawn from the quality documents and staff interviews of the collaborative company.

Afterwards, the designed manufacturing processes and quality control plan can be integrated into the field production as guidance for actual operations and in-process inspections. The items required airworthiness visual inspection will be submitted to the relevant airworthiness representatives for visual verification.

If any defect is found in field production, the defect should be returned to the quality department and manufacturing engineer. Root causes and suggested improving actions should be recommended by the quality engineer and manufacturing engineer. Then, the defect record with defect description and the recommended improving actions will be sent to the designer through quality department for approved solutions to the current defect. If the defect is caused by the supplier's product, the defect record should also be sent to the relevant supplier for confirmation, suggested improvement and defect tracing. Monitoring work on these defects will last until the defects are eliminated. The OEM quality department records all the defects found in field production and monitors the improvement process within the company as well as with the suppliers. When the product has gone through all the inspections, the product can finally be delivered to the customer.

From the AS-IS product based quality control workflow and staff interviews, the following problems can be found:

(1) Only the defects found in field production are recorded and documented for tracing through the formal format; while the defects found in product design and manufacturing process reviews are recorded through meeting notes. Because the meeting note is a kind of informal format, not integrating into the rigorous documentation system, it is not always available for the staff within the whole product development. They are also easily lost. Therefore, the functions of documentation and traceability of defects found in planning stages are too weak.

(2) The only involvement of the manufacturing engineer in product design is the design signing before being released. However, the manufacturing engineers are usually required to sign, guaranteeing product design release

to the manufacturing system on time. Hence, the effectiveness of this review is doubtful.

(3) The manufacturing process design is carried out by the manufacturing engineers without any others' involvement. The assessment is implemented based on team work, but without the involvement of the relative designer.

(4) The quality control plan is designed and reviewed by the quality engineer individually, without involvement of any others;

(5) The product design and manufacturing process review work is carried out based on the product development procedures. However, the importance of the reviews are not stressed enough by the management and staff; sometimes the review process is not prepared adequately; sometimes, the staff involved in reviews are too conservative to make contributions and so on.

The first problem reflects that more attention is paid to field production defect documentation and tracing, while defect documentation and traceability functions in reviews are rather weak;

Problem (2) to problem (4) show that the product design, product review, manufacturing process design, manufacturing process assessment and quality control plan process are carried out separately without any integration;

The last problem indicates that the importance and benefits of reviews for defect identification and elimination before integration into production are not fully realised by management and staff.

4.4. Field study questionnaire of FMEA application

Based on the analysis of the AS-IS product based quality control process and the synthesized best practices, a questionnaire is designed carefully and carried out for data collection, identifying the current FMEA application performances in the collaborative aerospace company.

The questionnaire is designed to identify the FMEA awareness, the FMEA performances, and integration of potential failures of functions of product design and manufacturing processes. The staffs' views on FMEA effectiveness and the need to develop an integrated FMEA framework for correct FMEA applications are also collected.

Fifteen questions are involved in the questionnaire. They include various topics of FMEA awareness and applications in the aerospace company. The questions and their topics are shown in Table 4.1.

The FMEA application performances or the engineers' views about FMEA are allocated with ranking from 1 to 5 that means from 'not at all' to 'excellent', comparing with the synthesized best practices. All these questions are designed as semi-closed questions for collecting relative data extensively. This is as shown in question 1.

Question 1: Do you know FMEA and its implementation procedures?

This question is about FMEA terminology awareness and implementation procedures understanding among staffs.

1 Not at all ☐ 2 Slightly ☐ 3 Average ☐ 4 Good ☐ 5 Excellent ☐

Specify the reasons for the answer:

Question 2: Do you think the company has applied DFMEA in its product design and evaluation?

Question 3: Do you think the company has applied PFMEA in manufacturing process design and assessment?

These two questions are designed to check whether the company has started to apply FMEA in its product design, manufacturing process design and their assessments.

Question 4: Do you think FMEA team can gain enough support of time and resources from the management?

This question is designed to identify the management awareness and support for FMEA applications in the aerospace company.

Question 5: Do you think the company can use FMEA systematically and timely?

This is to find if FMEA applications are implemented systematically and timely in the aerospace company.

Question 6: Do you think the product is designed and assessed through DFMEA by the designer individually or basing on team work?

Question 7: Does the manufacturing process is designed and evaluated through PFMEA by the manufacturing engineer individually or basing on team work?

They are designed to check if the product design, manufacturing process design and their reviews are based on individual work or team work.

Question 8: Does the company integrate the potential failures of manufacturing process design with the failures of functions of product design?

This question is used to indicate if the integration of potential failures of the manufacturing process and failures of product functions exists in the collaborative aerospace company.

Question 9: Do you think this company involves its suppliers into relative product design reviews, interface manufacturing process design, defect analysis and elimination?

The answers to question 9 will reveal the supplier involvement in relative product design, interface manufacturing process design, defect analysis and elimination.

Question 10: Do you think the company traces the defect elimination actions effectively, including the suppliers' as well as their own?

It is designed to check if the recommended actions implementation are monitored and traced effectively.

Question 11: Do you think the company has the effective documentation system for defect tracing and knowledge accumulation?

Question 11 is designed to identify the effectiveness of the defects elimination system and the defects documentation system which is also knowledge accumulation and defect tracing system.

Question 12: Do you think FMEA is an effective technique to prevent quality defects in design and manufacturing in advance?

This question is designed to gain the staffs' views on the effectiveness of FMEA with regard to defect prevention in product design and manufacturing process design.

Question 13: Do you think the company has its FMEA audit function?

This question is designed to reveal if the audit function of FMEA performance exists in the collaborative company.

Question 14: Do you think it is necessary to integrate DFMEA, PFMEA and the quality control plan?

Question 15：Do you think it is necessary to develop an integrated FMEA framework for the aerospace company?

The last two questions are designed to obtain the engineers' views on the integration of DFMEA, PFMEA and quality control plan as well as the demand

for an integrated FMEA framework for correct FMEA applications in the aerospace company;

Eight engineers are involved in this questionnaire participation; two manufacturing engineers can reflect the FMEA applications in manufacturing process design; Two quality engineers can express their ideas from the perspective of quality control, two structure designers and two system designers can reveal FMEA applications in the product design system.

Question No.	Questions for data collection	Topic
Q1	Do you know FMEA and implementation procedures?	Awareness of FMEA and its procedures
Q2	Do you think the company has applied DFMEA in its product design evaluation?	DFMEA application
Q3	Do you think the company has applied PFMEA in its manufacturing process design assessment?	PFMEA application
Q4	Do you think FMEA team can gain enough support of time and resources from the management?	Management support
Q5	Do you think the company can use FMEA systematically and timely?	Systematic and timeliness
Q6	Do you think the product is designed and assessed through DFMEA by the designer individually or basing on team work?	Team work in product design and review
Q7	Does the manufacturing process is designed and evaluated through PFMEA by the manufacturing engineer individually or basing on team work?	Team work in manufacturing process design and review
Q8	Does the company integrate the potential failures of manufacturing process design with the failures of functions of product design?	The integration of failures of product functions and failures of manufacturing process
Q9	Do you think this company involves its suppliers into relative product design reviews, interface manufacturing process design, defect analysis and elimination?	Supplier involvement
Q10	Do you think the company traces the defect elimination actions effectively, including the suppliers' as well as their own?	Follow-up actions implementation
Q11	Do you think the company has the effective documentation system for defect tracing and knowledge accumulation?	Documentation system
Q12	Do you think FMEA is an effective technique to prevent quality defects in design and manufacturing in advance?	Effectiveness of FMEA
Q13	Do you think the company has its FMEA audit function?	Audit function
Q14	Do you think it is necessary to integrate DFMEA, PFMEA and quality control plan?	Necessity for integration of FMEA and quality control plan
Q15	Do you think it is necessary to develop an integrated FMEA framework for the aerospace company?	The necessity for FMEA framework

Table 4.1 Questions and topics for data collection

4.5. Data analysis and gap identification

In this part, the collected data is analyzed and compared with the synthesised best practices. The mean ranking values of those topics about FMEA applications in the aerospace company are illustrated in Figure 4.2.

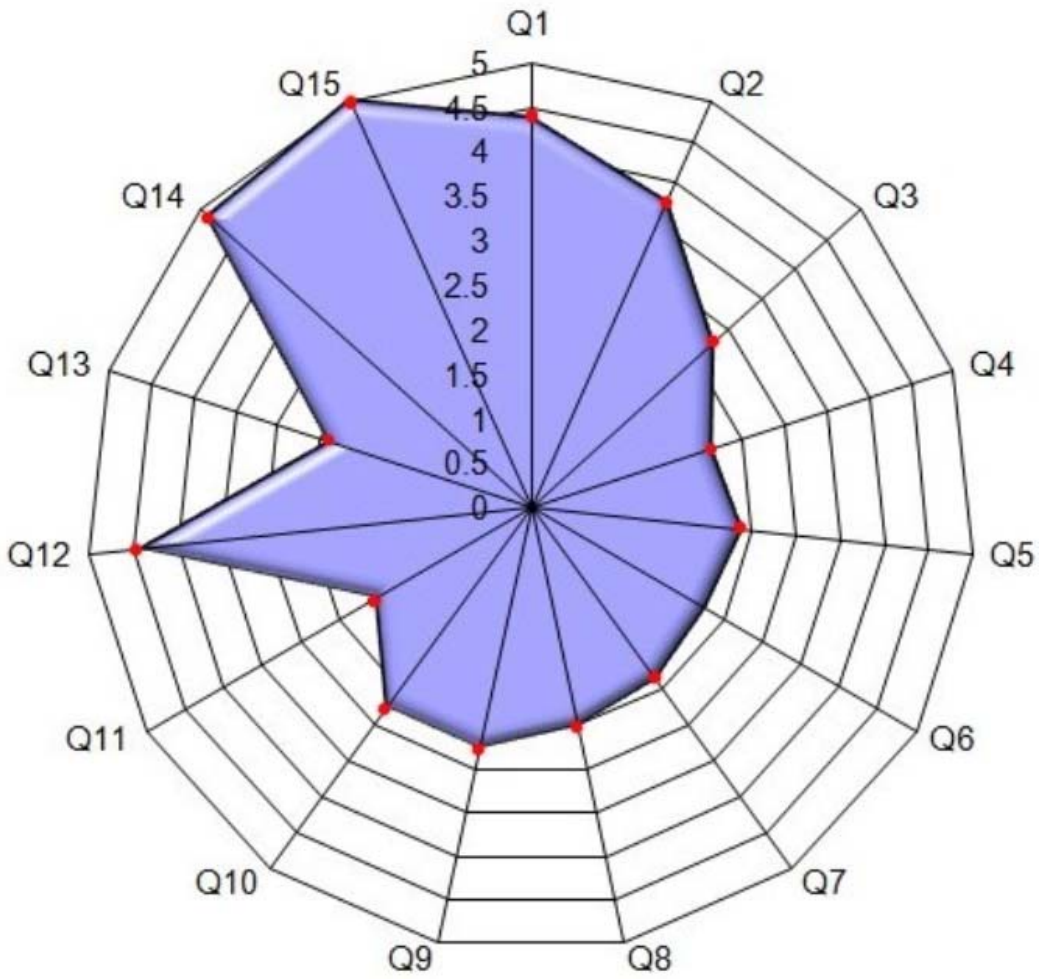

Figure 4.2 Current performance and demand for the FMEA framework

Note: The values indicate FMEA performance against the best practices.

Number 1 stands for very not at all;

Number 2 stands for slightly;

Number 3 stands for average;

Number 4 stands for good;

Number 5 stands for excellent;

It can be seen that only answers to questions 1, 12, 14 and question 15 exceed the ranking number 4. This means that FMEA application performances in the collaborative aerospace company in other aspects require to be improved.

According to the Figure 4.2:

(1) The mean ranking value of answers to question 2 exceeds 3.5, indicating that FMEA being implemented in product design is ‘average’.

Both the system designers consider FMEA application in system design analysis excellent, while structure designers don't think that DFMEA is involved much in the structure design analysis. According to the specific information, it is not a mandatory requirement in the product design process.

(2) Answers to question 3 reveal that FMEA applications in manufacturing process design need to be improved, the ranking number being 2.75.

According to the specific information provided by the engineers, most manufacturing engineers in the aerospace company are new staff with less experience in manufacturing process design. They have no sense about the importance of implementing the preventive quality control concept and eliminating the potential defects in manufacturing process design in advance. Hence, the FMEA applications in manufacturing process need to be improved.

(3) The mean ranking value of the answers to question 4 is between 2 and 3, illustrating that not enough management support is provided in the aerospace company.

The engineers consider that this might be caused by lack of awareness of the importance of the concept of preventive quality control as well as the benefits which can be gained through effective FMEA applications at management level.

(4) Question 5 reveals that FMEA application in the company is not systematic way, the performance ranks between 2 and 3.

The usage of the preventive quality control concept of FMEA mainly depends on the engineers themselves and their experiences and sense of responsibility. If the engineers understand the importance of preventing defects in advance, more attention is likely to be paid to controlling the critical items. If not, critical things might be treated as normal. As no specification has been established for its mandatory application during the product design and manufacturing process design; nobody knows how to use this concept correctly and effectively.

(5) Responses to question 6 and 7 rank between 2 and 3. This shows that DFMEA and PFMEA are implemented based on individual rather than the team work.

Product designers and manufacturing engineers are not integrated together in product design and manufacturing process design or evaluations; Even though the manufacturing engineers review on the product design before signing on drawings, they are usually forced to finish the review and signing of all the drawings within one period in order to release the design on time. The review work is also based solely on the manufacturing engineer's own understanding. The manufacturing process design and quality control plan are also carried out separately without the involvement of product designers, just being reviewed within manufacturing system.

(6) According to the answers to question 8, it is ranked as 2.5. The ranking value indicates that the integration of potential failures of functions of product design and manufacturing process is not realised in the aerospace company. This means separate applications of DFMEA and PFMEA.

(7) Both mean ranking value of answers to question 9 and question 10 are 2.75 the former one means that the involvement of suppliers is not effective, while the latter means that the company do not trace defect effectively.

Based on the responses of these two questions, the suppliers are involved in relative design reviews, because the relative product designs are

reviewed and signed by suppliers; they are also involved in relative interface manufacturing process design; despite the suppliers' involvement in defect tracing and elimination, the recommended actions are not likely to be monitored and implemented rigorously. Hence, effectiveness for improvement is reduced greatly;

(8) Just three responses to question 11 are ranked as 'average'. The rest are bad or very bad. This reveals that FMEA performance documentation system appears 'bad' in this company.

Effective documentation system in FMEA application is used as a defect tracing system as well as an accumulation system is for knowledge and experience. Without this, effectiveness and benefits of FMEA will be greatly reduced.

The specific information indicates that the company has a rigorous defect documentation system for the field production, but it doesn't cover the defects which are found in the planning stage. Sometimes, thee defects are not paid enough attention to be eliminated and would be missed. This will cause afterward problems in the field production.

(9) Question 13 reveals that the company doesn't have an effective audit system.

Even though the FMEA application performance in the aerospace company is not well, answers to question 1 indicate that FMEA has gained a high rate of awareness among the staff in the company; the replies to question 12 indicate the staffs' positive beliefs regarding FMEA application effectiveness with regard to risk prevention and product quality enhancement; question 14 reveals that the staffs' belief on the necessity of integration of DFMEA, PFMEA and quality control plan; the last question reveals the urgent demand for an integrated FMEA framework to guide the company to apply FMEA correctly and effectively, enhancing its product quality control.

4.6. Summary of the identified gap

Based on the data analysis as well as AS-IS product based quality control workflow analysis, the gaps between the AS-IS quality control process and the best practices can be summarised as follows:

(1) It is not applied in a systematic and correct way, and it is not a mandatory requirement in this aerospace company;
(2) Product design, manufacturing design and reviews are carried out without integration;
(3) Management support is not sufficient;
(4) Supplier involvement is not effective;
(5) Recommended actions are followed up ineffectively;
(6) Effective documentation and experience accumulation system doesn't exist;
(7) No effective audit system for checking FMEA application performance exists.

The gaps identified in this section can also be categorised as follows:

(1) Management support: it is clarified in gap (3) that management support is not enough;

(2) System for systematic FMEA applications: these are presented in gap (1), (2) and (4). FMEA is not implemented systematically and mandatorily, and requires effective involvement of suppliers and integration of interrelationships between DFMEA and PFMEA;

(3) Technical procedures: this is shown in gap (5), this means that technical procedure is not implemented well;

(4) Documentation system: This is presented in gap (6).

(5) Audit system: This is presented in gap (7).

5. FMEA framework development

5.1. Introduction

This chapter mainly focuses on the integrated FMEA framework generation. The interrelationships between DFMEA and PFMEA are presented firstly. The close relations of potential failures of functions of product design and potential failures of manufacturing processes are emphasised. An example is then provided to illustrate the concept of integration. Following that, an integrated FMEA framework designed to interrelate and provide traceability of potential failures of functions of product design and manufacturing processes is developed, bridging the gap identified in chapter 4. This framework is to be used for guiding correct FMEA applications in the collaborative aerospace company, enhancing its product quality control. The best practices of FMEA implementation are also used to support the framework generation.

5.2. The interrelationships between DFMEA and PFMEA

As presented in section 2.4, FMEA has been implemented in companies widely and researches are carried out to support its effective applications. However, the integration of DFMEA and PFMEA is not developed well.

Based on a sound understanding of product quality, product design and manufacturing process design, DFMEA and PFMEA should be integrated for defect prevention and product quality improvement. The integration is based on the close links of potential failures of functions of product design and manufacturing processes.

5.2.1. Close links of potential failures of functions of product design and manufacturing processes

As shown in Figure 5.1, the whole process of product planning can be divided into 4 stages: product design, product design evaluation, manufacturing process design and manufacturing process assessment.

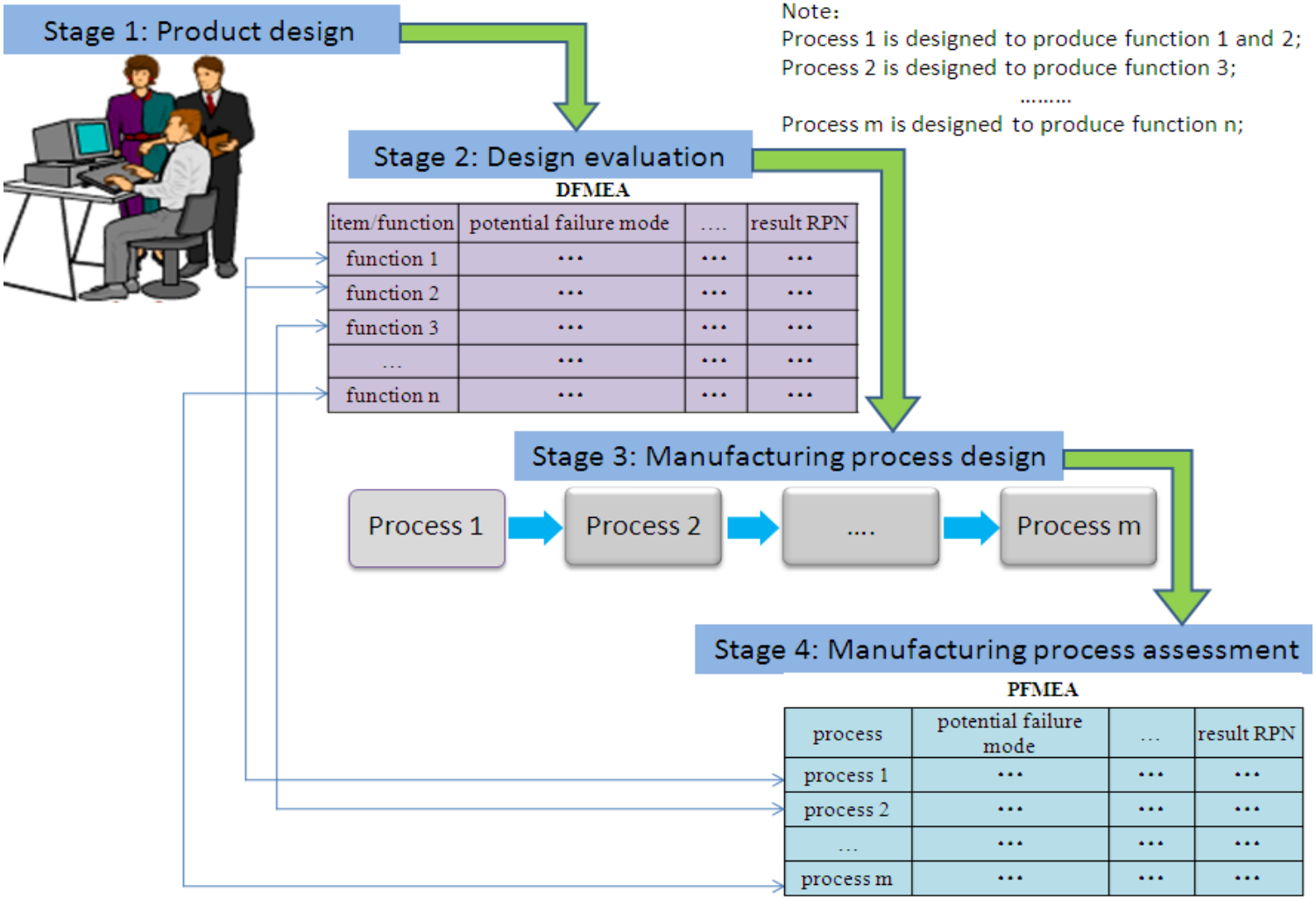

Figure 5.1 Interrelationships between DFMEA and PFMEA

Stage 1: Product design stage

Product designers produce engineering solutions based on customer requirements and relative specifications.

Stage 2: DFMEA (product design evaluation)

The product design can be passed to the DFMEA team for design evaluation at different stages which include conceptual design, preliminary design, detail design. This earlier the DFMEA is launched, the easier the design modifications can be implemented. This can avoid the resources waste caused by afterward modifications.

The functions of product design and potential failures of functions which are caused by improper design should be listed in the DFMEA report. If the severity ranking or RPN is high, the item should be returned to designers for further improvement. Otherwise, product design as well as DFMEA report should be transmitted to stage 3 for manufacturing process design.

Stage 3: Manufacturing process design

Manufacturing processes should be designed to achieve the functions of product design which are listed in the DFMEA report. As shown in Figure 5.1, process 1 is designed to produce function 1 and function 2; process 2 is designed to produce function 3; while function n can be produced through the manufacturing process m, and so on.

Stage 4: PFMEA (manufacturing process assessment)

The manufacturing processes should be assessed through PFMEA, identifying any potential failure in the process which might cause product function failure. Whenever the specific process fails, it will fail to produce the related function of product design. This means poor product quality. If there seems no defect, the product design and manufacturing processes should be released to field production.

Only if the potential failures of functions of product design and manufacturing process are integrated in FMEA applications, the product manufacturability in product design and the manufacturing process design can be analysed thoroughly and the defect prevention can be efficient. This increases the effectiveness of product quality control in product design and manufacturing process design.

Effective integration in FMEA applications can be established through the following three ways:

(1) Involve the manufacturing engineer into the DFMEA process.

When the design review is carried out with the manufacturing engineer involved, the feedback on manufacturability as well as effective recommended actions for improvement can be provided based on their experience from field production. Another advantage of involving the manufacturing engineer within design reviews and DFMEA is that it enables them to understand the design intent, product functions and critical issues correctly in advance. They can then plan their manufacturing process earlier. All these plans are designed on papers or in computer systems without any waste of resources, while the potential problems can be found as early as possible.

(2) Release the product design accompanying DFMEA report, which lists functions of product design as part of input of the manufacturing process design.

When the functions are analysed and identified in DFMEA, they should be released to the manufacturing system to allow them to be integrated into the manufacturing process design. As these functions are transferred in a formal way rather than mouth to mouth, the designer is more likely to treat them seriously. The manufacturing engineers, especially the new ones, can also understand the design intent and functions of product design correctly. Then the manufacturing process can be designed properly and effectively.

(3) Involve the product designer and the links of potential failures of functions of product design and manufacturing processes within the manufacturing process design and PFMEA process

During the manufacturing process design, all the functions of product design should be involved. Involvement of the product designer can help to verify if the product design is understood thoroughly and the manufacturing processes are designed to produce the functions effectively.

The potential failures caused by improper product design can be returned to designers directly without delay. As the potential failures of manufacturing processes caused by product design cannot usually be eliminated through manufacturing process improvement, these problems should be analysed and fully understood in the analysis by the product designer. Then he/she can improve the product design effectively, based on the recommended method in PFMEA.

If DFMEA and PFMEA are integrated in the way described in Figure 5.1, the product design quality control and manufacturing process design quality could be controlled effectively, enhancing the ultimate product quality.

5.2.2. Case study of the interrelationships of DFMEA and PFMEA

A simple example of aerospace flange is used to illustrate the close links between potential failures of functions of product design and manufacturing processes clarified in Figure 5.1.

Stage 1: product design

The flange is an aerospace part being fixed on the spar for fixing and holding the system pipe. The product design is shown in Figure 5.2.

Stage 2: DFMEA

Based on the part design, DFMEA is implemented to identify the functions of product design as well as the potential failures which might cause failure in the fixing to the spar and holding the system pipe in the current design.

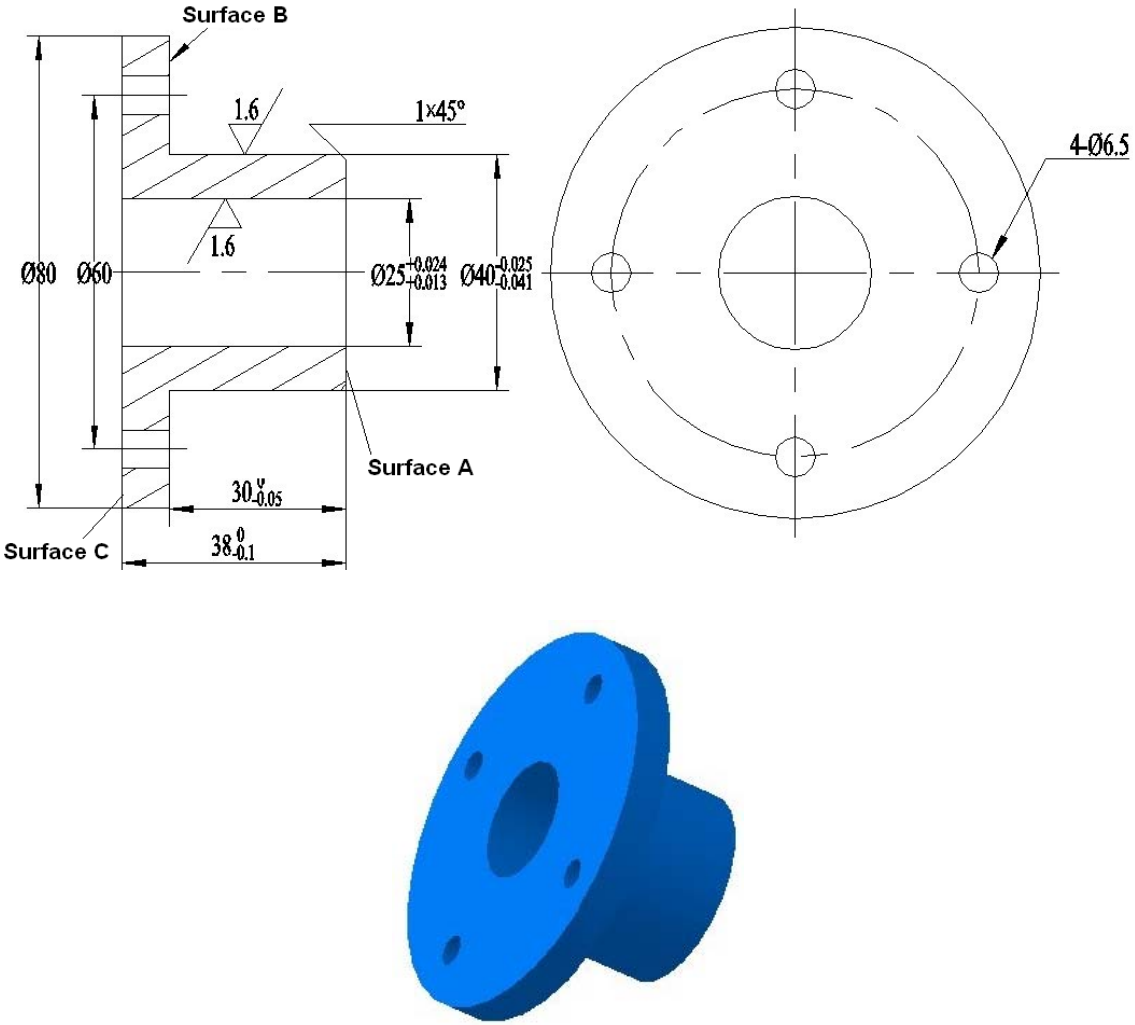

Figure 5.2 Flange used in the aerospace company

The dimensions in Figure 5.2 are in mm.

Note: The design requirements for this flange are as follows:

a) The material is 45# steel;

b) Quenching-tempering the material to HRC 28-32°;

c) Undefined surface smoothness is 3.2;

d) Surface blueing;

The function of product design are analysed and listed in DFMEA format which is shown in Table 5.1:

Function 1: The ex-circle with diameter of 40 mm is to clearance fit with the hole in the spar;

Function 2: The inside bore with a diameter of 25 mm is to hold and fix the system pipe;

Function 3: Surface B will get in touch with the spar;

Function 4: Surface C will get in touch with the bolt heads;

Function 5: 4 small holes with diameter of 6.5 mm are used to install the bolts connecting the flange to the spar;

Function 6: Material treatment will help to adjust the material to a suitable condition;

Function 7: Surface blueing can be carried out for gaining an oxide layer which can protect the part surface from being eroded.

Function 8: Surface A is the end surface, without any special function;

As shown in Table 5.1, just the function 2 (the inside bore with a diameter of 25 mm) is analysed through DFMEA. Based on the listed function of holding and fixing the system pipe, one potential failure is identified. The inside bore is designed without a step for locating the system pipe position. There is also no prevention or detection method in the current product design. Then, the pipe will be located in different positions in different airplanes. Despite the moderate severity (this might cause improper pipe installation) and detection, the defect occurrence and RPN are really high. The recommended action is to design a step in the inside bore for locating the pipe position accurately. Thereby, the product design is improved, preventing improper pipe installation.

POTENTIAL FAILURE MODE AND EFFECTS ANALYSIS (DESIGN FMEA)										
item/function	potential failure mode	effects of potential failure	sev	class	potential cause(s)/ mechanism(s) of failure	occur	current design control	detec	RPN	recommended action(s)
Function 1: the ex-circle with a diameter of 40mm is to clearance fit with the hole in the spar	……..	…..	…	…..	…..	…	…..	…	…..	…
Function 2: inside bore with a diameter of 25 mm is to hold and fix the system pipe	The pipe position cannot be fixed and will move around	Cannot find right relative position of pipe for assembly	6	none	No locator step to locate system pipe position	9	none	8	432	Improve part design through adding locate step
Function 3: surface B will get in touch with the spar	……	……	…	…	……	…	……	…	……	…
Function 4: surface C will get in touch with the spar and bolts heads separately	……	……	…	…	……	…	……	…	……	…
Function 5: 4 holes with diameter of 6.5 mm are to fix the part to the spar through four bolts	……	……	…	…	……	…	……	…	……	…
Function 6: suitable material condition which comes from material treatment										
Function 7: oxide coating which comes from surface blueing	…….	…….	…	…….	…….	…	…….	…	…….	…
Function 8： Surface A is end surface without special function	…….	……	…	……	……	…	……	…	……	…

Table 5.1 DFMEA of Flange

Stage 3: Manufacturing process design

After the final product design and DFMEA report are released to the manufacturing system, the manufacturing processes are designed, linking with the functions listed in DFMEA. The manufacturing process flowchart is shown in Figure 5.3.

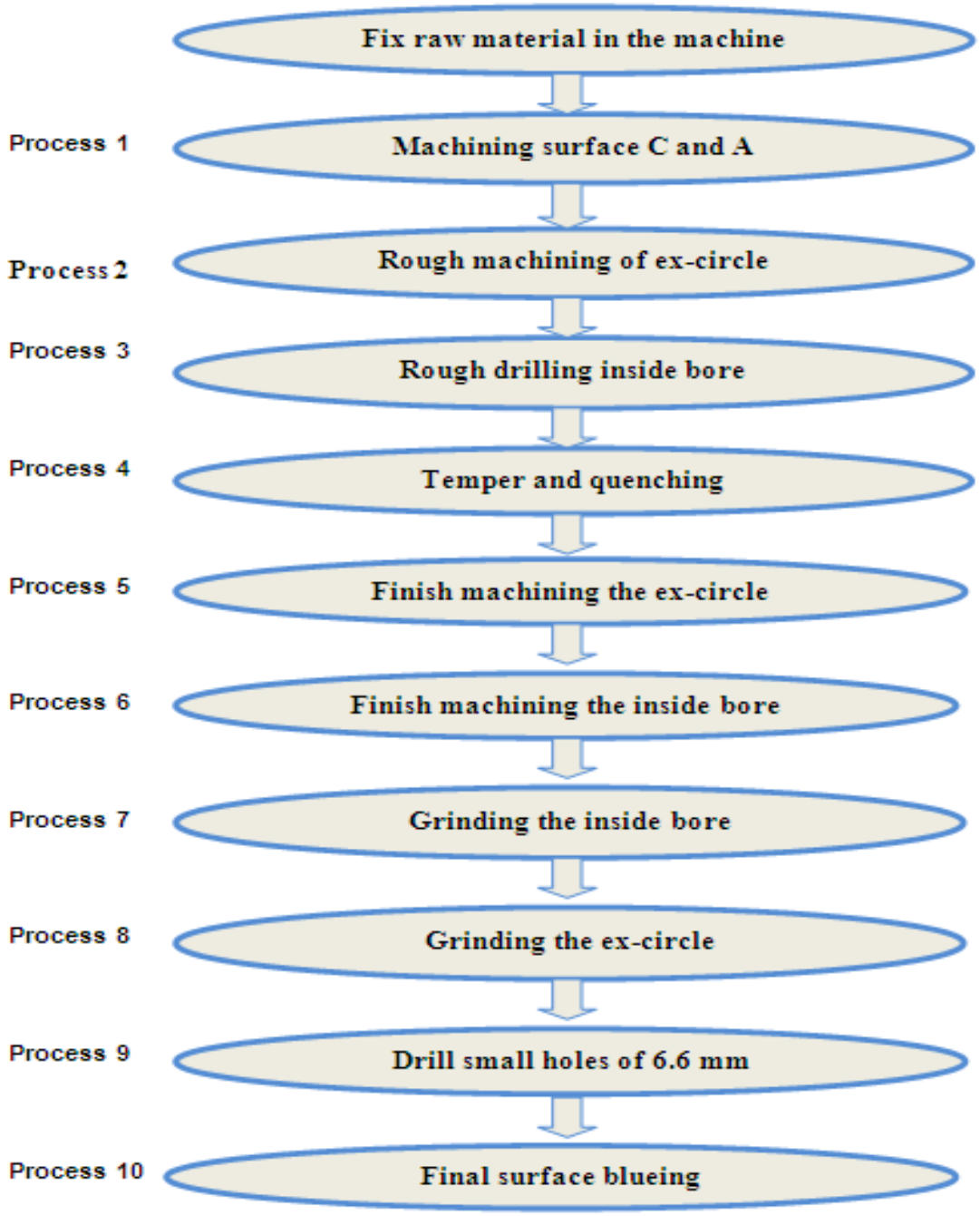

Figure 5.3 Flange manufacturing process flowchart

Process 1(machining the surface A and C) is to achieve the designed function 4 (surface C to contact with bolt heads) and function 8 (end surface A);

Process 2(rough machining ex-circle), process 5 (finish machining ex-circle) and process 8 (grinding ex-circle) are designed to obtain the designed function 1 (ex-circle); function 3 (surface B) can also be obtained at the same time;

Process 3 (rough drilling inside-bore), process 6 (finish drilling inside-bore) and process 7 (grinding inside-bore) are designed to gain the designed function 2 (inside bore);

Process 9 (drill small holes) is designed to make function 5 (4 holes for flange assembly);

The function 6 (suitable material condition) can be completed through process 4 (material temper and quenching);

The design function 7 (oxide coating) can be acquired by implementing process 10 (Surface blueing).

If one of the processes fails, it fails to produce the relevant designed function(s).

Stage 4: PFMEA

The manufacturing processes designed in stage 3 should be evaluated through PFMEA, checking that if the part manufacturing processes are adequate to achieve the functions of flange design. PFMEA is implemented for identifying the potential failures in manufacture the functions listed in DFMEA. As shown in Table 5.3, only manufacturing process 1 and 9 are analysed. Two potential failures of the manufacturing processes are identified. One is the perpendicular position of surface B and surface C to the central axis. The other one is the positions of the assembly holes for inter-changeability. The recommended actions for improving the manufacturing process are provided in PFMEA of Flange.

POTENTIAL FAILURE MODE AND EFFECTS ANALYSIS (PROCESS FMEA)										
process function and requirements	potential failure mode	potential effects of failure	S e v	class	potential cause(s)/ mechanism(s) of failure	occur	current design control	Detec	R. P. N.	recommended action(s)
process 1 is to manufacturing surface C to contact with bolt heads; surface A is made just as end surface	Surfaces are not perpendicular to central axis of hole	Cannot contact to the spar surface and bolt head rightly	8	key	Raw material fix is not right because of broken locator of the machine	5	none	5	200	Check locator regularly and check the perpendicular before machining
Process 2, 5 and 8 are to manufacture ex-circle of 40 mm as well as the surface B which will contact with the spar	……..	…..	…	…..	…..	…	…..	…	…..	…
Process 3, 6 and 7 are to fabricate inside-bore to fix hold pipe	……	……	…	…	……	…	……	…	… …	…
process 9 is to make 4 holes of 6.5 mm for assembly	Distances of holes are not correct	Have no inter-changeability	7	critical	Drill the holes manually	8	none	7	392	Use hole template for ensuring the hole positions
Material temper and quenching, is completed through process 4 to adjust material situation;	…….	…….	…	…….	…….	…	…….	…	… ….	…
Surface blueing can be acquired by implementing process 10	…….	……	…	……	……	…	……	…	… …	…

Table 5.2 PFMEA of Flange

After improving the manufacturing processes, the final product design, the final manufacturing process should be released to field production. If any defects are found in field production, they should be recorded and released to product design system and manufacturing process design system for future improvement. These processes should be followed rigorously.

5.3. Method to develop the integrated FMEA framework

Combining the categorisation of the best practices in section 2.3.2 and gaps categorisation in section 4.6 as well as the interrelationships between DFMEA and PFMEA, the following 2 items are needed to be integrated in the FMEA framework for setting up the FMEA application system:

(1) Management awareness and commitment;

Only if the management are aware of the importance, benefits and crucial elements of effective FMEA applications, the resources for FMEA could then be guaranteed; otherwise, it is impossible for the staff to launch FMEA effectively and correctly.

(2) FMEA application system should be established, which should include general requirements, technical procedures, documentation system and audit system;

As one of the effective quality control techniques, FMEA should be integrated into the AS-IS quality control process for mandatory and systematic application. The interrelationships between DFMEA and PFMEA should be emphasised, which means integration of DFMEA and PFMEA. This work can be completed through new quality control workflow design.

The FMEA preparation, FMEA procedures and ranking rules should be standardised, enabling all staff to follow rigorously;

The documentation system should be generated for easy defect tracing and effective knowledge accumulation;

The audit system should also be designed to run for FMEA performance and specification improvement.

After setting up the FMEA application system, the following work is also crucial to allow correct and effective FMEA applications.

(1) Staff and facilitator training should be launched.

This is to raise staff awareness of the importance and benefits of FMEA; the most important purpose is that staff can understand the FMEA preparation requirements and technical procedures as well as the ranking rules correctly; while the facilitators can gain the facilitation techniques for effective teamwork organisation. Only if the staffs have a thorough understanding, can FMEA applications and teamwork be run smoothly.

(2) FMEA implementation

Only if FMEA is applied in the product design and manufacturing process design evaluation, can the potential failures be found and eliminated for quality improvement. Otherwise, the FMEA system means nothing with regard to quality control and improvement.

(3) FMEA performance and specification auditing

FMEA implementation performance and specifications should be audited for continuous improvement. Otherwise, no one knows if the FMEA performances and specifications are effective or not.

As discussed above, the framework should involve 5 main parts: management awareness and commitment, FMEA application system establishment, staff training, FMEA implementation and FMEA auditing.

5.4. FMEA framework development

The integrated FMEA framework developed for the aerospace company are shown in Figure 5.4. The framework can be divided into 5 parts which stand for 5 stages for applying FMEA in the aerospace company. They are as follows:

Part 1: Management awareness and commitment on FMEA applications;

Part 2: FMEA application system establishment;

Part 3: Staff training on FMEA applications and facilitation techniques;

Part 4: FMEA implementation;

Part 5: FMEA performance and specification auditing.

Stage 1 Management awareness and commitment on FMEA applications

In this stage, the management commitment should be set up. The management level should understand the benefits of effective FMEA applications, key elements for successful FMEA applications and the management responsibility in implementing FMEA applications thoroughly. Only if they understand these well, will management be willing to commit to effective FMEA applications. The required time, expense, access to relative documents and other resources can then be guaranteed.

This part can be completed through providing training courses at management level. The training courses should mainly focus on the importance and benefits of effective FMEA applications, key elements for successful FMEA and the management responsibility in FMEA applications.

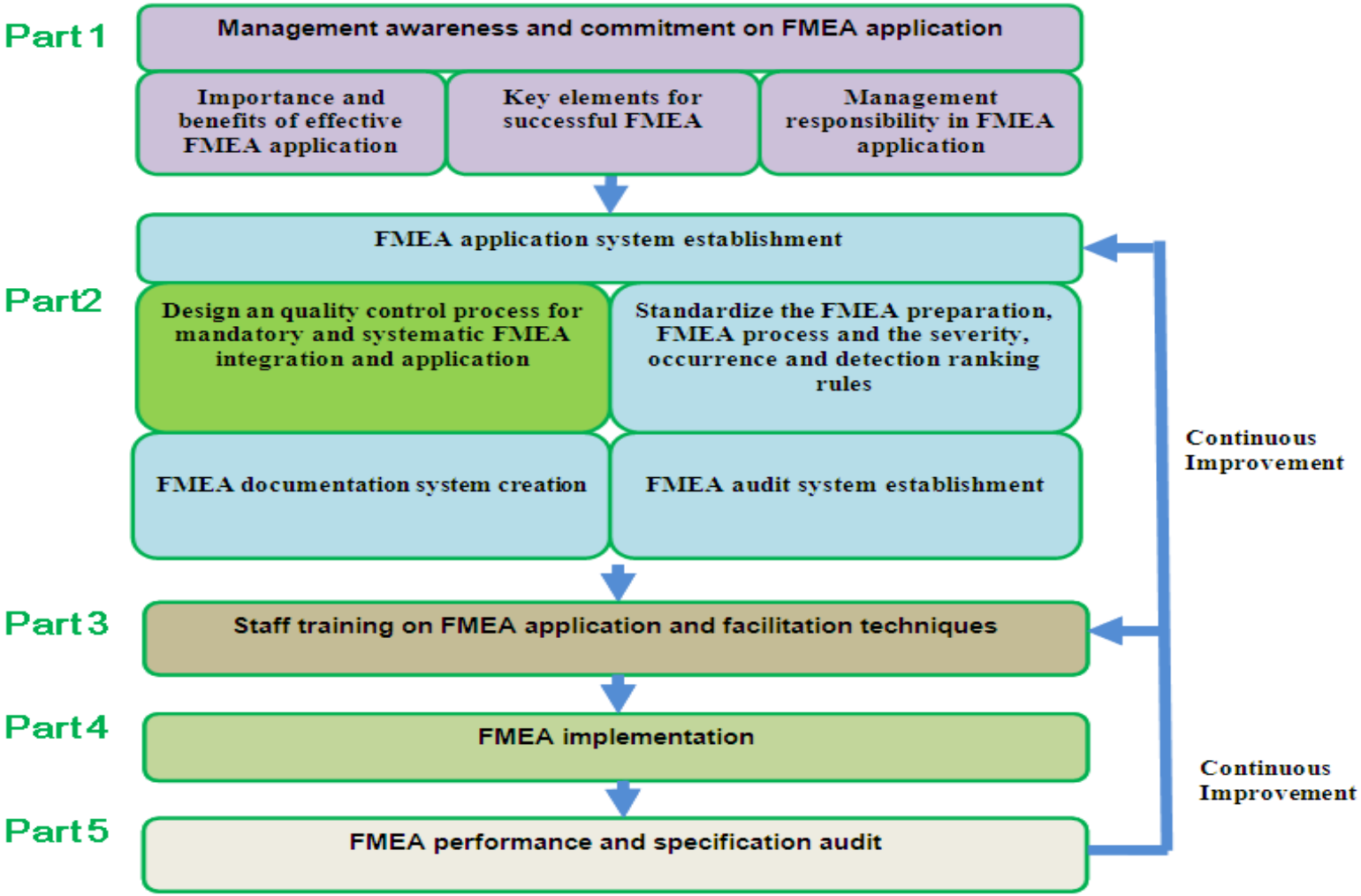

Figure 5.4 Integrated FMEA framework for the aerospace company

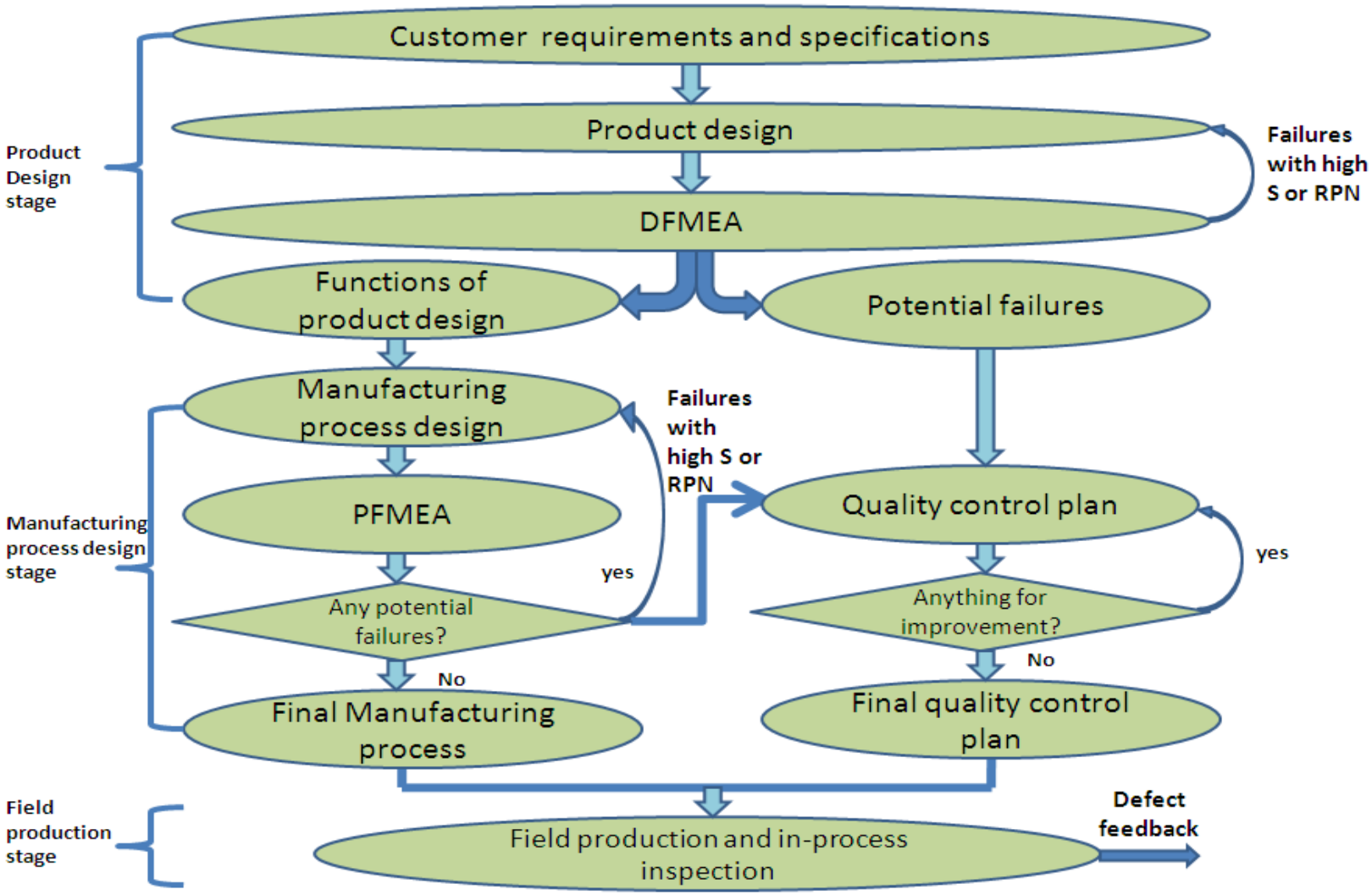

Figure 5.5 New product quality control process

Stage 2 FMEA application system establishment

After gaining management support, efforts should focus mainly on the FMEA application system establishment. This work is divided into 4 parts:

(1) Design new product quality control process

A new quality control process should be designed integrating DFMEA and PFMEA as well as their interrelationships. It can define FMEA applications as a mandatory requirement in product development, integrating FMEA into the whole product development cycle.

The new product quality control process shown in Figure 5.5 is designed based on the AS-IS quality control process identified in chapter 4 and the interrelationships between DFMEA and PFMEA. It can be divided into three stages, based on product development.

Product design stage

Firstly, the customer requirements and relevant product specifications are used as input for product design.

Secondly, as soon as the product concept is determined, DFMEA should be launched for product design risk assessment. It is carried out by the DFMEA team. The output of DFMEA includes designed functions, potential failures, and items with high RPN (Risk Prioritise Number) or severity.

Thirdly, the items with high RPN or severity are returned to the product designer for design improvement; design functions are transferred to the manufacturing system as the part of input to manufacturing process design; while potential failure modes are delivered to the quality engineer to inform the quality control plan.

Manufacturing process design stage

Firstly, designed functions gained from DFMEA, combining with the final product design are part of the input for the manufacturing process design; the manufacturing processes are designed to manufacture the product and produce functions of product design.

Secondly, PFMEA is carried out by the PFMEA team for manufacturing process evaluation as soon as the manufacturing process concept is determined. The outcomes of PFMEA include manufacturing process functions, potential failures and items with high RPN (Risk Prioritise Number) or severity.

Thirdly, the items with high RPN or severity caused by inadequate product design are returned to the product designer for design improvement; items with high RPN or severity caused by inadequate manufacturing process design are returned to the manufacturing engineer for improvement. The potential failure modes listed in DFMEA and PFMEA combined with the final product design and final manufacturing processes should be transmitted to the quality engineer to inform the quality control plan. Potential failures in the quality control plan should be given particular attention to allow more effective control.

Field production stage

After freezing the product design, manufacturing process and quality control plan, they should be released to field production for manufacturing and in-process inspection. The defects found in field production will be submitted to the quality engineer, manufacturing engineer and product designer for improvement, based on field analysis.

Even though FMEA has been involved in the whole quality control system, the preparation, technical process and other details of FMEA implementation are also crucial for the final success in improving product quality. They should be standardised.

(2) Standardise the FMEA preparation, FMEA technical process and ranking rules.

Specifications should be established for defining the details for FMEA applications. The following items should be included：

When to start FMEA and when to finish?

FMEA has the characteristic of timeliness. It should be launched as early as possible in the product development cycle and should be finished before integration into field production. DFMEA should be employed as soon as the design concept is determined; it should be completed before design freezing; PFMEA should be started as soon as the manufacturing processes are determined and completed before being released to field production.

Who takes charge of FMEA and who should be involved in FMEA?

Usually the product designer takes charge of DFMEA, whilst the manufacturing engineer is responsible for PFMEA. This means that they work as facilitators in the FMEA team. For DFMEA, the product designer, sales engineer, manufacturing engineer, quality engineer, relevant supplier and customer should be involved; while the product designer, manufacturing engineer, quality engineer, operator and supplier should be involved in PFMEA. Suppliers are only involved in relevant product or interface analysis.

Who is responsible for documentation?

The quality engineer is usually assigned to document FMEA, which includes potential failure modes and recommended actions. These should be monitored until the latent risks are eliminated.

Who is responsible for implementing recommended actions?

This should be based on the content of recommended actions: design improvement should be completed by the designer; manufacturing process

changes should be assigned to the manufacturing engineer; equipment or fixture manufacturing defects should be assigned to the relevant departments.

What is the relationship between OEM and suppliers in FMEA applications?

It is recommended that OEM should involve suppliers in the FMEA applications.

a) FMEA specifications should be provided to suppliers for mandatory applications;

b) Suppliers should be involved in related product design review and analysis;

c) The DFMEA report should be released with accompanying product drawings;

d) OEM should clearly define the supplier responsibilities;

e) The supplier should provide its PFMEA reports and defects to OEM, accompanying delivery product(s) and documents;

f) OEM should inform supplier whenever defect is found afterward in supplier's product, the defects should be monitored rigorously until being eliminated;

g) Customer feedback about the product should be passed to the relevant supplier(s);

What is the standard FMEA process?

a) Analyse the product or manufacturing process being reviewed thoroughly;

b) List the potential failures and their effects extensively;

c) Rank the effect, occurrence and detection reasonably;

d) Identify the root cause correctly;

e) Calculate RPN and rank them;

f) Take actions rigorously for afterward improvement;

g) Monitor the implementation process of recommended actions.

What are the rules for severity, occurrence and detection ranking?

In the whole product development system, FMEA ranking scales should be consistent with the whole product life cycle, including in suppliers' FMEA process. The scale rules should be defined based on the nature of the product.

(3) FMEA audit functions development

Audit function should be established for FMEA performance evaluation and continuous improvement. Without this function, nobody would know whether the FMEA performances were valid, or the effectiveness of the FMEA applications.

(4) FMEA documentation system establishment

FMEA No. should be designed for easy tracing and simple connection with the product themselves. The documentation system should keep monitoring FMEA reports, updating them to reflect the latest product design and manufacturing process as well as defect conditions.

Stage 2 is the main part of this integrated framework development; the system defines the specific steps and procedures for FMEA applications within the product development cycle.

Stage 3 Staff training on FMEA and facilitation techniques

(1) Staff training on FMEA applications

(2) Facilitator training on communication techniques, organizing techniques.

In this stage, all the staff and facilitators should be trained to form a sound understanding of the FMEA application system and specifications. Because this technique is based on team work, correct understanding of standardised FMEA process and effective facilitation will increase the efficiency of FMEA implementation.

Stage 4 FMEA implementation

In the fourth stage, the FMEA should be implemented for product risk assessment and elimination at all the planning stages, including conceptual design, preliminary design, and detail design. Without FMEA implementation, the FMEA application system means nothing for defect elimination and quality improvement.

Stage 5 FMEA performance and specification auditing.

The audit system should be launched to check if FMEA performances are in line with the established FMEA specifications, based on the questionnaire among the staff in the company or field checks during its implementation. If not, root cause should be identified and correct actions taken for FMEA performance improvement. If the FMEA performances conform to the specifications, but the effectiveness is not obvious in the long-term, specifications for FMEA applications should be examined and analysed carefully to identify if there is anything improper hindering successful FMEA applications. Continuous auditing will ensure that the FMEA specifications and application performances will be improved continuously.

6. FMEA framework validation

6.1. Introduction

This chapter aims to validate the integrated FMEA framework through expert judgement in the collaborative aerospace company.

6.2. Validation of the generated FMEA framework

The author has maintained continuous involvement with the sponsored aerospace company. Ten key experts were identified by the author in the aerospace company, consisting of two project managers, three quality engineers, two product designer and three manufacturing engineers. The author has also incorporated their points of view relating to the generated FMEA framework. Their comments supported to validation of the integrated FMEA framework. This section presents the process of validating the integrated FMEA framework as well as the experts' comments on the framework.

6.2.1. Framework validation process

(1) The following information about the research was sent to the experts. The first two items provide an overview of the whole research and the last two concern the framework.

   a) The project aim and objectives which were presented in section 1.4;

   b) Research methodology as presented in section 3.1;

   c) The interrelationships between DFMEA and PFMEA which were shown in Figure 5.1;

   d) The integrated FMEA framework, illustrated in Figure 5.4 and new product quality control process shown in Figure 5.5;

(2) Two initial internet meetings were held in order to explain the information, especially the interrelationships between DFMEA and PFMEA and the

integrated FMEA framework to the experts. Each meeting lasted about 2 hours to make sure each expert could understand the information thoroughly.

(3) Two meetings were held in the company to allow sufficient discussion of the integrated FMEA framework without the attendance of the researcher. This supported the gathering of authentic information from the point of view of the collaborative aerospace company. Each meeting lasted about 2 hours.

Whenever they had any issue to query, they would contact the author through the internet or text messages.

(4) A short report is provided, outlining the experts' comments on the research and the generated FMEA framework, which is being presented in section 6.2.2.

6.2.2. Expert judgements on the FMEA framework

According to the report, the experts' comments on the integrated FMEA framework can be divided into 2 parts. One part concerns their positive comments; the other part the shortcomings of the framework.

(1) Positive comments on the FMEA framework are as follows:

a) It is believed that it is absolutely necessary to involve management awareness and commitment in FMEA application system. Without the support from the management, the motivation to implement FMEA will be less and the demanded resources for FMEA applications cannot be guaranteed.

b) The framework will definitely support the company to apply FMEA step by step. The new product quality control process will guide and motivate the company staff to apply FMEA systematically, treating FMEA as a mandatory requirement in the product design and manufacturing process design.

c) The interrelationships of DFMEA and PFMEA highlight the links of potential failures of functions of product design and manufacturing processes, integrating DFMEA and PFMEA; the integration of FMEA and quality control plan can focus more attention on critical issues and defect elimination before their occurrence.

d) The documentation system allows powerful defect traceability and knowledge accumulation.

   The defects do not only comprise those found in field production, but also those identified in product design and manufacturing process design. Hence, all the defects without exception can be included in the documentation system.

   As an aerospace company, knowledge accumulation is crucial for product development. The company doesn't want to suffer knowledge loss caused by employee switching. The collaborative company suffered from this for a long period.

   Hence, the company stressed that the documentation system is crucial for FMEA applications.

e) The training program will make the company staff understand the techniques of FMEA applications thoroughly, which will help them to implement the technique effectively.

f) All the experts believed that the auditing system which helps to check the effectiveness of FMEA applications is also necessary in the FMEA application system.

However, experts also provide advice for improving the FMEA framework.

(2) The shortcomings of the framework

The problem arises of the reuse of accumulated knowledge and experience. With the applications of FMEA, the number of documents increases, making it

difficult to find the specific information. The reuse of knowledge will be lessened. The advice is to integrate IT technology with FMEA applications for convenient defect querying and relative solutions searching.

7. Discussions, conclusions and future work

7.1. Introduction

This chapter will discuss the research work implemented and achievements of this research. In addition, the contribution to knowledge, research limitations and recommendations for future work are also clarified in the remaining sections.

7.2. Discussions

The aim of this research is to develop an integrated FMEA framework designed to interrelate the potential failures of functions of product design and manufacturing processes. This framework will be used as guidance for correct FMEA applications in the collaborative aerospace company. With purpose of achieving this aim, several objectives are carried out: (1) Synthesise the best practices of FMEA application through literature review; (2) Examine the gap between current F in an aerospace company and the identified best practices of FMEA application; (3) Develop an integrated FMEA framework for the correct and effective application in an aerospace company; (4) Validate the integrated FMEA framework through the experts' judgement.

7.2.1. Research methodology and achievements of objectives

The research methodology adapted in this research has provided an effective process to guide the project step by step. The specific order of the steps provided proper information for the research at the proper time. This methodology has led to an integrated FMEA framework designed to interrelate the potential failures of functions of product design and manufacturing processes which was the aim set up at the beginning of the research.

The comprehensive literature review on FMEA carried out at the beginning of the research helped to form the solid theory foundation of FMEA. It also helped the author to synthesise the best practices of FMEA applications. Most of the researches are carried out for FMEA applications in automotive industry.

However, in the author's opinion, the product development processes are similar. The best practice of FMEA applications in the former should also be applicable to the aerospace industry.

Because of the active participation of the company staff in interviews, the AS-IS quality control process was quickly identified. Based on the synthesised best practices and AS-IS quality control process and the author's own engineering background, it was not very difficult to design a suitable questionnaire for data collection. The active participation in the interviews and questionnaires of the staff indicated the company's great interest in this research, providing qualified data for gap identification. The collected data has been elaborated and analysed carefully. The author has found that many aspects of FMEA applications need to be improved for potential defect prevention and quality control.

The interrelationships of DFMEA and PFMEA, associated with the synthesised best practices, identified gap as well as their categorisations have led to the integrated FMEA framework for the collaborative aerospace company. The most important point, integrating DFMEA and PFMEA based on the interrelationships of potential failures of functions of product design and manufacturing processes would make defect elimination more systematic and effective. Even though the integrated FMEA framework was developed for the collaborative aerospace company, it could also be used by other companies. The only difference is that specifications for FMEA applications should be based on their product nature and details specific to their companies.

Finally, the integrated FMEA framework was validated through expert judgement in the collaborative aerospace company. The positive comments provided by them showed that the framework can guide mandatory, systematic and integrated FMEA application in the collaborative aerospace company.

7.2.2. The integrated FMEA framework

The development of the FMEA framework is based on categorisation of the synthesised best practices and identified gap. Most companies apply FMEA unsystematically, improperly and isolated. Efforts are made to solve these problems through developing an integrated FMEA framework which will guide systematic, proper and integrated FMEA applications.

The framework covers the aspects of management awareness, system establishment, staff training, and FMEA implementation to FMEA auditing. According to the validation, it will guide effective FMEA step by step in a systematic and integrated manner.

7.3. Contribution to knowledge

FMEA has been developed for many years; however, unsystematic, improper and isolated FMEA applications have cut down its effectiveness. The contribution of this research is the integrated FMEA framework which inter-relates the potential failures of functions of product design and manufacturing processes, enhancing product quality control and defect tracing. This framework can guide companies to apply FMEA in a systematic, proper and integrated way.

7.4. Conclusions

Based on the discussions above, the research has achieved the aim and objectives set up initially. The conclusions are drawn as follows:

(1) The good literature that describe both D-FMEA and P-FMEA and their applications in the different sectors. However there is no indication about the integration between them that will ensure a better quality control.

(2) The research methodology has been developed with intention to have good interaction with the potential end user of the research output. This has given the indusial driven approach to make sure that the results will be easy to transfer to the company.

(3) Using real industrial case study helped to understand the need of the link and integration between DFMEA and PFMEA which then let the proposed framework be presented in chapter 5.
(4) The proposed integrated FMEA framework has been designed in the way to make sure the step by step practical guide can develop and integrate DFMEA and PFMEA. However, it required a person with a level of experience to use and implement to get the good results.
(5) Due to time limitation, integrated FMEA framework has been developed as paper bases exercise. The author believes that this could also be developed based on IT-based framework.
(6) The expert judgment opinion has been good to give valuable feedback to improve the framework. However, it would be good to have full implementation using a pilot industrial cases study. This could not be achieved due to the limitation of time and resources of this research.

7.5. Research limitations

Not all the engineers involved were aware of FMEA applications in this company. Sometimes, disagreements on the company performance existed.

The validation was carried out within the collaborative aerospace company alone; it might be validated further by use in more companies.

Because of time limitations, the standardisation of rankings rules and language used to describe the defects are not designed in detail; the framework was not developed based on IT.

7.6. Recommendations for future work

This research has developed an integrated framework for the aerospace company. However, the following work would need to be completed to enable real FMEA applications in product development.
(1) Establish specifications with details.
(2) Put the framework into pilot applications to test it.

(3) Intelligent FMEA data management and searching should be integrated in the framework, gaining defect checklist which needs more attention for tracing and controlling throughout the whole product development.

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