

Department of Mechanical, Materials & Manufacturing Engineering

Investigating innovative technique for managing Failure Modes and Effects Analysis

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Abstract

The investigation of failures and their prevention throughout a design process forms an effective approach that can reduce such occurrences during manufacturing. To address this issue, Failure Modes and Effects Analysis (FMEA) was developed as a methodology to proactively evaluate the potential failures in a product, process or service. In the context of the product development process, FMEA is employed in three distinct areas, labelled: (1) Functional FMEA – looking at the potential failures associated with product and system functions, (2) Design FMEA – considering the potential failures identified in the product sub-system functions and component designs and (3) Process FMEA – evaluating the potential failures found in manufacturing and assembly processes.

In its current form, FMEA implementation is marred by high resource requirements, lack of available data and difficulty of deployment. Consequently, attempts to integrate FMEA with other systematic methodologies have, at best, been sporadic, yielding inconclusive outcomes. To address these problems, this research used a score-based metric to empirically identify the challenges associated with FMEA deployment and the impact of combining other methodologies with it. The influence of other factors, such as industry membership, amount and level of engineering experience held and organisational size were also analysed by executing an ordered probit model, which sought to examine the effect of such factors on the score-based metric developed to measure the level of challenge associated with FMEA deployment. The findings reveal that Fault Tree Analysis and Axiomatic Design methodologies significantly reduce the perceived level of challenge for FMEA deployment in the sample of firms that were investigated. These findings represent a promising development as it has helped to improve the understanding of the impact

associated with integrating these methods and the variation in other managerial factors on FMEA implementation.

In terms of measuring the performance of FMEA deployment, this is also an area that has not previously been clearly understood in the literature. In order to investigate this part of FMEA deployment, this research applied graphical and descriptive analysis methods in order to understand the current systems/targets used for measuring FMEA-related performance. The results identify diverse approaches/targets that were recognised as being the most frequently used based on the sample investigated, in the following order: mitigating failure modes, the capability of FMEA practice to recognise failure modes and document the relevant knowledge and actions. It was also noted that these approaches were widely managed subjectively for assessing the themes outlined above. These results suggest that these are the most important goals for deploying FMEAs. Also, these results indicate the demand for a computable metric, which would help to certify the outputs of FMEA execution. Initial investigation was then conducted into determining such a cost model. However, the host company was unable to disclose its records to validate the proposed cost model and so the validation process will be conducted at a later date.

Building on the above findings of the ordered probit model and the targets required by deploying FMEAs in industry, this research also sought to integrate Functional, Design and Process FMEAs into a working model in an attempt to achieve its targets outlined in above; an area that has been hitherto under-researched. This research developed the framework of combining FMEA applications to offer a hybrid risks assessment model that should be able to synchronise FMEA applications and catch the cascaded failures. In this regard, it could be said that the framework developed in this research is novel, as it aims to improve FMEA deployment in and reduce associated costs. The developed framework was then evaluated based on feedback provided by FMEA subject-matter experts, whose responses were

analysed using the t-test model. The findings suggest that this framework is easy to use, useful, applicable and able to cascade and catch failures over Functional, Design and Process FMEAs.

Declaration

I, Mansoor Alruqi, hereby declare that this thesis titled "Investigating innovative techniques for managing Failure Modes and Effects Analysis in" is my own work from the time of my PhD at University of Nottingham under supervision of Dr Martin Baumers and Dr David Branson III, and that it has never been submitted for the award of any degree, diploma or any similar type of recognition.

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Abbreviations

ABS – Activity-Based Costing
AD – Axiomatic Design
AESQ – Aerospace Engine Supplier Quality Committee
AHP – Analytic Hierarchy Process
CoGQ – Cost of Good Quality
CoQ – Cost of Quality
CoPQ – Cost of Poor Quality
D – Detection rate of a failure
DAIREC – Define, Analysis, Improve, Recommend, Evaluate and Control
DM – Design Matrix
DSM – Design Structure Matrix
DPs – Design Parameters
DVP – Design Verification Plan
FFBD – Function Flow Boundary Diagram
FRs – Functional Requirements
FTA – Fault Tree Analysis
FMEA – Failure Modes and Effects Analysis
KBS – Knowledge-Based System
KDDM – Knowledge Discovery and Data Mining
LC – Level of Challenge associated with FMEA deployment
O – Occurrence rate of a failure
PVs – Process Variables
QFD – Quality Function Deployment
RPN – Risk Priority Number
S – Severity rate of a failure
ZDM – Zero-Defects Manufacturing

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1. Introduction

This chapter introduces the background and motivation for conducting this research, as well as the aim and objectives. It also outlines the overall structure and the publication strategy for this thesis.

1.1. Background and motivation

Up until this point, risk management has been one of the key strategical elements for any organisation looking to introduce new products/services and support modifications to existing designs (Best, Valence and Langston, 2007; Clarke and Varma, 1999). Generally, risk management can be categorised as 'reactive' or 'proactive', with the difference between the two being in the way failures are tackled. The first of these categories copes with failures once they emerge, with the second focusing merely on problem-solving (i.e., firefighting) rather than prevention.

Product failures are understood to be deviations in a product or process from the required targets, which result in non-compliance with customer requirements, additional costs and delivery delays (Carlson, 2012). Failures are usually associated with costs of either reworking product components to fix problems or, if this is not possible, scrapping some or all the product components (Riggs, 2017). Such costs can be substantial; therefore, preventing failures from occurring, or at least reducing the associated impact, is a major cost saving which can bring about an increase in profit (Riggs, 2017).

In terms of coping strategies used for tackling failures when occurred, performing reactive management, where a test and fix mode is adopted as a methodology, could lead to costs of non-conformance and delays, coupled with, for example, reworking and/or scrapping product elements for resolving failures. For instance, Rolls-Royce Holding (i.e., supplier of

aeroengines and other power systems) is expected to incur £2.4 billion in the period between 2017-2023 to fix such faults that have emerged from the servicing of the Trent 1000 aeroengine as a result of adopting a reactive management approach (Tovey, 2019). Another example, the profits of General Motors (i.e., automotive supplier) were hit by a $1.3 billion bill in 2014 as the company was forced to recall millions of cars and correct faulty ignition switches (Klyatis, 2015).

For many aerospace organisations, the Aerospace Engine Supplier Quality Committee (AESQ), a group of large aerospace companies united to form a common practice for managing quality requirements, expects that the cost of failures will amount to around 20-25% of sales, including cost of reworking, scrap, concessions and missed delivery penalties (Riggs, 2017). Therefore, AESQ has been working to develop a practice that aims to reduce that such costs and place the aeroengine industry on a competitive edge thereby improving performance (Riggs, 2017).

Diverse methodologies have been developed to perform the role of proactive management and to prevent the likelihood of failures occurrence; one such common approach involves Failure Modes and Effects Analysis (FMEA). A suitable definition for FMEA approach is provided by Liu (2016, p.3) and Stamatis (2003, p.21):

> "*A Failure Mode and Effect Analysis (FMEA) is an engineering technique used to define, identify, and eliminate known and/or potential failures, problems, errors, and so on from the system, design, process, and/or service before they reach the customer.*"

Another suitable definition is:

> "*An FMEA is an engineering analysis done by a cross-functional team of subject matter experts that thoroughly*

> *analyses product designs or manufacturing processes early in the product development process.*" (Carlson, 2012, p.21)

FMEA has always been an important factor and key dimension in improving the performance of the developmental process of products as well as being able to generate lessons that can be learned for proactive management (Carlson, 2012; Segismundo and Miguel, 2008; Chin, Chan and Yang, 2008; Lam, Sherwood and Shu, 2001; Montgomery and Marko, 1997; Teng and Ho, 1996; Bednarz and Marriott, 1988). As a core element in the reliability/quality fields of product development, FMEA is adopted in 3 distinct applications (Carlson, 2012; Stamatis, 2003): (1) Functional FMEA – evaluating product/system functions-related failure modes, (2) Design FMEA – appraising the associated failure modes with sub-system functions and component designs and (3) Process FMEA – assessing failures identified in manufacturing and assembly processes.

However, these applications are still individually applied, which makes it difficult to achieve the overall aim of this methodology for tracking the impact of such failures on connected items (Carlson, 2012; Teng et al., 2006; Ginn et al., 1998). Therefore, these different tasks of FMEA must be synchronised to effectively trace and capture failure modes and maximise the benefits of applying FMEA (Henshall, Campean and Rutter, 2014; Soufhwee et al., 2013; Carlson, 2012; Xiao et al., 2011; Popović, Vasić and Petrović, 2010; Teng et al., 2006; Kmenta and Ishii, 2004). This means that all the above-mentioned applications should be interlinked to cascade and capture failures, as well as tracing their associated impacts and causes. This would help prevent and minimise failures at the early stages in a more proactive manner (Henshall, Campean and Rutter, 2014; Soufhwee et al., 2013; Carlson, 2012; Xiao et al., 2011; Popović, Vasić and Petrović, 2010; Teng et al., 2006; Kmenta and Ishii, 2004).

In terms of its establishment, FMEA was developed in the 1960s as a formal design methodology by the National Aeronautics Space Agency (NASA) to address a way of improving the reliability of military equipment (Bowles and Peláez, 1995). By late 1973, Ford Motor Company was one of the first early adopters of FMEA in the automotive industry to promote the required quality of its products (Doshi and Desai, 2017). The next phase of FMEA deployment saw its rapid acceleration and use in tackling major quality issues and reliability challenges faced by others automotive manufacturers such as Chrysler (Bell et al., 2012). Moving forward to more recent times, the potential benefits proffered by FMEA deployment has seen it being used in various industries, such as electronics, nuclear, medical, mechanical and chemical (Chang and Cheng, 2011; Chin et al., 2009; Sharma, Kumar and Kumar, 2005).

Its spread and greater acceptance has led to standardisation/benchmarking. Various standards and manuals have been published to describe the general procedure for deploying FMEA. Some of the most common from those in circulation are:

- FMEAAV-1: AIAG & VDA FMEA Handbook (published in 2019).
- AS13004: Process Failure Mode and Effects Analysis (PFMEA) and Control Plans (published in 2017).
- J1739_200901: Potential Failure Mode and Effects Analysis in Design (Design FMEA), Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA) (published in 2009).
- IEC 60812: Analysis techniques for system reliability – Procedure for failure mode and effects analysis (FMEA) (published in 2006).

The fact that FMEA acts in a preventive mode makes it an attractive addition to the product development process and highly relevant in modern quality management systems, particularly in terms of supporting the purpose of

failure prevention and in minimising process variations (Stamatis, 2003; Baxter, 1995; Webber, 1990). For instance, recent legal changes in corporate responsibility have led companies to adopt FMEA to build quality levels required within certain conditions (Johnson and Khan, 2003). For example, the joint team of the Ford Motor, Chrysler and General Motors companies developed a guidance for FMEA implementation to complement the product development process, which is available through J1739_200901 (2009). This standard mandated the deployment of Design and Process FMEAs.

AESQ has also developed a standardised approach for executing Process FMEA procedure and a reference manual for implementing Design FMEA as a requirement in the product development process, which is coded as AS13004 (Riggs, 2017). This promotes a specific quality standard for the aeroengine supply chain in the movement towards achieving the goal of Zero-Defect strategy (Riggs, 2017). This standard aims to provide guidance for implementing Process FMEA and improving the performance of products and manufacturing processes (Riggs, 2017). This particular manual encourages aeroengine suppliers to conduct a common practice for deploying FMEA, which would enable all suppliers to share and follow-up on FMEA trends and development (Riggs, 2017). AESQ has shared some positive experiences, presented in AESQ – Aerospace Engine Supplier Quality Strategy Group (2019). For example, using this standard has helped to highlight the power of collaboration between team members, early engagement with failures, increased product understanding and the building of formal recording based on lessons that have been learnt (Riggs, 2017).

Cutting-edge developments in the automotive and the aerospace industries led to adopt FMEA as a standard process has motivated the desire to research the challenges associated with deploying FMEA and feasible

practices that can be employed to handle these challenges. This research has also been motivated by a desire to cover the process of investigating how the performance of FMEA deployment can be measured in both industries.

An integrated product such as an aeroengine, that is made from different engineering disciplines combined with advanced technologies, undoubtedly increases the challenge for implementing FMEA (Walker et al., 2009; Suma and Gopalakrishnan Nair, 2008). These challenges can vary between the required intensive resources (Peeters, Basten and Tinga, 2018; Estorilio and Posso, 2010; Zheng, Liu and McMahon, 2010; Trammell, Lorenzo and Davis, 2004; Wetterneck et al., 2004), availability of data (Peeters, Basten and Tinga, 2018; Spreafico, Russo and Rizzi, 2017; Henshall, Campean and Rutter, 2014; Soufhwee et al., 2013; Carlson, 2012; Menis et al., 2012; Xiao et al., 2011; Popović, Vasić and Petrović, 2010; Teng et al., 2006; Kmenta and Ishii, 2004) and the scale of knowledge of the recruited team (Banghart, Bian and Babski-Reeves, 2016; Carlson, 2012; Bluvband and Grabov, 2009). They are often motivated by the required depth of analysis (Peeters, Basten and Tinga, 2018; Henshall, Campean and Rutter, 2014; Soufhwee et al., 2013; Yu et al., 2011; Abbas and Vachtsevanos, 2009; Walker et al., 2009; Suma and Gopalakrishnan Nair, 2008) and the gap in knowledge between design and manufacturing organisations (Henshall, Campean and Rutter, 2014; Soufhwee et al., 2013; Xiao et al., 2011; Popović, Vasić and Petrović, 2010; Teng et al., 2006; Kmenta and Ishii, 2004).

Various proposals have been made and exploited to enhance FMEA deployment practices and reduce the impact of the challenges outlined in the above. Some proposals are based on the systemised tools of: Fault Tree Analysis (FTA), Function Flow Boundary Diagram (FFBD), Analytical Hierarchy Process (AHP), Quality Function Deployment (QFD), Knowledge-

Based System (KBS), Define, Analysis, Improve, Recommend, Evaluate and Control (DAIREC) and Axiomatic Design (AD). However, estimating the impact of these proposals on FMEA deployment has rarely been studied directly in the literature, which is targeted for investigation in this research. One of the major topics also to be investigated in this research is the methods of measuring the performance of FMEA deployment, where the literature shows a dearth of research on this side of FMEA deployment management.

Unlike FMEA, which follows inductive logic, FTA is a deductive failure analysis method that models and quantifies the system failures in a top-down approach (Peeters, Basten and Tinga, 2018; Han and Zhang, 2013; Yu et al., 2011; Ferdous et al., 2009; Arcidiacono and Campatelli, 2004; Bluvband, Polak and Grabov, 2005). FFBD is a system engineering tool that promotes a hierarchical decomposition of system functions (Yildirim, Campean and Williams, 2017). AHP is a well-thought-out technique to manage the decision-making process (Wang et al., 2020; Battirola Filho et al., 2017; Tang, Wang and Wang, 2007; Bayazit, 2005). It is pushed by the hierarchical decomposition to accommodate multipart information in multi-criterion decision-making (Bayazit, 2005).

QFD is a quality management technique used to capture the customer needs, translate them into product requirements and cascade down to the product development domains (Gu, Cheng and Qiu, 2019; Ma et al., 2019; Chen, 2016; Liu et al., 2016; Wang and Chang, 2010; Hassan et al., 2009; Almannai, Greenough and Kay, 2008; Ginn et al., 1998). KBS is the combination of artificial intelligence techniques and databases to imitate human problem-solving vis a vis of subject specific knowledge (Renu et al., 2016; Augustine et al., 2012).

DAIREC is an element in the Lean Six Sigma toolkit following the "DAIREC" cycle (Define, Analysis, Improve, Recommend, Evaluate and Control);

working as a closed-loop process to determine and evaluate the critical characterises that affect the performance of a product (Soufhwee et al., 2013). AD is a design management methodology that was developed by Suh (2001) to reduce the level of integration in a design and logically provide the foundations for the designers to improve the design workflows by cascading customer requirements into functional, design and process domains (Suh, 2001).

1.2. Research aim and objectives

The overarching aim of this research is to conceptualise a framework to synchronise Functional, Design and Process FMEAs. This architecture shall provide a means of tracing the functional requirements from the top level through all system levels and enable bi-directional risks flow up/down the product structure. To achieve that aim, this research is led by four specific objectives as follows:

1. Review the state-of-art of FMEA deployment and measurement.
2. Survey the current practical challenges for deploying FMEA and the impact of combining other systematic engineering methods, also the influence of other managerial factors on the progress of executing FMEA methods.
3. Survey the current industrial practice for measuring the performance of FMEAs implementation.
4. Develop and validate the integrated framework of synchronising FMEA methods.

This proposed framework is sought to identify and analyse failures, also chase their impacts during the product development process, helping to minimise the cost of failures. It should be noted that working closely with the host company, one of the leading aeroengine manufacturers in the United Kingdom, played an important role in establishing the research

objectives and executing this research. However, the company's name and details was anonymised to maintain confidentiality requirements.

1.3. Thesis outline

This thesis has been organised into two main themes to provide greater clarity. The first of these, FMEA deployment, seeks to research the practical challenges involved with FMEA implementation and its impact when combined with other engineering tools such those are outlined above. The second theme deals with the performance measurement of FMEAs deployment. This involves discussing the current systems used for the performance measurement in this regard. The purpose of this theme is to identify the tasks required by the deployment of FMEA methods from practical perspective to develop the framework of integrating FMEAs. This section goes on to present a proposed cost model for measuring the performance of FMEA deployment. As a results of these themes, this thesis describes the development and validation processes of the proposed framework for integrating the applications of FMEA. The entire thesis is structured into seven chapters. The main outlines for each chapter are explained in the following.

Chapter 1 provides an introductory outline including the research background and motivation to conduct this research. It also depicts the research aim and objectives. This chapter concludes with expressing the thesis structure and publication plan.

Chapter 2 starts with explaining the background on the characteristics/models for deploying FMEA and deployment benefits. Focal reviews on FMEA deployment and the relative performance measurement are then presented.

Chapter 3 exhibits the adopted methodologies for guiding this research along with the research strategies, design and data source. The data collection methods are also explained.

In chapter 4, there are three main sections. The first section displays the research findings of the current challenges associated with deploying FMEA. In addition to this, it presents the examination findings on the impact of co-adopting various methods, outlined above, and the change in other managerial factors to improve the practice of FMEA deployment. The second section presents the results on the investigation of the current measurement/objectives used for evaluating the performance of FMEA implementation. The third section explains the initial investigation of the cost model proposed for measuring the performance of FMEA employment. Although the ambition was to execute the proposed cost model in practical cases and determine its applicability, this cannot be happened in this project due to the limitations of data access and given time of this PhD.

Chapter 5 starts with presenting the framework developed for incorporating FMEA applications into a working architecture. Then, it displays the process for validating the proposed framework.

In Chapter 6, the key findings derived from the previous chapters along with the potential benefits of the cost model are discussed in the light of the two organised themes: FMEA deployment and performance measurement.

The last Chapter, 7, provides an overview of the key research findings, contributions, practical implications, limitations and suggestions for future work. Figure 1 graphically summarises the structure of the thesis.

Chapter 1
Describes the research background, motivation, aims, objectives, thesis outline and publication strategy.

Chapter 2
4.1. Provides a background on the deployment of FMEA.
4.2. Presents the focal literature on the current challenges for implementing FMEA and related development.
4.3. Presents the focal literature on the performance of FMEA deployment.

Chapter 3
Presents the applied research methodologies, data collection tools, the relevant validation process and data analysis methods.

Chapter 4
4.1. Presents the results of the current challenges of FMEA deployment and the impact of co-adopting other tools on the performance of its deployment.
4.2. Presents the current applied measurement systems of FMEA deployment performance.
4.3. Exhibits the developmental process of the proposed cost model as an outcome of section 4.2.

Chapter 5
5.1. Describes the developmental process of the proposed framework of integrating FMEA applications.
5.2. Presents the process of validating the proposed framework.

Chapter 6
6.1. Presents the discussion of this research project from FMEA deployment perspective.
6.2. Presents the discussion of this research project from the performance measurement of FMEA deployment perspective.

Chapter 7
Presents the summary of this research project, contributions, implications, limitations and future work.

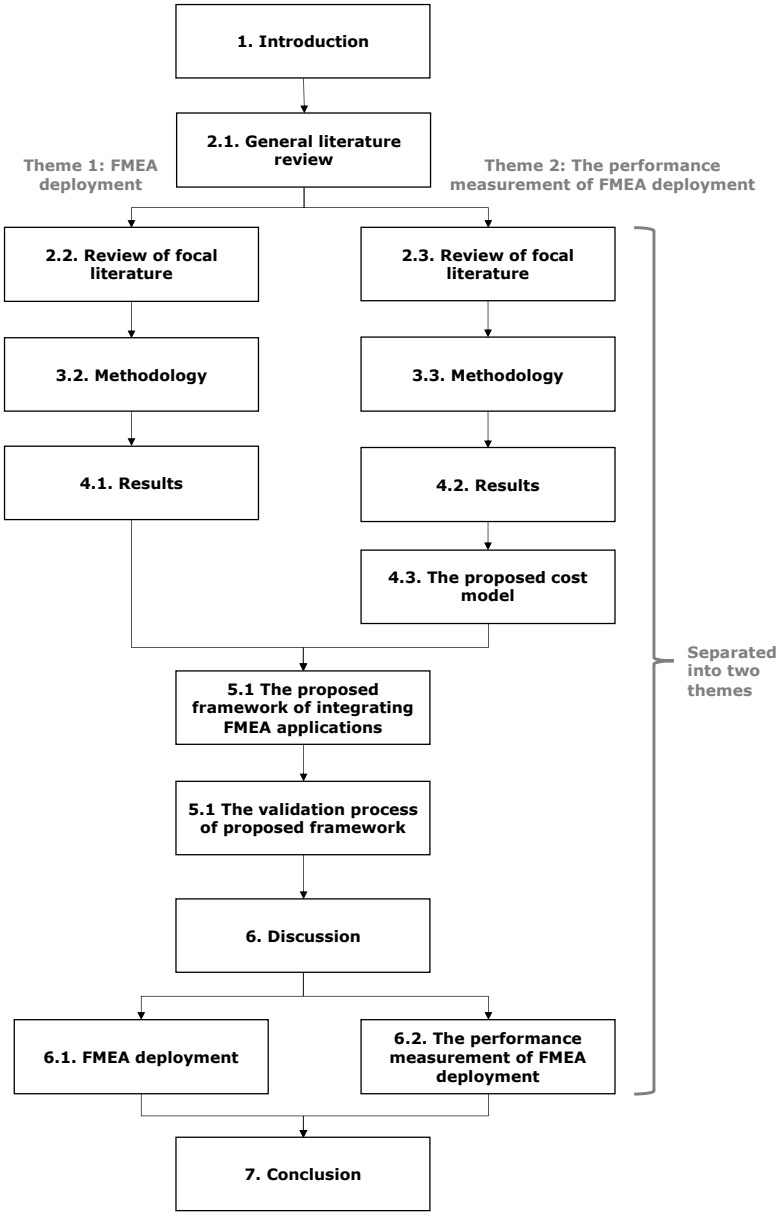


Figure 1: Thesis structure

1.4. Publication strategy

During the process of undertaking this research, a publication strategy was formulated. The framework developed for integrating FMEA applications was presented in the 2019 International Conference on Product Innovation and Design (ICPID 2019), that was held in Loughborough University in London.

Two journal articles were produced. The first, entitled "*The challenge of deploying Failure Modes and Effects Analysis – Quantification and Analysis*", was prepared and submitted to the *International Journal of Agile Systems and Management*, and is currently under review. This paper, represented in section 4.1, reports the statistical analysis of the level of challenge associated with FMEA deployment. This is significant since FMEA execution is encountered with various challenges on those applications, where such co-adoption with other systematic engineering methodologies were proposed with no empirical quantification of the associated impacts. This paper provides empirical investigation of the associated effects of these techniques. Through the proposed score-based metric, this work measures the performance of those methodologies on the implementation of FMEA. It also articulates the dynamic part of the relationship between the managerial factors of industry membership, engineering experience held, and organisational size and impact on the FMEA deployment.

The second paper, derived from chapter 5, had been prepared during the process of this project and is meant to expand the work of the first paper. It is titled *"A Structured Approach for Synchronising the Applications of Failure Mode and Effects Analysis*". This paper describes the framework developed for integrating Functional, Design and Process FMEAs, where new methodology is introduced. It also presents the empirical evaluation of the application of this framework from the practical contexts. This evaluation contributes and validates one of the outcomes of the first paper.

This paper is now published in the journal of *Management Systems in Production Engineering*.

2. Literature review

This chapter has been organised into three main, distinct sections to support this research investigation. Section 2.1 starts by initially presenting a brief background of the characteristics and models of FMEA deployment along with the drivers for adopting it. Section 2.2 highlights the focal literature surveyed on the deployment of FMEA as well as a critical discussion on the current efforts that have been made to improve its implementation. This section also elucidates the methods that could potentially address the requirements for synchronising Functional, Design and Process FMEAs. Finally, section 2.3 provides an overview and analysis of recent works that have been devoted towards measuring the performance of FMEA execution. The potential link between FMEA and the Cost of Quality framework (CoQ) is also presented in this section to justify how this costing approach could efficiently manage the performance measurement of FMEA implementation.

2.1. Background

2.1.1. The characteristics of FMEA

FMEA is based on two co-existing distinct terms: failure modes and effects analysis. Failure modes analysis refers to the systematic approach to anticipate failures during design, production and service stages for identifying and quantifying their rates and root causes (Carlson, 2012; Stamatis, 2003). Carlson (2012, p.28) provides a definition for a failure mode as follows:

> "*Failure mode is the manner in which the item or operation potentially fails to meet or deliver the intended function and associated requirements.*"

Depending on the level of integration in the specified system, design or process, a failure mode may cascade over several hierarchical levels (Liu, 2016; Carlson, 2012). Potential failure modes are normally identified through the review of warranty records, historical documentation and customer complaints (Stamatis, 2003).

In the context of product development process, failure can be categorised into two types (Carlson, 2012). First, products' failures, those malfunctions influence the product/systems' functionality, safety and regulatory concerns (Carlson, 2012). These issues could arise from for example, the following:

- The required products' specifications (Carlson, 2012).
- Engineering noises like meeting the environmental requirements (Kimita et al., 2021), interfaces between components/systems (Henshall, Campean and Rutter, 2014; Carlson, 2012) and products' degradation (Bektas, Alfudail and Jones, 2017; Carlson, 2012).

The second failure's category is the process's failure (Carlson, 2012). This category concerns factors that affect the products' quality and manufacturing/assembly process's reliability (Carlson, 2012), as well as those pose dangers to environment (Vinodh, Arvind and Somanaathan, 2011). Those failures could result from for example, the following:

- Used materials (Vinodh, Arvind and Somanaathan, 2011).
- Used processing procedures (Riggs, 2017, Carlson, 2012; Vinodh, Arvind and Somanaathan, 2011).

Effects analysis, however, is a term used in the product development process to describe the evaluation process when a failure occurred, and the consequences of that failure (Liu, 2016; Carlson, 2012; Stamatis, 2003). In the context of FMEA, an effect can be defined as follows:

> "*A description of the impact of a failure mode on the operation, function, or status of the part, assembly, subsystem, system, product, customer, manufacturing operations, manufacturing operators, manufacturing tooling and equipment, or government regulations*." Stamatis (2003, p. 426: Glossary)

Just as the failure mode may have more than one effect, an effect could be the result of more than one failure mode (Carlson, 2012). There are three methods used to categorise a failure effect (Carlson, 2012). Firstly, the "local effect" denotes where the impact of failure is noticed at item level or in adjacent items (Carlson, 2012). The second category is known as the "next higher-level effect" and indicates the failure consequence at the next higher level (Carlson, 2012). The last of the effect categories is the "end effect", which demonstrates the failure consequences observed on the top-level system or for the end user (Carlson, 2012). Therefore, FMEA deployment provides a systematic approach to compare and examine all possible ways in which failures could occur from low to high levels by considering the local, next level and end effects (Carlson, 2012; Stamatis, 2003).

FMEA deployment is geared by the metric of Risk Priority Number (RPN) to facilitate the process of ranking failures for control (Liu, 2016; Carlson, 2012; Stamatis, 2003). RPN is the product of three ranking rates (Liu, 2016; Carlson, 2012; Stamatis, 2003). First, severity (S) is the rate assigned to the effects of a failure mode to classify the seriousness of the failure that is under analysis (Liu, 2016; Carlson, 2012; Stamatis, 2003). Next, occurrence (O) is the rate reflects the likelihood of the failure, due to a certain cause, will occur (Liu, 2016; Carlson, 2012; Stamatis, 2003). Lastly, detection (D) rate which exchangeably represents the probability of the actions suggested to detect, prevent or minimise the impact of the failure (Liu, 2016; Carlson, 2012; Stamatis, 2003). RPN is calculated as follows (Liu, 2016; Carlson, 2012; Stamatis, 2003):

$$RPN = S \times O \times D \quad (1)$$

To introduce a prioritisation scheme, the focus of executing the proposed control actions should be pointed to those failures with high RPNs scores for further reduction (Peeters, Basten and Tinga, 2018; Spreafico, Russo and Rizzi, 2017; Carlson, 2012; Menis et al., 2012; Stamatis, 2003). Regardless of other measures, some use severity rate (S) to rank the priority for tackling failures, particularly those are related to system functions (Riggs, 2017). However, a threshold value can be used to select which RPNs are going to be improved, as presented in Peeters, Basten and Tinga (2018).

There are two main parts for performing FMEA. The former is identifying the potential failure modes, their causes, effects and the feasible control actions (Liu, 2016; Carlson, 2012; Stamatis, 2003). This part should be done alongside with the process of detailing product designs; to catch the potential failures across all product levels and in the enabled manufacturing and assembly processes (Carlson, 2012). The second part is evaluating and ranking the criticality of the identified failure modes (Liu, 2016; Carlson, 2012; Stamatis, 2003). The criticality of the failure is ranked by assigning RPN value for each cause that initiates the failure (Liu, 2016; Carlson, 2012; Stamatis, 2003). Following that, the design is revised to identify and trace the proposed failures-related control actions and investigate their effectiveness, which is managed by another FMEA deployment to scan whether the determined RPNs have been either minimised or maximised (Carlson, 2012; Stamatis, 2003).

FMEA is elaborately detailed and involves a well-defined procedure (Liu, 2016; Carlson, 2012; Stamatis, 2003). Figure 2 presents the general procedure for implementing FMEA. There are 11 steps generally involved in performing FMEA to ensure the success of the analysis as follows (Carlson, 2012; Stamatis, 2003):

1. Listing the targeted items to be evaluated.

2. Listing the main design and process-related features.
3. Identifying the modes of the current and potential failures.
4. Identifying the consequences for each mode of failures (i.e., the impact of the failures identified at the local level and next to the highest).
5. Rating the severity (S) for each effect in the scale of '1' to '10': a standard example is presented in Table 1.
6. Identifying the causes leading to these failures.
7. Rating the probability of occurrence (O) of each cause in between '1' to '10', a criterion example is shown in Table 2.
8. Identifying the best process/design controls and indicators (i.e., by detecting or preventing the motivated causes and participate to reduce any, or all measures of S and O).
9. Rating the probability of detection (D) in the scale of '1' to '10' for each control assigned: an example is available on Table 3.
10. Calculating the RPN to prioritise failures.
11. Listing the action plans to follow-up and perform the identified control programs and minimise the likelihood/the impacts of failures.

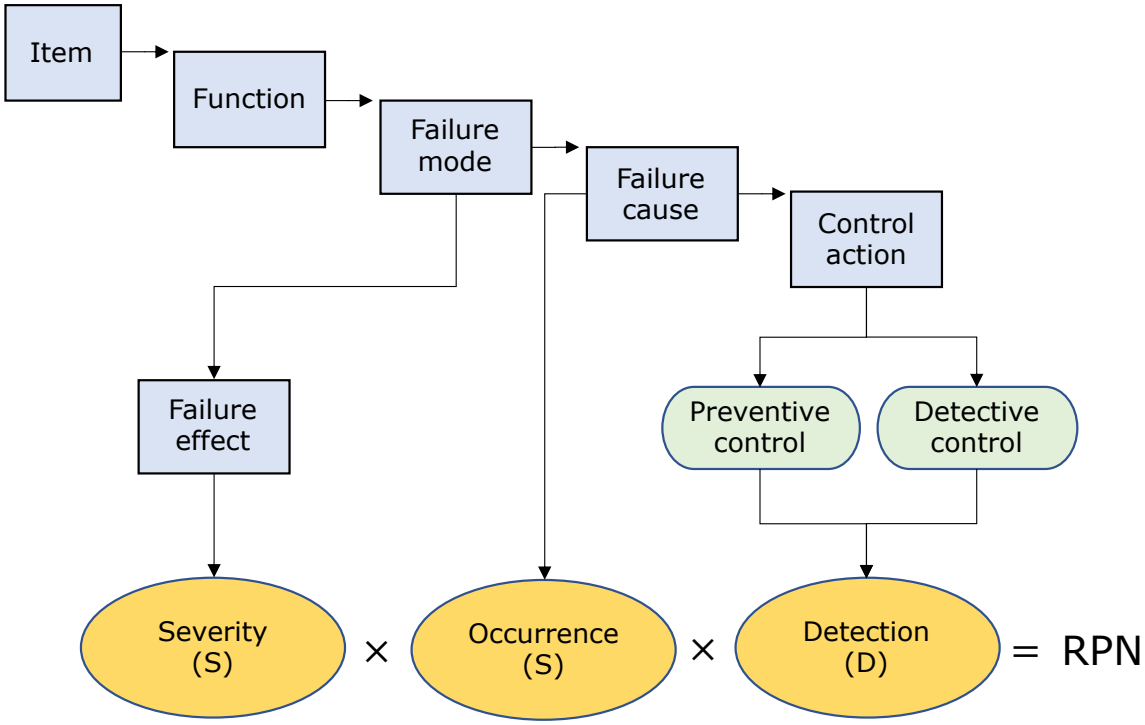


Figure 2: The sequence of performing FMEA

Table 1: Illustration of qualitative ratings for the severity of a failure mode, adapted from Stamatis (2003)

Rate (S)	Severity level	Criteria
10	Hazardous	Hazardous effect. Safety related, sudden failure and non-compliance with government regulation
9	Serious	Potential hazardous effect. Able to stop product, time dependent failure and potential non-compliance with government regulation
8	Extreme	Very dissatisfied customer. Product and system inoperable but safe
7	Major	Dissatisfied customer. Product performance severely affected but functionable and safe and system impaired
6	Significant	Discomfort on customer experiences. Product performance degraded, but operable and safe. Partial failure, but operable
5	Moderate	Some dissatisfaction on customer experiences and moderate effect on product or system performance
4	Minor	Minor nuisance on customer experiences and minor effect on product or system performance
3	Slight	Slightly annoyed customer and slight effect on product or system performance
2	Very slight	Customer not annoyed and very slight effect on product or system performance
1	None	No effect

Table 2: Illustration of qualitative ratings for the occurrence of a failure mode, adapted from Stamatis (2003)

Rate (O)	**Occurrence level**	**Criteria**
10	Almost certain	History shows failures exist from previous or similar designs
9	Very high	Very high number of failures is likely
8	High	High number of failures is likely
7	Moderately high	Moderately high number of failures is likely
6	Medium	Medium number of failures is likely
5	Low	Occasional number of failures is likely
4	Slight	Few numbers of failures is likely
3	Very slight	Very few numbers of failures is likely
2	Remote	Rare number of failures is likely
1	Almost never	Failure is unlikely where history shows no failure

Table 3: Illustration of qualitative ratings for the failure detection, adapted from Stamatis (2003)

Rate (D)	Detection level	Criteria
10	Almost impossible	Unavailable techniques
9	Remote	Available unproven or unreliable techniques
8	Very slight	Proving durability tests on system components
7	Slight	Available tests with prototypes with system components
6	Low	Tests on similar system components
5	Medium	Tests on pre-production of system components
4	Moderately high	Tests on early prototype system components
3	High	Simulation and, or modelling in early stage
2	Very high	Proven computer analysis existing in the early stage of the design process
1	Almost certain	Proven detection methods presented in the concept stage

For the RPN, it should be noted that every firm may have its own grading system for severity (S), occurrence (O) and detection (D), even for every FMEA application. Severity rating schemes for instance may differ but they should have a clear statement of the impact of a such failure on customers' experience, as presented on Riggs (2017) for aeroengine applications and Stamatis (2003) for automotive applications. As observed in both standards, a high value implies a critical score (i.e., catastrophically severe and very regular occurrence). For more consistency and robust results, the rating scheme chosen for RPN's measures must be followed throughout the deployment of FMEA (Carlson, 2012; Stamatis, 2003).

However, there are several administrative factors that help to maintain the full deployment of FMEA. One of these is the timing of FMEA deployment,

which stipulates that FMEA should be implemented as soon as the data is made available (Riggs, 2017; Paciarotti, Mazzuto and D'Ettorre, 2014; Carlson, 2012; Segismundo and Miguel, 2008; Cassanelli et al., 2006; Stamatis, 2003). This implies that FMEA as a practice is meant to be a proactive action plan, and not a simple fire-fighting tool. FMEA deployment is of no value where the proposed control actions are not put in place to address failures (Riggs, 2017; Carlson, 2012; Cassanelli et al., 2006).

Another key factor is the level of detail required to complete the process of FMEA deployment (Peeters, Basten and Tinga, 2018; Riggs, 2017; Spreafico, Russo and Rizzi, 2017; Carlson, 2012; Menis et al., 2012; Stamatis, 2003). This level of detail can be determined by the reliability and quality requirements (Peeters, Basten and Tinga, 2018; Riggs, 2017; Carlson, 2012; Stamatis, 2003). FMEA deployment is required to cover every end item together with every possible connection to other components (Peeters, Basten and Tinga, 2018; Riggs, 2017; Spreafico, Russo and Rizzi, 2017; Carlson, 2012; Menis et al., 2012; Stamatis, 2003).

To achieve a high quality, FMEA is executed through six main moves as demonstrated in Figure 3 (Carlson, 2012). Starting from FMEA scope, its deployment should be limited to specific systems and components; so that is for establishing the boundaries and maximising the benefits of FMEA deployment (Carlson, 2012). Then, the functions concerned and the associated failure modes should be determined to understand the impact of those modes and assess the possible improvement actions (Carlson, 2012). The next is to perform a detailed analysis and prioritise the criticality of failures using RPN measure (Carlson, 2012). Lastly, FMEA review is the activity of evaluating the FMEA conducted (Carlson, 2012). Every FMEA process should have an owner, who can revise the progress of FMEA and approve the relevant outputs (Carlson, 2012).

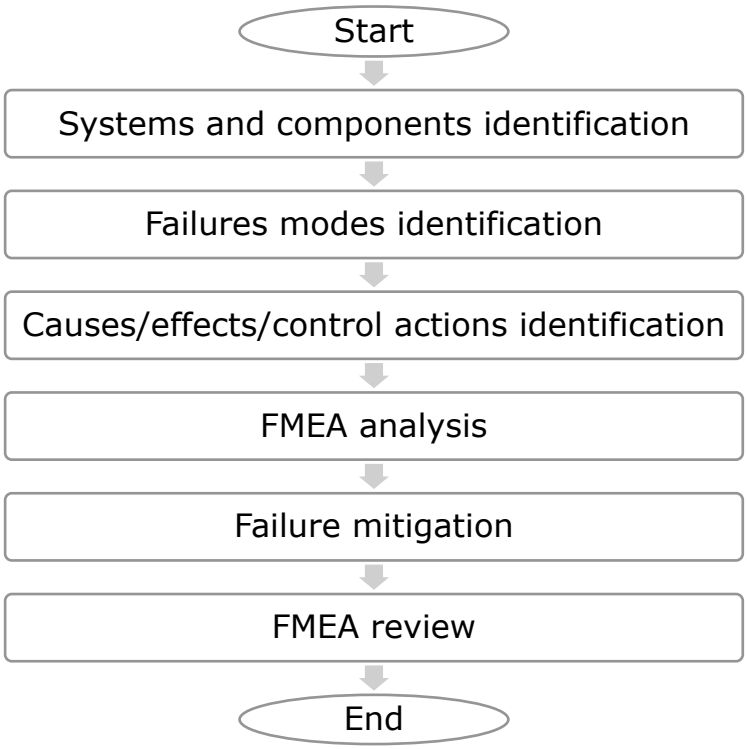


Figure 3: The main activities for deploying FMEA, adapted from Carlson (2012)

2.1.2. FMEA deployment models

Failures can occur during the product development process and products being in-service (Riggs, 2017; Carlson, 2012). However, as Riggs (2017) points out, decisions made during the design process have an impact on the downstream process like the operations of a product being in-service. Therefore, proactive analysis and mitigation process are required to determine the capability of manufacturers to implement engineering changes in first instance and address the requirements of product services (Riggs, 2017; Carlson, 2012; Stamatis, 2003). This also leads to speed up the product development process and deliver the product on the planned time (Riggs, 2017; Carlson, 2012; Stamatis, 2003).

FMEA adoption, as proposed in the literature and practise, can provide a thorough framework that demonstrates the necessity of evaluating design

and process flaws throughout the product's early development process. Early anticipation, also known as feed forward planning, implies anticipating such information as early in the product development process as feasible, so that corrective actions developed in the early stages account for downstream limitations and possibilities (Riggs, 2017; Carlson, 2012; Stamatis, 2003). In general, FMEA can be used to investigate different manufacturing issues including manufacturability (Riggs, 2017; Carlson, 2012; Stamatis, 2003), safety (Riggs, 2017; Carlson, 2012), services (Riggs, 2017) and recyclability (Abdullah et al., 2014). These elements reflect various stages of the product's life cycle.

Much of the new product development literature emphasise on the use of multi-disciplined teams as a strategy for improving not just the product development timelines but also the product’s quality. FMEA deployment brings those such teams to gather and address the potential issues in the product development. As suggested by Riggs (2017), the cross-functional team required for deploying FMEA should include expertise from manufacturing engineering, design engineering, services, quality and suppliers. Those team, as Riggs (2017) suggests, should have expertise on product functional/safety requirements, producibility, product assembly, installation and product’s service life.

Generally, FMEA can be applied in any phase of the production management starting from prior project risks assessment (Zheng, Liu and McMahon, 2010; Carbone and Tippett, 2004; Stamatis, 2003)) across the product development process (Carlson, 2012; Chan, Ip and Zhang, 2012; Hassan et al., 2010; Stamatis, 2003) down over to the product service cycle (Geum, Cho and Park, 2011; Lipol and Hag, 2011), like Service FMEA as presented in Geum, Cho and Park (2011) for post-production assessment. To provide focus, this study discusses the application of FMEA in the product development and prior production process, these applications are: Functional, Design and Process FMEAs.

Product development is the whole process of transforming a conceptual idea into tangible and profitable products (Hart, 1996). Generally, there are four stages for developing a product, as presented in Figure 4. First, design concept is a planning stage to build the framework of the design process, where the product design is conceptualised and evaluated to meet customer needs (Li, Kim and Jeswiet, 2015). This stage is also called preliminary design, pre-design, schematic design or conceptual design. Second, detailed design is an execution phase where the design concepts are augmented and refined with all associated specifications and estimates including the build-up costs (Li, Kim and Jeswiet, 2015). Third, process planning is a decision-making process whereby operational processes and their sequences are determined (Kulkarni, Marsan and Dutta, 2000). In this phase, parts designs are interpreted to specify the relevant production and assembly processes (Kulkarni, Marsan and Dutta, 2000). Finally, production is an ongoing activity to convert the preliminary stages into finished products (Kulkarni, Marsan and Dutta, 2000).

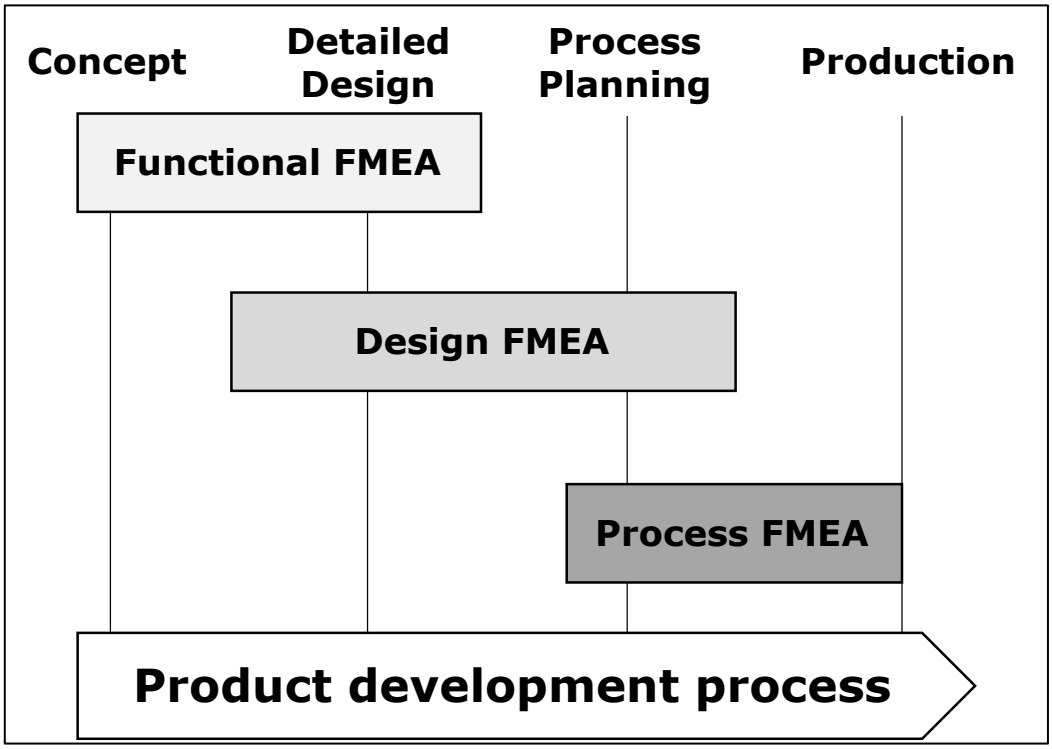


Figure 4: The deployment models of FMEA in the product development context, inspired by Würtenberger et al. (2014)

For the application of FMEA, each FMEA model should be executed at different stages in the product development process as demonstrated in Figure 4. FMEA is initially conducted at the concept level and continued for other levels in the product development process. Table 4 presents the summary of these models to which shows the differences between Functional, Design and Process FMEAs.

Table 4: Summary of FMEA deployment models, in the application of the product development process

Type of FMEA	Functional FMEA	Design FMEA	Process FMEA
Focus	Determine system and product-related failures (Carlson, 2012; Burge, 2011)	Determine failures related to embodiment and detailed designs (Riggs, 2017; Pawar and Mukhopadhyay, 2015; Carlson, 2012; Teng et al., 2006; Stamatis, 2003)	Determine product-related and process failures (Riggs, 2017; Carlson, 2012; Stamatis, 2003)
Failure modes	On product and system functions (Carlson, 2012; Burge, 2011)	On product design (Riggs, 2017; Pawar and Mukhopadhyay, 2015; Carlson, 2012; Teng et al., 2006; Stamatis, 2003)	On manufacturing and assembly processes (Riggs, 2017; Carlson, 2012; Stamatis, 2003)
Causes	Both non and functional requirements (Carlson, 2012; Burge, 2011)	Engineering efforts (Riggs, 2017; Pawar and Mukhopadhyay, 2015; Carlson, 2012; Teng et al., 2006; Stamatis, 2003)	From manufacturing and assembly processes (Riggs, 2017; Carlson, 2012; Stamatis, 2003)
Effects	Impacts on the product and customers (Carlson, 2012; Burge, 2011)	Impacts to the connected items/customers and enabled process (Riggs, 2017; Pawar and Mukhopadhyay, 2015; Carlson,	Impacts on product quality and local/ downstream operations (Riggs, 2017; Carlson, 2012; Stamatis, 2003)

		2012; Teng et al., 2006; Stamatis, 2003)	

2.1.2.1. Functional FMEA

Functional FMEA, or called System FMEA, is applied in the concept and detailed design stages of product development to evaluate the identified product and system levels-related failure modes, their effects and causes (Carlson, 2012; Burge, 2011). It is a member of FMEA family, and it differs from its siblings as it concentrates on the abstraction levels of product and system levels (Carlson, 2012; Burge, 2011). Prior to realising the design of components, it is applied to validate that the system design specifications can reduce the risk of a functional failure to the lowest level, which conceivably influences the design and make the system resilience to failures (Carlson, 2012; Burge, 2011). As illustrated in Figure 4, Functional FMEA is deployed in the concept stage, and continued to cover part of the detailed design stage (Carlson, 2012; Burge, 2011). The information is usually used to develop Design FMEA (Carlson, 2012).

2.1.2.2. Design FMEA

Design FMEA is a design risk assessment that is specifically applied in the product design to assess failures that were initiated by design deficiencies (Riggs, 2017; Carlson, 2012; Teng et al., 2006; Stamatis, 2003). Design FMEA plays a role in assessing and transferring the product requirements to the manufacturing and assembly processes (Riggs, 2017; Pawar and Mukhopadhyay, 2015; Carlson, 2012; Teng et al., 2006; Stamatis, 2003). Potentially, it also helps to improve the design iteration process (Riggs, 2017; Pawar and Mukhopadhyay, 2015; Carlson, 2012; Teng et al., 2006; Stamatis, 2003). Design iteration is an iterative loop of proposals, testing and modification to arrive at the design desired for developing products (Smith and Eppinger, 1997).

However, Design FMEA should be carried out well in advance, before releasing the design drawing to identify the appropriate control actions and proactively prevent further failures (Riggs, 2017; Pawar and Mukhopadhyay, 2015). As can be seen in Figure 4, the employment of Design FMEA begins between concept and process planning phases and works simultaneously with Functional and Process FMEAs (Riggs, 2017; Pawar and Mukhopadhyay, 2015). During these phases, Design FMEA is iteratively revised as the design being decomposed to validate the design parameters chosen for a specified functional performance requirement (Riggs, 2017; Pawar and Mukhopadhyay, 2015).

Design FMEA provides a list of key failures in the form of higher RPNs, that should be addressed by the improvement team during the next phases of the product development (Riggs, 2017; Carlson, 2012). Design FMEA also can be used as input to develop Process FMEA, as it can inform the Process FMEA with the effects and severity of certain product failure modes (Riggs, 2017; Carlson, 2012; Stamatis, 2003).

2.1.2.3. Process FMEA

Process FMEA is an application of FMEA in which is applied in the manufacturing and assembly processes for a certain item, so to identify and evaluate the potential failures (Riggs, 2017; Carlson, 2012; Stamatis, 2003). Additionally, Process FMEA supports the determination of the impacts of design-related and operational failures and identifying/prioritising the actions required to eliminate those failures (Riggs, 2017; Carlson, 2012; Stamatis, 2003). In top of that, it is a living document that should be introduced in advanced to be used as a guidance and reference for carrying the production process (Riggs, 2017; Baghery, Yousefi and Rezaee, 2016; Carlson, 2012; Stamatis, 2003). When the initial design has been created and the manufacturing procedures have been discussed, the employment of Process FMEA is carried out in parallel with Design FMEA (Riggs, 2017; Carlson, 2012; Stamatis, 2003).

2.1.3. Drivers for adopting FMEA

2.1.3.1. Defect prevention approach

Zero-Defect Manufacturing (ZDM) is a manufacturing strategy coined by Philip Crosby in 1979 to minimise the number of defective products and errors in manufacturing and assembly processes to nearly zero (Crosby, 1979). The journey towards ZDM begins by introducing the right first-time designs, meaning products should be manufactured and assembled within the given original design tolerances with minor defects (Suresh, Ramabalan and Natarajan, 2016; Batalha, 2012; Parker, 2006; Batchelor and Schmidt, 2000; Crosby, 1979). Recently, ZDM has become an evolving concept that has received more attention in academia and practice as a goal of preventive management (Di Foggia and D'Addona, 2013; Calvin, 1983), and continued to grow in importance, especially for sensitive industries such as the aerospace sector (Riggs, 2017; Zhan, Zhao and Wang, 2000).

In Crosby' book, the preventive management system is defined as the best practice to address ZDM. To extend and support this claim, Rolls-Royce Holding has launched its Zero-Defect program in 2016 to shift its practice from reactive to proactive (Riggs, 2017). Defect prevention is a proactive strategy that is applied to determine the causes of problems and prevent them from occurring, or at least minimise the likelihood of them (Riggs, 2017; Chan, Ip and Zhang, 2012; Mays et al., 1990). Rolls-Royce Holding' approach involves a set of practices and tools combined together to systematically monitor and evaluate the performance of the product development process (Chan, Ip and Zhang, 2012). One of these practices is proactively appraising the product and process concerned to identify and mitigate the potential failures as early as possible (Riggs, 2017; McMahon and Browne, 1999; Gevirtz, 1994).

Proactive failure assessment is one of the crucial actions to create awareness of failures and identify the consequences effects (Riggs, 2017;

Liu, 2016; Carlson, 2012; Segismundo and Miguel, 2008; Chin, Chan and Yang, 2008; Lam, Sherwood and Shu, 2001; Montgomery and Marko, 1997; Teng and Ho, 1996; Bednarz and Marriott, 1988). This practice has a direct and extensive influence on performance of the product development process, which greatly affects the product cost and quality (Albertelli, 2019; Doshi and Desai, 2017; Riggs, 2017; Vinodh and Santhosh, 2012).

For example, correcting problems in the design stage is considered minimal as the cost might be limited to re-designing processes (Riggs, 2017). This argument is supported by Riggs (2017), Campean, Henshall and Rutter (2013), Yang, Basem and El-Haik (2003), Johnson and Khan (2003) and Kara-Zaitri et al. (1991), who outline that adopting FMEA is the most indispensable approach for supporting problems prevention.

FMEA is set to form a defect prevention practice for managing the quality of products and processes (Riggs, 2017; Schmidt, 2013; Carlson, 2012; Stamatis, 2003; Gevirtz, 1994; Webber, 1990). This can be clearly reflected through its aim to prevent as many potential failures as possible; by identifying them and taking appropriate up front mitigating actions in all stages of the product development. By using RPN metric, FMEA execution provides an effective approach to categorise risks and assure that all problems associated with products and processes are addressed based on three dimensions, reflecting different perspectives (Liu, 2016; Carlson, 2012; Stamatis, 2003). As pointed out previously, these are: severity of failures (S), failures occurrence (O) and ability for detecting and preventing failures (D).

Doing FMEA effectively, it can contribute to reduce both the internal cost due to rework and the like, also the external cost such as warranty costs, which of course leads to improve customer satisfaction (Carlson, 2012). FMEA deployment has been found on several occasions specifically in the product developmental process imperative to enable the prevention of the

potential failures (Dumitru and Cherciu, 2015; Parsana and Patel, 2014; Chan, Ip and Zhang, 2012). For example, Rolls-Royce Holding has deployed Process FMEA in the development of aeroengine Trent-XWB, the sixth generation of the Trent family (Albertelli, 2019). This deployment has participated to launch the aeroengine production with zero-defects (Albertelli, 2019). GKN Ltd, an automotive and aerospace company, has also adopted various Zero-Defects toolkits including Process FMEA on the production process of aeroengine' fan cases, and had saved two quarters of the time planned (Albertelli, 2019).

2.1.3.2. The role of FMEA deployment to document knowledge

To establish a robust design, engineers are required to hold a high level of specific knowledge and expertise for designing the products concerned. Discussions accumulated over the engineering and organisation understandings and familiarities of products and processes failures provide a very valuable source of knowledge for the next generation of engineering products and processes (Baghery, Yousefi and Rezaee, 2016; Teoh and Case, 2004). FMEA has been widely used for this purpose to record such information and act as a communication tool that facilitates the synergistic value of teamwork and in doing so, supports a cross-functional and multi-disciplinary team efforts (Liu, 2016; Carlson, 2012; Chin, Chan and Yang, 2008; Segismundo and Miguel, 2008; Teng et al., 2006; Stamatis, 2003; Lam, Sherwood and Shu, 2001; Montgomery and Marko, 1997). According to Carlson (2012) and Stamatis (2003), the well-documented FMEA records the historical information of the following:

- Product and process requirements.
- Design and process characteristics that contribute to the potential failures.
- Failure modes, failures causes and possible effects.
- Methods and procedures to detect and prevent product and process failures.

- RPNs of the product and process deficiencies.
- The responsible team.

In addition, FMEA documents have been acknowledged as key contributors to the successful implementation of the Design Verification Plan (DVP) for prioritising and sourcing improvement actions (Riggs, 2017; Carlson, 2012; Teng et al., 2006; Stamatis, 2003; Ginn et al., 1998). The FMEA-derived control actions are often fed into DVP to update and develop the improvement measures (Riggs, 2017; Carlson, 2012; Teng et al., 2006; Stamatis, 2003; Ginn et al., 1998). DVP is the process of documenting all strategies for product verification plans suggested to address design specifications and requirements (Carlson, 2012). This information is listed in the DVP sheet together with the associated physical tests and analytical models; validating whether the product satisfies its requirements (Riggs, 2017; Carlson, 2012; Teng et al., 2006; Stamatis, 2003; Ginn et al., 1998). Consequently, this information is important as it can be used to guide necessary design changes (Carlson, 2012; Teng et al., 2006; Ginn et al., 1998).

In addition to the documentation advantages, FMEA deployment can be used as a tracking approach for assessing the control actions identified to tackle failures (Baghery, Yousefi and Rezaee, 2016; Teng et al., 2006). With the evolve of the product development, FMEA is continually implemented and revised to determine and chase RPNs, as well as reflecting design changes and knowledge identified as valuable input to the forthcoming assessment process (Riggs, 2017; Carlson, 2012; Stamatis, 2003). The determined RPNs are compared with each other for prioritisation purpose, and the higher RPNs are classified as a first priority for the improvement team to start with and implement the appropriate control actions (Peeters, Basten and Tinga, 2018). To assess the effectiveness of these control plans, another cycle of FMEA is then performed with the same procedure and with new RPNs being determined (Riggs, 2017; Carlson, 2012; Stamatis, 2003). Meaning that, all potential improvements

suggested including design changes are revised and re-assessed to chase the associated impacts on the performance of product development and ensure that RPNs of failures are lowered (Riggs, 2017; Carlson, 2012; Stamatis, 2003).

2.2. Review of focal literature on FMEA deployment

Considering FMEA approach has been proven as a successful and powerful tool in assessing and identifying control actions to eliminate the potential failures (Liu, 2016; Carlson, 2012; Segismundo and Miguel, 2008; Chin, Chan and Yang, 2008; Stamatis, 2003; Lam, Sherwood and Shu, 2001; Montgomery and Marko, 1997; Teng and Ho, 1996; Bednarz and Marriott, 1988), its current version still encounters a range of challenges in various applications (Emovon et al., 2015; Onofrio, Piccagli and Segato, 2015; Henshall, Campean and Rutter, 2014; Soufhwee et al., 2013; Vinodh and Santhosh, 2012; Yu et al., 2011; Ebrahimipour, Rezaie and Shokravi, 2010; Abbas and Vachtsevanos, 2009; Walker et al., 2009; Chen, 2007; Sharma, Kumar and Kumar, 2005; Rhee and Ishii, 2003). One of these challenges that receives more attention is the inconsistency in the ranking criterion of RPN measure. The relative importance among severity of failures (S), failure occurrence (O) and detection/prevention of failure (D) rates is not considered (Chen, 2007; Sharma, Kumar and Kumar, 2005; Rhee and Ishii, 2003). Different combinations of S, O and D measures can generate the same value of RPN measure, where the implications of risks may be dissimilar (Chen, 2007; Sharma, Kumar and Kumar, 2005; Rhee and Ishii, 2003). Thus, RPN is not enough measure to prioritise actions, where the severity score of failure (S) can be sometimes supportive to rank actions (Riggs, 2017).

To improve this shortcoming, extensive developments have been demonstrated in the literature, where diverse approaches were suggested to improve the conventional RPN measure and re-prioritise failure modes. The major trends of these developments were extended upon different methodologies; for example, multi-criteria decision making, such as those are presented in Lo and Liou (2018) and Liu et al. (2015), and fuzzy logic

models, such as those are available on Safari, Faraji and Majidian (2016) and Tay and Lim (2006).

There are other challenges highlighted which are exacerbated in situations of a product with a high level of integration (Henshall, Campean and Rutter, 2014; Soufhwee et al., 2013; Yu et al., 2011; Abbas and Vachtsevanos, 2009; Walker et al., 2009), which may be characterised by the presence of a multitude of integrated functionalities, intricate hierarchical system structures and a large volume of design details. However, the scope of this research is limited to these challenges as presented in the next sections. The following sections elucidate these challenges in three dimensions: economical, practical and managerial.

2.2.1. Deployment challenges

2.2.1.1. Economic challenge

FMEA has being perceived as a time-consuming and tedious process due to the resources required for its execution (Peeters, Basten and Tinga, 2018; Estorilio and Posso, 2010; Zheng, Liu and McMahon, 2010; Trammell, Lorenzo and Davis, 2004; Wetterneck et al., 2004). FMEA deployment can require an excessive use of resources, requiring significant monetary expense, time commitment and personnel involvement, leading to even longer total design times thus, making it not only time consuming, but also quite expensive (Peeters, Basten and Tinga, 2018; Carslon, 2012; Estorilio and Posso, 2010; Zheng, Liu and McMahon, 2010; Trammell, Lorenzo and Davis, 2004; Wetterneck et al., 2004).

Zheng, Liu and McMahon (2010) and Trammell, Lorenzo and Davis (2004) argue that FMEA deployment being tedious, as it is almost applied to cover all of product features rather than the critical features. This creates a large amount of data that requires extensive resources to digest and provide useful information for completing the process of FMEA deployment (Zheng, Liu and McMahon, 2010; Trammell, Lorenzo and Davis, 2004). In addition,

FMEAs generated are followed up with another deployment of FMEA as this is used to trace potential improvements, which requires yet further resources (Riggs, 2017; Carlson, 2012; Stamatis, 2003).

Another issue, Riggs (2017), Liu (2016), Carslon (2012), Stamatis (2003) and Price (1996) argue that the driver for FMEA being slow-moving methodology because the practice requires to regular execution and review whenever improvement changes have been applied. This is to ensure the effectiveness of the improvements as well as altering the effects of the evaluated failures and determine new potential failures (Riggs, 2017; Liu, 2016; Carlson, 2012; Stamatis, 2003).

Over the years, continuous research efforts have been made in an attempt to reduce the time taken to perform FMEA (Peeters, Basten and Tinga, 2018; Banduka, Veža and Bilić, 2016; Chen, Wu and Qin, 2014; Hata and Kimura, 2003; Price and Taylor, 2002). For example, Price and Taylor (2002) developed an automated FMEA known as AutoSteve, which sought to reduce the time taken to identify the critical failures. The establishment of this system works through using a blend of qualitative simulation and functional abstracting techniques to provide rapid and accurate early analysis reports. As Price and Taylor (2002) claim, this system can allow users to compare different reports on the same scale.

In line with Price and Taylor's work, Hata and Kimura (2003) developed a computer-aided FMEA technique to automate the deployment of FMEA and make it accessible to use with efficient time. This work is based on failure analysis and function-dependency path. Another improvement, Banduka, Veža and Bilić (2016) integrated lean six sigma tools with Process FMEA through four basic Toyota principles: Genchi Genbutsu (i.e., go and see for yourself), Kaizen (i.e., continuous improvement), teamwork and respect for people and challenge. This work was aimed at promoting an organised way for gathering ideas from different perspectives and developing the data collection plans.

2.2.1.2. Practical challenges

Debates have been around the practical implementation pitfalls of FMEA for unambiguously identifying primary functional requirements and failure modes (Peeters, Basten and Tinga, 2018; Spreafico, Russo and Rizzi, 2017; Henshall, Campean and Rutter, 2014; Menis et al., 2012; Kmenta and Ishii, 2004). Building on this, the current approach of FMEA impedes the systematic capture of functional requirements in a detailed bottom-up approach and transfer these requirements to process domain (Henshall, Campean and Rutter, 2014; Kmenta and Ishii, 2004). Meaning that, the traditional practice of FMEA is not able to cascade and capture failures over the different applications of FMEA (Henshall, Campean and Rutter, 2014; Soufhwee et al., 2013; Carlson, 2012; Xiao et al., 2011; Popović, Vasić and Petrović, 2010; Teng et al., 2006; Kmenta and Ishii, 2004). These pitfalls of FMEA potentially contribute to the economic challenge presented above in terms of being able to utilise time and cost appropriately.

As aforementioned, FMEA is a bottom-up and structured approach to analyse failure modes, design and process deficiencies. The degree of system integration and the importance of the level of knowledge required for evaluating new/modified designs point to the challenge for performing FMEA to maintain the depth of analysis required (Peeters, Basten and Tinga, 2018; Spreafico, Russo and Rizzi, 2017; Menis et al., 2012). As a result, this presents difficulties for defining the start point to which the process of FMEA implementation can commence and therefore, searching for failure modes, causes and their effects (Peeters, Basten and Tinga, 2018; Spreafico, Russo and Rizzi, 2017; Menis et al., 2012).

Another criticism of FMEA deployment is that it may be difficult to meet the extensive information requirements to bridge the knowledge gap between Functional, Design and Process FMEAs and their objects, likely leading to an inability to shift the product requirements and catch the associated failures cascading over the product developmental process, illustrated in

Figure 4 (Henshall, Campean and Rutter, 2014; Soufhwee et al., 2013; Xiao et al., 2011; Popović, Vasić and Petrović, 2010; Teng et al., 2006; Kmenta and Ishii, 2004). The data required can take the form of design characteristics relating to failures (i.e., secondary functional requirements of a specified system) and empirical data relating to actual failures (i.e., causes, effects, control actions and RPNs). Cascaded failures are the diverse of consecutive failures in parts integrated in a system, which these failures are triggered and undiscovered (Kmenta and Ishii, 2004).

For example, integrated failures between system levels, with interdependences between the levels, are sometimes difficult to capture and address by using the traditional FMEA deployment (Shaker, Shahin and Jahanyan, 2019; Henshall, Campean and Rutter, 2014). This is due to the nature of FMEA and its inability to imperfectly synthesise and manage the transformation of the failures analysis downstream to detailed levels (Henshall, Campean and Rutter, 2014). It is also because of the poor connection that exists between system levels, which leads to difficulties when it comes to highlighting and tracing failure effects and their underlying causes (Henshall, Campean and Rutter, 2014; Carlson, 2012). To make a strong communication, FMEA deployment requires a systematic decomposition of the overall system in their components as far as touching the targeted ones to provide a scope for the analysis focus and a good understanding of the functions and hence failure modes associated with a particular system design (Peeters, Basten and Tinga, 2018; Henshall, Campean and Rutter, 2014).

In practice, Functional, Design and Process FMEAs are usually carried out separately, and so, as a result, several links in between are generally not understood, which clearly forms a challenge for the full and effective execution of FMEAs (Carlson, 2012; Teng et al., 2006; Ginn et al., 1998). Carlson (2012) states that all FMEAs are dependent upon each other, and every individual FMEA application is used as a form of orientation and guidance for the others. For example, Design FMEA outputs are used to

generate Process FMEA (Riggs, 2017; Carlson, 2012). Thus, integrating all FMEA procedures into one practice can lead to efficiency in their applications in terms of a more optimal resource usage (Carlson, 2012; Teng et al., 2006; Ginn et al., 1998). A significant advantage of the synchronised FMEAs is the ability to identify the cascaded failures that may escape during the product development process (Henshall, Campean and Rutter, 2014; Soufhwee et al., 2013; Xiao et al., 2011; Popović, Vasić and Petrović, 2010; Teng et al., 2006; Kmenta and Ishii, 2004).

Few studies have considered this strategic element by presenting such improvements. Kmenta and Ishii (2004) suggested the Scenario-Based FMEA approach that is organised around the failure chain (i.e., another meaning of the cascaded failure) to track the effects of failures over the product life cycle, from the failure root causes across the intermediate effects to end effects (please refer to Figure 5). This approach is potentially applicable to connect Functional with Design FMEAs; chasing the failure effects down-up to the system level, vice versa for chasing failure causes up-down to component level (Campean, Henshall and Rutter, 2013). In addition, this approach could be used to interrelate Design with Process FMEAs through transferring and tracing design-related issues over Process FMEA. However, this approach could be improved if the failure scenario is represented through a systematic approach to correlate these concerns to the associated manufacturing and assembly processes (Teng et al., 2006).

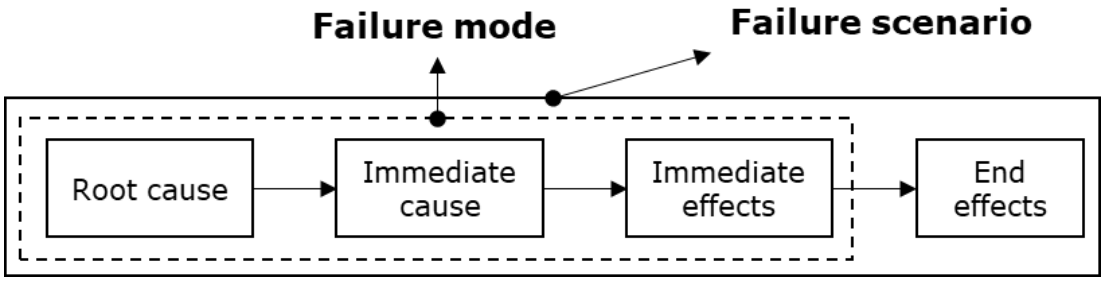


Figure 5: Failure Scenario-Based FMEA approach, adapted from Kmenta and Ishii (2004)

In addition to the Scenario-Based FMEA approach, Cooper (2015) developed and used a systematised approach for decomposing system functions and capturing all critical failure modes into Design FMEA; just using a P-Diagram to trace the next level effects, as a way for catching the cascaded failures. The P-Diagram, sometimes called Parameter Diagram, is a tool used to show the system boundaries including the input resources, noise factors and targeted outcomes (Stamatis, 2003; Juran, 1993), a schematic model is presented in Figure 6. Cooper's (2015) work has focused on the preparation process for deploying Design FMEA by using the decomposition table; however, this work has failed to acknowledge the significance of the linkage between all FMEAs. To improve this work, it would be more effective if this approach is supported with a structured tree to represent the system hierarchy. Having this tree developed could help to trace and link system levels and parallel to process domain, and consequently catch the cascaded failures (Teng et al., 2006; Mohsen and Cekecek, 2000).

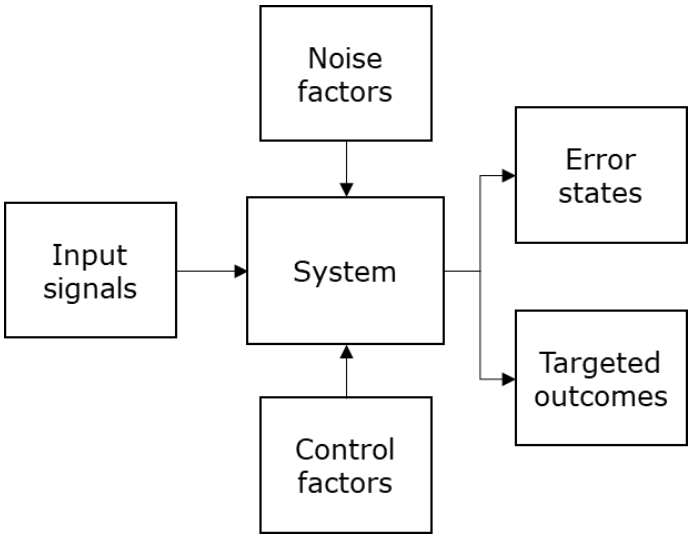


Figure 6: A representative example of P-Diagram, inspired by Carlson (2012)

Carlson (2012) elucidates various links between Functional, Design and Process FMEAs correspondingly for sharing knowledge between them and enabling their full and comprehensive execution. For the potential link

between Functional and Design FMEAs, Carlson (2012) believes using the failure chain hierarchy (i.e., developed and presented in Figure 7) can serve as a valuable tool for promoting that linkage. For example, causes at the system level can be treated as failure modes on the next level. This follows the chain of failures and can delve into the root causes and elemental failure mechanisms. On the other side of the spectrum, local failure effects at a certain level are triggered and classified as failure modes for analysis on the next upper level.

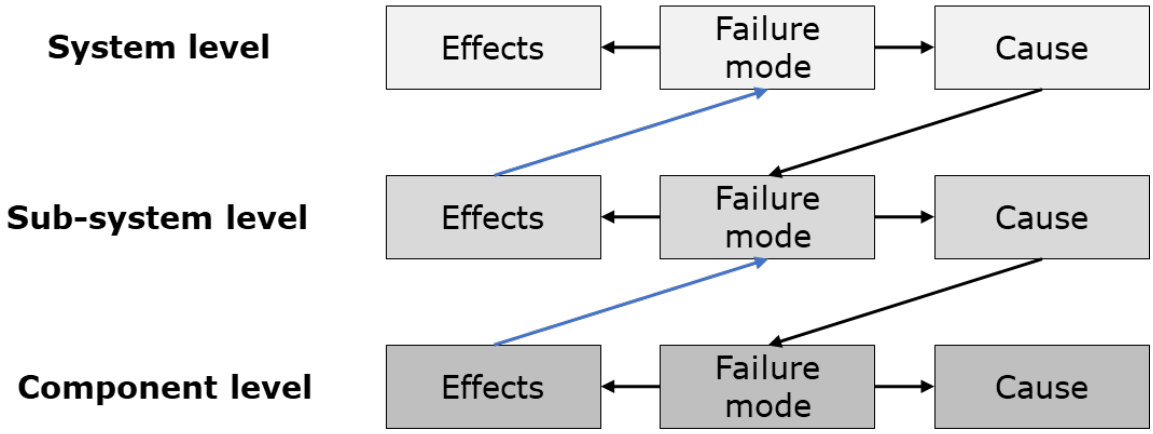


Figure 7: Failure chain hierarchy, inspired by Carlson (2012)

To potentially create a link between Design and Process FMEAs, Carlson (2012) clarifies that there are potential physical and conceptual connections between these applications. From the physical angle, Design FMEA is considered a key source to establish Process FMEA (Riggs, 2017; Carlson, 2012; Stamatis, 2003). For example, Design FMEA transfers failures and causes to be classified as effects and failures in Process FMEA simultaneously (Carlson, 2012). In addition, key product characteristics and noise factors, which may hinder the performance of products, are used as the primary links between Design and Process FMEAs (Carlson, 2012). Design FMEA team identifies and evaluates these characteristics and factors, which are then introduced to Process FMEA as prime inputs (Carlson, 2012). Then, Process FMEA team should discuss these characteristics and factors to determine the corresponding key control

characteristics, then exchanging this information back with Design FMEA team to manage design modifications (Carlson, 2012).

From a conceptual angle, a range of producibility issues linked to product designs is evaluated in the application of Design FMEA with the involvement of process and quality engineers to address these issues (Carlson, 2012). For instance, potential causes of product failures can be initiated in the related process, where Process FMEA team should go, investigate and improve process parameters that govern these product failures (Carlson, 2012). Therefore, the focus of Process FMEA should be consistence and based on the design flaws and concerns identified in the application of Design FMEA (Carlson, 2012).

2.2.1.3. Managerial challenges

An additional challenge in such situations might be posed by a lack of experience on the part of the FMEA practitioner (Banghart, Bian and Babski-Reeves, 2016; Carlson, 2012; Bluvband and Grabov, 2009). FMEA is a team-oriented approach that recruits various experiences for ensuring that failures are recognised, recorded and tackled, as well as their associated causes and effects (Carlson, 2012; Stamatis, 2003). Hence, the results of FMEA deployment are effective when the relevant team has the right level of experience and knowledge around the product components concerned (Banghart, Bian and Babski-Reeves, 2016; Carlson, 2012; Bluvband and Grabov, 2009). Creativity and brainstorming are the heart of FMEA deployment (Liu, 2016; Carlson, 2012; Stamatis, 2003). This means that the team with such expertise can take problems to the imaginary extent to understand these problems in detail (Liu, 2016; Carlson, 2012; Stamatis, 2003). Issues are beyond the knowledge and expertise of the relevant team are unlikely to be caught and solved; for example, failing to capture the potential failures and causes, then determine the associated impacts (Carlson, 2012; Stamatis, 2003).

Another important challenge could be observed via the incorrect ranking of RPN measures, which can bias the results of FMEA deployment (Lipol and Haq, 2011; Bluvband and Grabov, 2009). As explained above, FMEA is required to be applied iteratively to pursuit and mitigate the potential failures. Variation in executing FMEA can lead to disagreement on the relevant results (Bluvband and Grabov, 2009). Therefore, proper training on the concepts and procedure of such best FMEA practice to follow are essential to minimise discrepancies between the team members for estimating the RPN measures and increasing the confident in the results driven (Bluvband and Grabov, 2009).

2.2.2. Current developments

The implementation of FMEA encounters a number of challenges, as outlined in the above sections. The focus of this section is to describe the current development devoted to address the practical pitfalls of FMEA deployment. The traditional practice of FMEA is un-structured approach to define the analysis focus, where it may be difficult to specify where to investigate the failure modes and reach a certain level of details (Peeters, Basten and Tinga, 2018; Battirola Filho et al., 2017; Spreafico, Russo and Rizzi, 2017; Henshall, Campean and Rutter, 2014; Han and Zhang, 2013; Menis et al., 2012; Yu et al., 2011; Korayem and Iravani, 2008; White et al., 2007; Polak and Grabov, 2005; Arcidiacono and Campatelli, 2004; Kmenta and Ishii, 2004). Moreover, the current form of FMEA is recognised as being less able to chase and capture the cascaded failures through its implementation in the product developmental stages (Cooper, 2015; Henshall, Campean and Rutter, 2014; Soufhwee et al., 2013; Carlson, 2012; Xiao et al., 2011; Popović, Vasić and Petrović, 2010; Teng et al., 2006; Kmenta and Ishii, 2004).

In support of FMEA execution, Carlson (2012) identifies two main tasks are required for effective management of FMEA deployment: decomposing system/product functions and identifying the associated failure modes, and

synchronising FMEA procedures. However, a multiplicity of methodologies has been proposed to address each of these tasks. These proposals are claimed to improve the practice of FMEA with the aim to address the above challenges coupled with FMEA deployment. The following sections present a brief overview of the current literature contributing to each one of the FMEA management tasks identified by Carlson (2012).

2.2.2.1. System decomposition and failure identification

The first theme addresses the combination of FMEA method with other systematic approaches, specifically: Fault Tree Analysis (FTA), Function Flow Boundary Diagram (FFBD) and Analytical Hierarchy Process (AHP). These methodologies were combined with FMEA to gain the individuals benefits for providing a structured approach to decompose system functions and identify the associated failure modes. The following sub-sections display the combination of these methodologies with FMEA method.

2.2.2.1.1. Fault Tree Analysis and FMEA

Both Fault Tree Analysis (FTA) and FMEA are considered one of the well-known methodologies in the field of reliability engineering (Peeters, Basten and Tinga, 2018). The combination of these approaches has been extensively demonstrated in the literature. Recently, Peeters, Basten and Tinga (2018) proposed a framework combining FTA with FMEA approaches to guide the overall process of FMEA deployment in an iterative manner. In their approach, both FTA and FMEA methods are used in order starting by applying FTA to decompose the system functions and identify failure modes then FMEA to assess the criticality of each failure mode in a top-down to a detailed level. In this proposal, the analysis starts with the definition of a system failure event and the construction of a fault tree for a particular system as a whole. Successively, each function is further analysed with the deployment of FMEA to identify the potential failure modes and the underlined causes. Peeters, Basten and Tinga (2018) believe this model

would help to provide a map where FMEA can be applied and improve the efficiency of the resources invested for applying FMEA. Their approach was applied by additive manufacturing company to assess a metal additive manufacturing system, and Peeters, Basten and Tinga (2018) states that the company is satisfied with the proposed framework.

Yu et al. (2011) proposed a mixed approach where FTA application guides FMEA deployment. In their proposal, the system functions and failures events are determined by FTA employment and the whole fault trees are then constructed to chase the failures causes. Then, each failure event is analysed with the deployment of FMEA.

Bluvband, Polak and Grabov (2005) developed Bouncing Failure Analysis model (BFA), where both FTA and FMEA methods are combined. In this work, the analysis process begins with defining the abstract level of system functions, which are termed: end effects. The fault tree is then built to identify the potential failures in a downstream approach. By bouncing back to the abstraction level, those failures, that would have direct impact on the end effects events, are then evaluated by the implementation of FMEA. In BFA, those failures are called: single-point effects. As a second priority, the employment of FMEA evaluates the other failures with the help of interaction matrix to determine the level of impact on end effects events. This work was aimed at providing a clear link between both FTA and FMEA methods by decomposing the system functions and identifying failures. This approach suggests a reference for FMEA implementation team to rank the priority for evaluating failures by two representations of failure behaviour: end effects and single-point effects.

Han and Zhang (2013) suggested a mixed approach of both FTA and FMEA methods for the software analysis. This idea of their approach was similarly reported in Yu et al. (2011) and Bluvband, Polak and Grabov (2005), although it is customised for the software application, which is characterised with different nature. Therefore, this work is considered being

less relevant to the scope of this research. Prior to these, Arcidiacono and Campatelli (2004) studied the combination of FTA and FMEA methods in the light of Axiomatic Design (AD) approach to manage the system decomposition and FMEAs synchronisation tasks.

In the light of the requirements identified by Carlson (2012), these proposals, reported above, claimed to improve the application of FMEA by providing a hybrid approach that decomposes system functions and identify the relevant failure modes. However, these proposals do not highlight the degree by which their suggested frameworks would improve the practice of FMEA.

It should be noted that FTA method has been identified as effective for managing risks analysis in couple of applications (Ferdous et al., 2009). Because, FTA method relies on the graphical presentation of the system, that could be easier to analyse and determine the interactions between system failures (Mentes and Helvacioglu, 2011; Ferdous et al., 2009). FTA application also works in a top-down approach from the system failures down to determine the root causes (Mentes and Helvacioglu, 2011; Ferdous et al., 2009). It uses a network of logical gates, constructed by Boolean logic (i.e., And/Or logics), to manage the combination of failures causes (Mentes and Helvacioglu, 2011). Boolean logic is a mathematical method in which all values are represented in either TRUE or FALSE (Mentes and Helvacioglu, 2011). However, FTA deployment has been found inadequate; requiring extensive resource to treat all combination of failures, as the importance of the analysis focus is not managed with emphasis (Peeters, Basten and Tinga, 2018; Bertsche, 2008).

2.2.2.1.2. Function Flow Boundary Diagram and FMEA

Korayem and Iravani (2008) combined Function Flow Boundary Diagram (FFBD) method with FMEA methodology to provide a failures analysis approach in the application of Robotics. In their approach, function blocks are developed and presented in a logical way to iteratively decompose

system functions down to the component level, as well as identifying the associated failures. Korayem and Iravani (2008) use these blocks to present functions with which are sub-divided into sub-blocks. Then, FMEA is deployed to evaluate the associated failures.

White et al. (2007) used FFBD approach to build the functional architecture of a rocket aeroengine system and decompose system functions, where FMEA is then applied to evaluate these functions and the associated failure modes. Sharma, Kumar and Kumar (2005) adopted FFBD method to present the structure of the system for identifying system functions and the association among them, as well as recognising failure modes. A range of further extensions have been proposed for example, Henshall, Campean and Rutter (2014) developed System State Flow Diagram to ensure that system functions are decomposed and contained with the deployment of FMEA.

These proposals may improve the practice of FMEA to specify a functional analysis tool that provides schematic representation of the system design structure. However, the impact of combining FFBD and FMEA approaches has not been empirically investigated.

FFBD approach consists of functional blocks used to display the functions in their logical and sequential relationship; using gates (i.e., And/Or) to highlight the potential connections between functions, and by means of bathes (i.e., Go/No Go) to indicate whether there is a fault or can proceed to the next connected items (Yildirim, Campean and Williams, 2017). FFBD method is used to map the flows of functions downstream into sub-functions (Yildirim, Campean and Williams, 2017). However, this approach has been subject to criticisms, which most relates to that FFBD method is being less able to catch the combination between function chains within the whole system (Yildirim, Campean and Williams, 2017).

2.2.2.1.3. Analytical Hierarchy Process and FMEA

Considering the difficulties of FMEA employment to define the analysis scope, Battirola Filho et al. (2017) combined Analytical Hierarchy Process (AHP) method with FMEA deployment. In their approach, AHP approach is used to obtain the failure hierarchy of the product concerned and introduce an approach for classifying the sub-criteria of the hierarchal structure into three sets: severity, detection and occurrence. This work was meant to provide a supportive methodology as is for decomposing systems in a hierarchical decision structure and prioritise failures beside RPN measure.

Tang, Wang and Wang (2007) also proposed the similar by linking AHP and FMEA methods with other approaches. This was aimed at aiding the decision makers in the field of the product development to evaluate the quality characteristics; by translating customer requirements into product-quality characteristics and decomposing them into detailed levels. In their approach, AHP and other approaches were used to decompose and transform quality characteristics into sub-quality characteristics. To optimise the product, these quality and sub-characteristics are evaluated by deploying FMEA and other analytical approaches. These works described above however, lack the empirical evidence to indicate the impact of co-adopting AHP method on FMEA implementation.

AHP reports the relative importance of risks in the form of a hierarchy of objectives based on weights attributed to product elements (Wang et al., 2020). Though AHP application may provide a better focus on specific element or criteria, it has been criticised for the intensive time required for building the hierarchical structure for integrated systems and conducting the accumulated procedure of pairwise comparisons (Hartwich, 1999).

2.2.2.2. Synchronising FMEA procedures

The second theme identified by Carlson (2012) is synchronising Functional, Design and Process FMEAs into a working practice to bridge the gap in

knowledge amid them. This section presents the co-adoption of other methodologies with FMEA deployment to foster its applications. The next sub-sections discuss the combination of the following methodologies: Quality Function Deployment (QFD), Knowledge-Based System (KBS), Define, Analysis, Improve, Recommend, Evaluate and Control (DAIREC) and Axiomatic Design (AD).

2.2.2.2.1. Quality Function Deployment and FMEA

Quality Function Deployment (QFD) and FMEA methods were found in various works glued together and navigated in an organised way and supportive to each other, forming a decision tool cycle (Gu, Cheng and Qiu, 2019; Ma et al., 2019; Shaker, Shahin and Jahanyan, 2019; Chen, 2016; Liu et al., 2016; Wang and Chang, 2010; Hassan et al., 2009; Almannai, Greenough and Kay, 2008; Ginn et al., 1998). QFD approach can be used to determine the degree of correlation between customer requirements and engineering characteristics, as well as FMEA is used to evaluate these correlations (Gu, Cheng and Qiu, 2019; Ma et al., 2019; Shaker, Shahin and Jahanyan, 2019; Chen, 2016; Liu et al., 2016; Wang and Chang, 2010; Hassan et al., 2009; Almannai, Greenough and Kay, 2008; Ginn et al., 1998).

For example, Gu, Cheng and Qiu (2019) presented an improved FMEA model that aims to provide a unique approach for prioritising control actions in the part of FMEA. They suggested a new sorting scheme beside RPN measure, that is customer needs-focused. Their approach was aimed at showing the compatibility and complementarity between both methodologies, where QFD could synchronise both Functional and Design FMEAs. Their proposed model was applied to evaluate the fuel system of diesel engine.

Shaker, Shahin and Jahanyan (2019) showed the extension of QFD method to support the deployment of FMEA in the blast furnace operation of a steel-manufacturing company. In their approach, a two-phase QFD to act as a

concurrent engineering approach was used to catch the integration among failure modes and their effects, also to improve the conventional RPN measure.

Hassan et al. (2009) deployed the combined approach of QFD and FMEA to analyse the car doors. This work was designed to show how QFD can help to correlate the different FMEA deployments across the product development. To improve FMEA, QFD approach was used to identify failure modes and causes to be entered FMEA for analysis. This process was carried out among the product development cycle. In support to Hassan et al. (2009), Liu et al. (2016) adopted QFD approach to link the deployment of FMEA in different stages of the product development. QFD method was utilised to transform the customer requirements into engineering characteristics between the design process of a packing system.

Ginn et al. (1998) presented a hybrid model of QFD and FMEA methodologies to push the last upstream along the product development process by the application of QFD. They argue that both methods support each other, where both approaches improve the same issue of customer satisfaction from different perspectives (Ginn et al., 1998). They classify QFD application as the voice of customer, where it streams the customer requirements into different product development stages (Ginn et al., 1998). FMEA application, as they classify it as the voice of engineer, is applied to understand the technical perspectives of these customer requirements from design and process angles (Ginn et al., 1998). The focus of the works presented above was to reassure the interlink between both methodologies and can both effectively support each other. However, the extent of influence of co-adopting QFD method to synchronise FMEAs was not considered in all proposed approaches outlined above.

QFD is run by a series of characteristic matrices called, House of Quality (Ginn et al., 1998). These matrices comprise two lists: the customer wants, and the wants being translated into product measures (Ginn et al., 1998).

The two lists are then compared to determine the strength of the correlations between them (Ginn et al., 1998). Unlike FMEA, QFD application is iterated down until the full process of the product development is understood throughout four phases: customer requirements, components characteristics, process and production control stages (Ginn et al., 1998). However, the outcomes of QFD application has been concerned due to the system integration, time length and resources demanded (Kenger and Erixon, 2005).

2.2.2.2.2. Knowledge-Based System and FMEA

To synchronise FMEA processes and introduce a relative time/cost effective deployment, Renu et al. (2016) developed a specified Knowledge-Based System (KBS) to align Design and Process FMEAs in the form of the Knowledge Discovery and Data Mining approaches (KDDM), and query data from historical records. As defined by Kurgan and Musilek (2006), KDDM is the interdisciplinary process to retrieve and analyse data, also to extract patterns from data in specific categories. KDDM have been utilised in Renu et al. (2016) work through three steps. The first is to perform the traditional FMEA for understanding components and the associated risks. Then, a tree-decision algorithm (i.e., where it can be used for classification) is applied in the data collected to set rules. Finally, the set of the developed rules is applied in a FMEA-related KBS to identify the failure modes and consequently determine the main contacts between both methodologies of Design and Process FMEAs.

Similarly, Augustine et al. (2012) adopted KBS technique and proposed a cognitive-map system for simulating and identifying the links between different failure modes among the product development stages. By developing a dedicated KBS, the cognitive maps were constructed with which different interactive failure modes among system levels concerned are identified. The cognitive maps were also used to recognise the nodes being with failures within the causality networks. Although these works may

promote that combining KBS technique can be able to ease the flow of information between FMEA applications, they still have not made reference to the impact of co-adopting KBS method to synchronise FMEA procedures.

As proposed by Dhaliwal and Benbasat (1996), KBS technique should be generally made of: knowledge-base, inference engine, knowledge engineering tool and specific user interface. Without setting new rules being enabled, the capability of these works to facilitate new/modified designs may be limited. Because KBS is made of the demand for managing historical data, where data may be not yet understood within the deployment of FMEA.

2.2.2.2.3. Define, Analysis, Improve, Recommend, Evaluate and Control and FMEA

To fulfil the knowledge gap between Design and Process FMEAs, Soufhwee et al. (2013) proposed an approach, called Define, Analysis, Improve, Recommend, Evaluate and Control (DAIREC). This work relies on utilising parameters selected from both Design and Process FMEAs to be chased up and managed (Soufhwee et al., 2013).

DAIREC method seems to be practical for new designs introduced, where much information is absence. Although this methodology may spark off teamwork in doing multidisciplinary work, it tends to be time-consuming and inefficient for such an integrated system (Lee et al., 2013). Because this process mostly relies on brainstorming to generate the information required for building all procedures of FMEA, which is classified key part in the design process and as tedious process (Lee et al., 2013).

2.2.2.2.4. Axiomatic Design and FMEA

Mohsen and Cekecek (2000) was among the first to propose the application of Axiomatic Design method (AD) to integrate Functional with Design FMEA in a hierarchical mode. They believe that FMEA deployment can be effective

by the integration with AD approach. In a systematic manner, they clarify that AD application could describe the functional requirements and design parameters, then present the relationships between them. For instance, design parameters represent the physical means that influence the functional requirements (Suh, 2001). This may lead to determine the functional requirements failures and their causes (Mohsen and Cekecek, 2000). All associated failure modes and causes can then be evaluated by the application of FMEA (Mohsen and Cekecek, 2000). To support this suggestion, Arcidiacono and Campatelli (2004) developed a framework combining AD and FTA methods to develop a reliability tree and evaluate product systems. This combination could additionally contribute to support the deployment of FMEA and underpin the reliability perspective of AD method to guarantee the reliability of design (Goo et al., 2019). In addition, Sadeghi et al. (2013) proposed 'Design for Safety' approach that integrates AD approach with FMEA method to analyse the reliability of the design. In this approach, only functional and design domains are considered within this model. This means that this model was aimed to integrate the Functional and Process FMEAs.

However, these works have discussed the combination with limited empirical validation of the extent that co-adopting AD method can improve the application of FMEA. In addition, these works are limited to Functional and Design FMEAs: in which have not addressed the linkage to Process FMEA. Therefore, the full potential combination of AD and FMEA methods to integrate Functional, Design and Process FMEAs has not yet been investigated, classed in this research as a target and is discussed in the next section.

AD implementation systematically transforms customer needs and functional requirements into design/process domains (Suh, 2001). It aims to reduce the lead time and the cost associated with the product development process; by minimising the random search process and allowing to catch customer needs at a detailed level (Suh, 2001). It also

helps to determine the best possible designs based on two axioms explained in the following section (Suh, 2001).

2.2.3. The potential use of Axiomatic Design and Design Structure Matrix for developing the integrated framework of FMEA applications

This section presents the potential extension of utilising AD approach to integrate Functional, Design and Process FMEAs, which in turn is assumed to support the works of Kmenta and Ishii (2004) and Cooper (2015) with a structured tree for chasing the cascaded failures, as well as presenting a method for identifying functional, design and process-related failures and their causes. In this section, an overview and critique on the potential combination of AD and Design Structure Matrix (DSM) approaches suggested for developing the targeted framework of interlinking FMEAs are articulated. DSM is suggested as a supportive approach to perform AD and manage the coupling between elements of each phase in AD deployment.

2.2.3.1. Axiomatic Design (AD)

As explained above, AD is a design methodology that works simultaneously to transform customer needs into the product development stages (Suh, 2001). Four elements are involved in employing AD: domains, hierarchy, zigzagging and axioms. Domains are the operational hub for facilitating the definition of a product (Suh, 2001). AD involves four design domains operating as a logical succession: (1) the customer domain, (2) the functional domain, (3) the physical domain and (4) the process domain (Suh, 2001). As presented in Figure 8, these domains consist of four elements, namely: customer needs (CNs), functional requirements (FRs), design parameters (DPs) and process variables (PVs). Cs are the customers desires to fulfil their needs (Suh, 2001). FRs are the functions identified to deliver the overall performance of a product (Suh, 2001). DPs are the physical characteristics that represent and implement FRs (Suh, 2001). PVs

are the attributes of controlling and building FRs and DPs (Suh, 2001). Each domain defines the targets to achieve, and next domain represents the solutions to accomplish these targets (Suh, 2001).

Then, hierarchy is the taxonomic operational process for extending these domains to embody the system architecture (Suh, 2001). More so, zigzagging is the iterative process for vertically and horizontally decomposing these domains: where zig stands for determining the CS/FRs/DPs/PVs and zag stands for locating the next level of CS/FRs/DPs/PVs (Suh, 2001). At increasing level of detail, these methodology's elements provide an iterative structure of product functions that can be cascaded to their solutions (Goo et al., 2019; Shao et al., 2016; Jefferson, Ratchev and Crossley, 2014; Guenov and Barker, 2005; Suh, 2001; Mohsen and Cekecek, 2000).

Finally, axioms are the set of rules defined to provide the boundaries and references for managing the design workflow and resulted in, potentially creating such robust design (Suh, 2001). AD introduces two axioms: independence and information axioms (Suh, 2001). The former requires FRs to be independent and ensure that each FR does not affect the others FRs, while the latter requires the minimisation of design contents (Suh, 2001). These axioms are translated into various corollaries and theorems, can be found in Suh (1998).

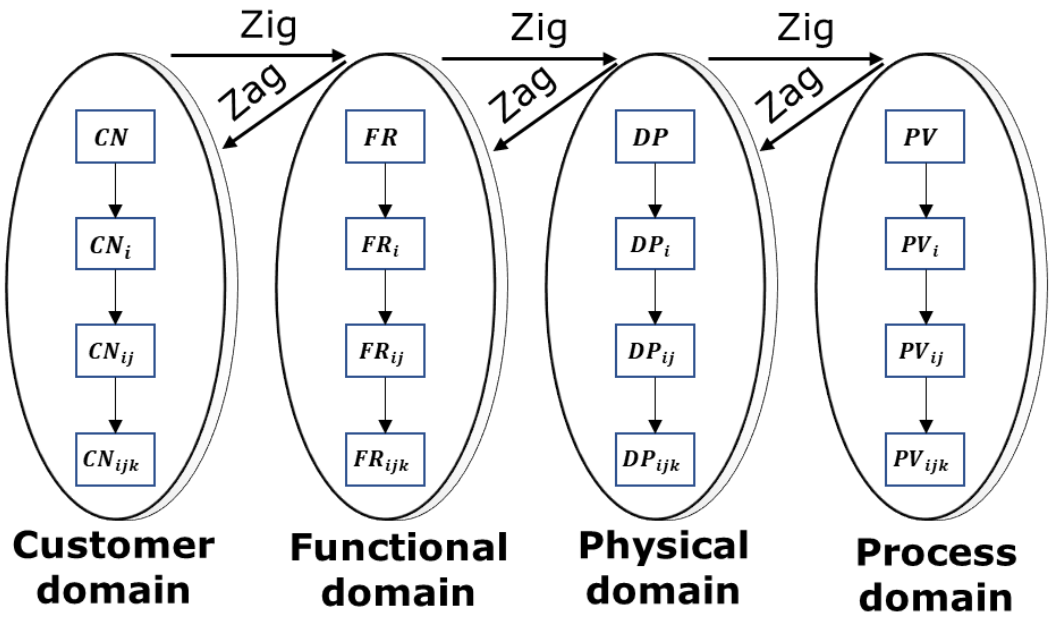


Figure 8: AD domains, adapted from Suh (2001)

To explain how AD works, the focus herein is maintained on FRs-DPs-PVs domains. FRs are cascaded into DPs and PVs domains throughout iterator chains (Suh, 2001). AD deployment process commences with setting FRs, DPs and PVs domains to define the abstraction level of the product developmental process, then establishing the hierarchy for each domain in parallel (Suh, 2001). Having the first level been identified, the next step is to link these domains using zigzagging process (Suh, 2001): a step for generating the system architecture and sketching the next level of these domains (Goo et al., 2019; Shao et al., 2016). The decomposition process is carried out until the final leaf of all branches of the established hierarchy has been reached, which reflect that the design under evaluation is understood and completed (Suh, 2001).

This hierarchical mapping of AD method is of advantage, by shifting the design process to be customer-oriented (Suh, 2001; Mohsen and Cekecek, 2000). This means that the design is customer-driven, and the associated process parameters are described to address the relative critical quality characteristics of design, as well as treating them in the first priority (Suh, 2001; Mohsen and Cekecek, 2000). This feature of AD method also, puts

emphasis on the innovation of design and manufacturing process (Suh, 2001; Mohsen and Cekecek, 2000).

Part of AD is Design Matrix (DM), which is employed with *m* rows and *n* columns to facilitate and mathematically illustrate the correlation between all domains demonstrated and ensure the consistency among them (Suh, 2001). Developing DM ensures that FRs, DPs and PVs are traceable and can be captured at different levels in the product development process (Suh, 2001). DM should produce the following scenarios: (1) coupled, (2) decoupled and (3) uncoupled designs (Suh, 2001). Decoupled and uncoupled scenarios are the only that can fulfil the requirement of the independence axiom (Suh, 2001). For producing these scenarios, DM must engender either diagonal or triangular matrixes (Suh, 2001). Inspired from Suh (2001), equations (2) and (3) exhibit the simple illustrative diagonal and triangular matrixes: triangular matrix can be the opposite, where the upper triangular element only equals zero.

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix} \quad (3)$$

Although AD application is argued to facilitate and ease the conceptual design process via the application of the independence and information axioms (Goo et al., 2019; Shao et al., 2016; Jefferson, Ratchev and Crossley, 2014; Guenov and Barker, 2005; Suh, 2001), utilising these axioms in real applications are problematic due to the associated cost and the level of integration in these applications (Kumar and Tandon, 2019; Frey et al., 2007). To support this argument, Frey et al. (2007) concern that designing independence FRs at detailed level is impossible for the application of aeroengine manufacturing particularly the modern design applications. For example, the modern jet engines present coupled designs at both system and component levels of the engine control system, and

across design and manufacture of component level of modern compressor, as observed in blisks (Frey et al., 2007).

However, partial fulfilment of these axioms can be considered as feasible design model (Frey et al., 2007). To address this imperfection of AD, Guenov and Barker (2005) proposed an improvement approach by integrating AD method with Design Structure Matrix approach (DSM) to improve the applicability of AD and manage the coupled designs.

2.2.3.2. Design Structure Matrix (DSM)

Design Structure Matrix (DSM) is a structured tool used to design and represent the interactive elements of the coupled designs (Eppinger and Browning, 2012; Tang, Zhang and Dai, 2009). DSM is considered good tool for representing the interactions between design elements and improving the design process' efficiency (Eppinger and Browning, 2012; Tang, Zhang and Dai, 2009). It is being recognised for its capability to decompose systems into constituent components, understand, model the associations between design elements and evaluate the possible re-integration of them (Eppinger and Browning, 2012).

In the basic DSM, the primary goal is to minimise feedback loops and their scopes by either re-structuring or re-architecting the design process, where the relevant square matrix is re-sequenced (Eppinger and Browning, 2012; Tang, Zhang and Dai, 2009). As presented in Figure 9, DSM works first by listing the design elements in a square matrix and then marking the relation to each other (Eppinger and Browning, 2012). The next step is partitioning, reordering DSM's rows and columns in which DSM is transformed into lower triangular form; to potentially reduce the size of feedback loops (Eppinger and Browning, 2012). The last step in DSM application is clustering the elements reordered based on common purposes, where to group the elements interconnected for further improvements and new insights into system decomposition and re-integration (Eppinger and Browning, 2012).

DSM has been used for such systems characterised by complicated links of dependent components (Eppinger and Browning, 2012; Tang, Zhang and Dai, 2009; Steward, 1981). There are various applications of DSM, the common for design process is component-based DSM, which is used to model either components/subsystem or system architectures (Eppinger and Browning, 2012).

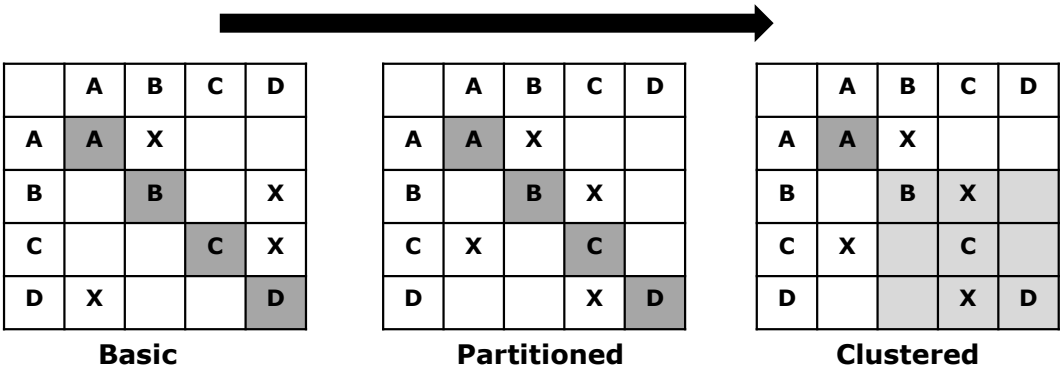


Figure 9: Simple presentation of DSM workflow, inspired by Eppinger and Browning (2012)

DSM has been recognised as less effective in the application of designing new products; as it is just being able to manage the already made designs (Tang, Zhang and Dai, 2009). Guenov and Barker (2005) proposed using the integration of AD and DSM methods for developing a new design, because AD application can define the design elements and determine the connection between domains (Suh, 2001), while DSM is a great strength for modelling the interaction between design elements (Eppinger and Browning, 2012; Tang, Zhang and Dai, 2009). Jefferson, Ratchev and Crossley (2014) have augmented the work of Guenov and Barker (2005) to model a reconfigurable assembly for aerospace applications.

2.3. Review of focal literature on the performance measurement of FMEA implementation

2.3.1. Background on the role of FMEA deployment on customers' satisfactions and firms' profit

Product reliability and quality are critical for both manufacturers and customers for achieving a good level of competitiveness (Kalaignanam, Kushwaha and Eilert, 2013; O'Connor and Kleyner, 2012; Murthy, Rausand and Virtanen, 2009; Chin, Chan and Yang, 2008). A product's reliability is a feature that expresses the concept of reliance or the lack of failure (Kalaignanam, Kushwaha and Eilert, 2013; Murthy, Rausand and Virtanen, 2009). As defined by Murthy, Rausand and Virtanen (2009), a product's reliability is the likelihood that the product will fulfil its intended function for a set amount of time while functioning under typical (or claimed) environmental circumstances. "How quality varies over time" is also another way to classify reliability. The distinction between quality and reliability is that quality refers to how well an item performs its stated function, whereas reliability refers to how well that item retains its original quality over time and under varied situations (Carlson, 2012). This means that product's quality is a sign of reliability.

As a result, manufacturers must decide on the best investment in maintaining a certain level of reliability and quality by establishing a reasonable trade-off between the two expenses (Oakland, 2014; Murthy, Rausand and Virtanen, 2009; Srivastava, 2008; Schiffauerova and Thomson, 2006; Tsai, 1998). It is expensive to build reliability and quality into a new product, but the repercussions of poor product reliability and quality can be far more expensive (Kalaignanam, Kushwaha and Eilert, 2013; O'Connor and Kleyner, 2012; Murthy, Rausand and Virtanen, 2009). One of the most important components of product development that

determines a successful design is the perceived product’s quality (Stylidis, Wickman and Söderberg, 2020). This means that the product must be designed in a way to provide the impression that the product is of high quality.

Product quality is determined by decisions made throughout the product's design and manufacture (Riggs, 2017). One way for manufacturers to assure these requirements is to build a certain reliability and quality levels into the product features (Kalaignanam, Kushwaha and Eilert, 2013; O'Connor and Kleyner, 2012; Murthy, Rausand and Virtanen, 2009). Investing in product quality is expensive since it necessitates significant spending during the design, development, and production phases of the product life cycle (Stylidis, Wickman and Söderberg, 2020; East et al., 2017).

However, failures in the product development result not only in increased warranty costs, but also in lower sales and income owing to the negative impact of consumer satisfaction caused by the potential product failures (East et al., 2017). Therefore, these failures should be corrected in first instance, which are usually associated with costs (East et al., 2017; Riggs, 2017; Schiffauerova and Thomson, 2006). Failure costs are the expenses spent by a producer when faulty items are produced (Schiffauerova and Thomson, 2006). Internal and external failure costs are the two forms of failure costs (Schiffauerova and Thomson, 2006). Internal failure costs incur prior to the distribution of products to customers, whereas external failure costs incur after the sale of products (Schiffauerova and Thomson, 2006). As a result, high production costs have been linked to external costs like product recalls, product repairs, accidents, and deaths caused by dangerous product designs and/or poor product quality (Riggs, 2017; Shah, Ball and Netessine, 2017; Carlson, 2012; Schiffauerova and Thomson, 2006).

According to Kotler (1996, p. 583), "customer satisfaction and company profitability are closely linked to product and service quality. Higher levels of quality result in greater customer satisfaction, while at the same supporting higher price and lower cost". Hoe and Mansori (2018) and Suchánek, Richter and Králová (2014) supported the theory of Kotler (1996, p. 583) in their studies and confirming the strong relationship between customer satisfaction and firms' profit with the product quality. Customers are more inclined to acquire a product if they are extremely happy with it, and customers who are very satisfied with it are more likely to stay loyal to it (East et al., 2017). To guarantee a high degree of customer satisfaction, manufacturers must first identify consumer demands and then respond with relevant products (East et al., 2017).

Customer satisfaction is often regarded as the best predictor of a company's future profitability (East et al., 2017). Satisfaction is defined as a post-purchase assessment of product quality based on pre-purchase expectations (East et al., 2017). It's a very subjective evaluation that is heavily influenced by customer expectations (East et al., 2017). Managers are more influenced by customer expectations in today's competitive companies climate and satisfying the need for customer satisfaction is critical for them (Hoe and Mansori, 2018). Effective engineering management is critical to create good social change by increasing product quality, decreasing manufacturing costs, guaranteeing safety, and encouraging better customer perception (Kim, 2019; East et al., 2017).

In the long term, poor product quality harms the manufacturer's reputation, has an influence on the balance sheet's bottom line, and threatens the manufacturer's viability (Kim, 2019; Hoe and Mansori, 2018; Zhang, Vonderembse and Lim, 2003). Poor quality, in the eyes of customers, lowers availability and raises maintenance costs during the product's service (Shah, Ball and Netessine, 2017; Carlson, 2012).

Retaining an existing client is considerably less expensive than acquiring new consumers (Kim, 2019). Customers who are dissatisfied can have two negative consequences: a lost client with no additional "lifetime value", and the propagation of poor word-of-mouth (Kim, 2019). This means that manufacturers must consider the investment in quality control from a business standpoint. Because firefighting and correcting failures as occurred in product and manufacturing process cost firms and thus impact the price of products and their customer satisfaction (East et al., 2017; Shah, Ball and Netessine, 2017).

Producing higher-quality products not only pleases customers but also has a higher probability for lowering expenses connected with failures and products' recalls caused by product faults (East et al., 2017; Shah, Ball and Netessine, 2017). High-quality, according to Edward Deming (2000), may be accomplished through measuring, controlling, and improving the processes involved in the design, manufacture, and delivery of products. From a larger perspective of continual development, Liu et al. (2019) echo Deming's view and argue for the implementation of proactive quality control to assess product's quality, which leads to affect consumer satisfaction. This indicates that engineers should keep an eye out for chances to use their technical knowledge, skills, and talents to improve products' quality and increase customer satisfaction.

As an important tool for quality evaluation and risks assessment, FMEA is utilised in the early stages of product development process to meet the product quality and reliability requirements (Peeters, Basten and Tinga, 2018; Koomsap and Charoenchokdilok, 2018; Riggs, 2017; Carlson, 2012; Chan, Ip and Zhang, 2012; Hassan et al., 2010; Stamatis, 2003). In a preventive mode, FMEA is increasingly being used to detect and analyse possible product or process failures, as well as their consequences, to identify measures that might prevent or minimise the likelihood of the

potential failures occurring (Peeters, Basten and Tinga, 2018; Koomsap and Charoenchokdilok, 2018; Riggs, 2017; Carlson, 2012; Segismundo and Miguel, 2008; Chin, Chan and Yang, 2008).

It is used to verify that all design and process failure modes have been examined and analysed with the goal of reducing, if not eliminating, failure modes (Carlson, 2012). FMEA deployment helps engineers' decision-making process through the review of designs, specifications, schedules, and production records (Koomsap and Charoenchokdilok, 2018; Riggs, 2017; Carlson, 2012). As suggested by Koomsap and Charoenchokdilok (2018), Riggs (2017) and Carlson (2012), FMEA deployment is considered as a long-term success through both customer satisfaction and firms' sustainability.

Thus, the potential cost savings of defects' corrections could be possible through FMEA deployment, as suggested by Riggs (2017). FMEA implementation enables the study and analysis of every failure in the product development process, resulting in a comprehensive understanding and improvement in the products and manufacturing process, as well as significant cost savings (Riggs, 2017; Liu, 2016; Carlson, 2012; Chin, Chan and Yang, 2008; Segismundo and Miguel, 2008; Teng et al., 2006; Stamatis, 2003; Lam, Sherwood and Shu, 2001; Montgomery and Marko, 1997). The return on the investment in FMEA deployment could be seen via minimising the impact or preventing failures occurrence, when FMEA is applied early as the product design is introduced prior manufacturing (Riggs, 2017; Carlson, 2012; Stamatis, 2003). This argument is supported by findings presented in Albertelli (2019), where GKN company had saved half of the time that had been set aside for the production process of aeroengine' fan cases using FMEA and other tools, as well as Rolls-Royce Holding had implemented FMEA, and this implementation contributed to the introduction of zero-defect aeroengine manufacture.

However, the conventional FMEA has been recognised with various pitfalls that hinder its effective deployment. These downsides are for example, excessive use of resources (Peeters, Basten and Tinga, 2018; Estorilio and Posso, 2010; Zheng, Liu and McMahon, 2010; Trammell, Lorenzo and Davis, 2004; Wetterneck et al., 2004), deployment difficulties (Peeters, Basten and Tinga, 2018; Spreafico, Russo and Rizzi, 2017; Henshall, Campean and Rutter, 2014; Soufhwee et al., 2013; Menis et al., 2012; Popović, Xiao et al., 2011; Vasić and Petrović, 2010; Teng et al., 2006; Kmenta and Ishii, 2004) and high uncertainty throughout the conventional procedure of RPN measure (Chen, 2007; Rhee and Ishii, 2003). To respond to these challenges, various works have been proposed in attempt to improve the practice of FMEA, such as those above-mentioned in section 2.2.2. However, few works were conducted to compare the differences between the traditional FMEA and the proposed models and measure the relative impact. The capability of these proposals appears unclear for practitioners to prove them for the full adoption and application.

2.3.2. Current performance measures of FMEA deployment

Considering FMEA deployment has become a required course in the product development process, measuring its performance is therefore, recommended (Shebl, Franklin and Barber, 2012; Estorilio and Posso, 2010; Pollock, 2005; Teng and Ho, 1996). This is to raise awareness of the potential problems associated with its deployment and support decision makers for further improvements and future implementation of FMEA (Shebl, Franklin and Barber, 2012; Estorilio and Posso, 2010; Pollock, 2005; Teng and Ho, 1996), also to report its value in relation to the invested resources (Teng and Ho, 1996).

According to Neely, Gregory and Platts (1995), the performance measurement is the process of quantifying the effectiveness and validating

the outputs of any action. These outputs should meet the goals targeted and ensure the alignment with business expectations (Teng et al., 2006; Tangen, 2004). Measuring the practice performance helps to monitor and improve such activities on continuous bases, where practitioners can see areas are required for improvements (Teng et al., 2006; Tangen, 2004). The Oxford English Dictionary defines performance as:

> "*How well or badly you do something; how well or badly something works*."

Measuring the performance of quality improvement tools is undoubtedly not something new, for example those were evaluated in Chen (2013). From this position and as a quality tool, the performance of FMEA deployment should be measured for exploring its ability to address the required targets and business objectives. The performance measurement of FMEA deployment can be defined as the process of reporting how good the outputs of FMEA implementation are (Shebl, Franklin and Barber, 2012). As suggested by Teng et al. (2006) and Tangen (2004), a good measurement system should be derived from the strategic objectives of such practices employed. This basis would imply that one way for measuring the performance of FMEA should be coherent with its required goals.

The primary aims of FMEA deployment are clearly emphasised in prior sections; identifying, analysing and mitigating failure modes to reduce the associated impact on the operational performance of the product development process. Another important aim of this method is to document the current knowledge and actions gained about failures, for use in continuous improvement (Liu, 2016; Carlson, 2012; Chin, Chan and Yang, 2008; Segismundo and Miguel, 2008; Teng et al., 2006; Stamatis, 2003; Lam, Sherwood and Shu, 2001; Montgomery and Marko, 1997). To this end, these listed objectives, recommendation and the use of resources

elucidate the bases for measuring the performance of FMEA deployment in terms of the level of ease of implementation as follows:

- The capability to identify failure modes.
- Mitigating failures.
- The capability to document the knowledge and actions for failures analysed.
- The capability to efficiently use resources.

Externally, the performance of FMEA deployment might be measured from the customers' perception (end-users). It might be also measured internally from the engineers' attitudes to see how easy its deployment would be, via the level of ease of implementation. However, these measures are difficult to understand because they are subjective and requires qualitative data, which might not report its accurate performance (East et al., 2017). These uncertainties do not imply that both engineers and customers' perceptions should be disregarded. However, the purpose of this research is to establish a quantitative metric to investigate the performance of FMEA deployment from cost lenses and explore its effect on the cost of failure. This cost metric should synthesise the potential cost saving on a firm's profit, as well as on both engineers and customers' perceptions.

Few investigations in the FMEA arena have focused on measuring the performance of FMEA execution, especially in the manufacturing industry. Limited considerations have also been reported in the healthcare industry. From those that have been reported however, Shebl, Franklin and Barber (2012), for example, examined FMEA deployment to count the number of the potential failures missed within its application in a hospital setting in the United Kingdom. This measure reflects one of the bases above-named for evaluating the capability of FMEA implementation to identify failure modes. Furthermore, Yang et al. (2015) have taken advantage of this index

to validate the outputs of the FMEA executed in the planning process of a Stereotactic Body Radiation Therapy treatment by reporting the failure modes uncovered by the deployment of FMEA.

As for providing guidance on measuring the performance of FMEA, Pollock (2005) has suggested three methods: (1) reporting the capability of FMEA deployment by the ratio of the number of failure modes determined by FMEA application over the number of warranty failure modes (i.e. refers to the failures that occurred under warranty obligation), (2) the number of warranty failure modes missed and (3) calculating the dollars saved through the control actions proposed by FMEA implementation to manage the failure modes. Pollock's (2005) proposals are aligned with the list of FMEA objectives defined in the above. This means that the first two approaches highlighted by Pollock (2005) report the capability of FMEA to identify failure modes, while the last approach measures the cost saved by deploying FMEA and the control actions proposed. By other means, the last method may report the efficiency of the resources invested in implementing FMEA; by comparing the cost saving of governing the defined failures with the invested resources. However, the question of how Pollock (2005) calculated the cost saving of FMEA deployment is still to be addressed, which forms a useful direction for this research and may be covered through the Cost of Quality (CoQ) framework. CoQ is a measurement methodology used to define, measure and compare the resources spent to improve the quality levels of a product or service (Srivastava, 2008; Schiffauerova and Thomson, 2006; Gupta and Campbell, 1995). More details are presented in the next section.

Another contribution is that Carmignani (2009) proposed priority-cost control actions. This work was aimed at measuring the outputs of FMEA implementation in relation to the business profitability, as well as providing a new approach for classifying the control actions. However, this approach would be more an aid for decision-making to assess the available control

actions (i.e., one element of FMEA) than measuring the performance of the whole process of FMEA deployment.

However, there have been extensive discussions over the literature for estimating the cost of failures in efforts to improve the deficiency in the traditional RPN measure by incorporating the failure cost factor into RPN's elements. For example, Rhee and Ishii (2003) introduced a new model called, Life Cost-Based FMEA, with the aim to resolve the ambiguity in the current RPN measure. This model analyses failures from the cost perspective by chasing the probability of failures occurrence and the associated cost. In this model, failures are assumed to be one-time event. Kmenta and Ishii (2004) departed from that model to chase the expected cost of failures over different stages in the product development through their model of Scenario-Based FMEA. Tazi, Châtelet and Bouzidi (2017) and Von Ahsen (2008) used cost-oriented approach to determine a new way for presenting RPN measure in an accurate form. While these works could potentially improve the understanding of the impact of executing FMEA, there is no specific discussion on the cost of deploying FMEA and its integral impact on the cost of failure. Specifically, subjectivity can be present during the performance evaluation process of FMEA employment, which may cast doubt on its validity.

Since the quality improvement and cost saving are ones of the targets for deploying FMEA (Peeters, Basten and Tinga, 2018; Pollock's, 2005; Kmenta and Ishii, 2004), these targets could be potentially addressed by the implementation of CoQ methodology to explore the impact of FMEA deployment on the business performance by highlighting the capability of its deployment in mitigating and reducing the cost of failures. Therefore, this research seeks to correlate the cost of deploying FMEA with the potential cost saving of preventing failures occurrence through control actions. However, this cost model may be used to assess the degree of

reliability in implementing FMEA by measuring the number of failures addressed by its deployment.

2.3.3. The potential use of cost of quality to report the performance of FMEA deployment

Quality is promoted as the central customer value, that it is considered as a critical factor for achieving a good level of competitiveness (Oakland, 2014; Srivastava, 2008; Schiffauerova and Thomson, 2006; Tsai, 1998). Maintaining the quality into products requires inputs from diverse sources to which are usually associated with costs. These sources can be value-added activities and vice versa (Oakland, 2014; Srivastava, 2008; Schiffauerova and Thomson, 2006; Tsai, 1998). Any attempt to improve the quality levels must account for minimising the unnecessary expenses could be caused by failures occurred in operations or products (Oakland, 2014; Srivastava, 2008; Schiffauerova and Thomson, 2006; Tsai, 1998). Categorising and measuring such costs can be achieved by the application of CoQ framework (Srivastava, 2008; Schiffauerova and Thomson, 2006; Gupta and Campbell, 1995).

As defined by Tsai (1998), quality costs are the total costs incurred by the problems occurring prior to and following the delivery of products or services. These costs are committed for continuous improvements through added-value activities for example, design process, operations, delivery, maintenance and all other non-value-added activities (Schiffauerova and Thomson, 2006). Costs can be categorised into well and ill-structured costs (Baumers and Tuck, 2019). The prior cost is mostly around all fully known and easy to identify costs such as materials and labours; vice versa for the latter such as failure cost, which requires further investigations (Baumers and Tuck, 2019).

The goal of CoQ framework is to offer a strategy for allocating resources and maintaining the continuous improvement efforts, which highlights the opportunities to reduce the cost of poor qualities (Srivastava, 2008; Schiffauerova and Thomson, 2006; Gupta and Campbell, 1995). From management perspective, it is also used to quantify the size of quality problems (Srivastava, 2008; Schiffauerova and Thomson, 2006; Gupta and Campbell, 1995). As clarified by Srivastava (2008), Schiffauerova and Thomson (2006) and Gupta and Campbell (1995), CoQ framework is the trade-off between good and poor qualities, represented by distinct themes: Cost of Good Quality (CoGQ) and Cost of Poor Quality (CoPQ). Figure 10 presents the structured hierarchy of CoQ framework.

CoGQ is the costs associated with making and assessing quality into a product or service, manifests through either the prevention or appraisal activities (Schiffauerova and Thomson, 2006; Gupta and Campbell, 1995). CoPQ is the costs incurred as a result of supplying a defective product and service (Schiffauerova and Thomson, 2006; Gupta and Campbell, 1995). In other words, CoGQ is the capital invested during the project to prevent non-conformance and appraise conformance to the requirements, like design, process/quality controls and inspection tests (Schiffauerova and Thomson, 2006; Gupta and Campbell, 1995). Whilst CoPQ is the money spent as result of scraps, reinspection and losing of sales (Schiffauerova and Thomson, 2006; Gupta and Campbell, 1995). Both measures are used to specify the importance vis a vis of monetary value; for the purpose of assigning resources within the project and reducing uncertainties therefore, developing the project at a reduced cost (Schiffauerova and Thomson, 2006; Gupta and Campbell, 1995).

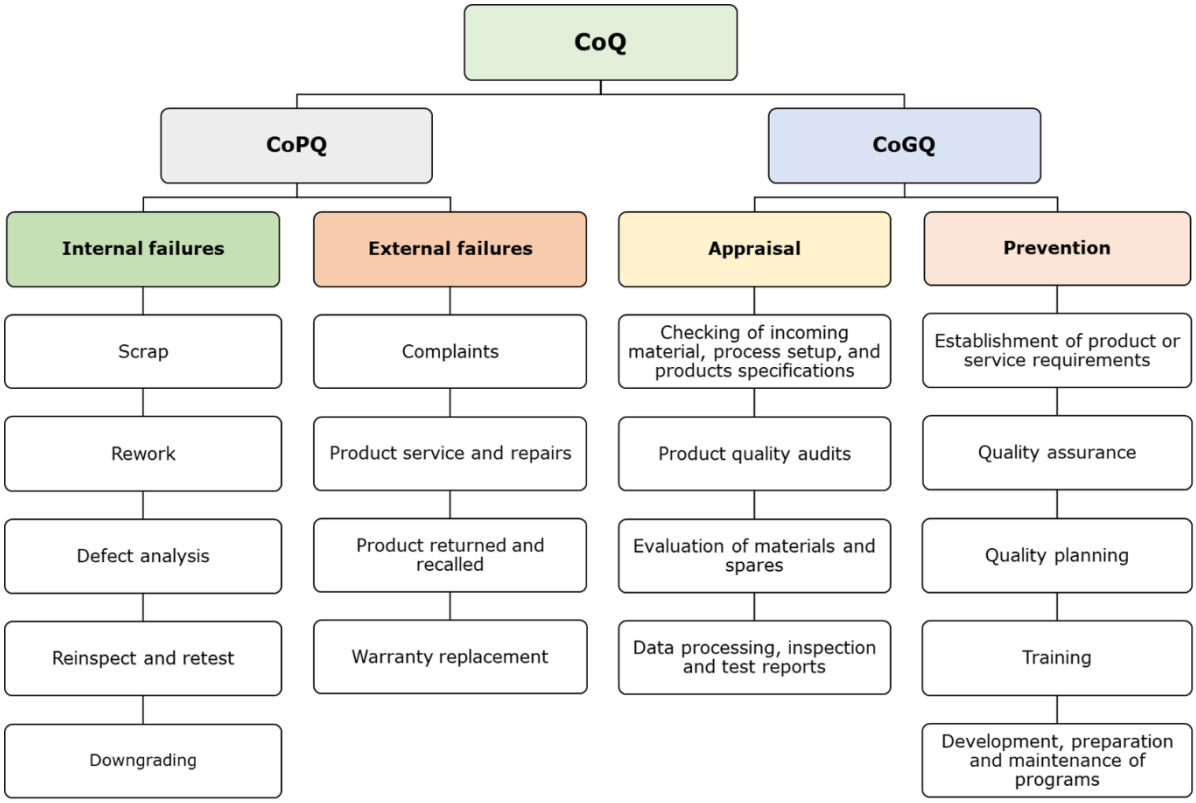


Figure 10: An example of CoQ hierarchy, inspired by Duffy (2013)

Figure 11 presents the classical view of CoQ framework by representing and theoretically contrasting its elements and highlighting the relevant impact on the quality level (Schiffauerova and Thomson, 2006; Chen and Tang, 1992). As shown in Figure 11, CoGQ shows a tendency to decrease the curve of CoPQ, indicating that greater investments in CoGQ elements will lower CoPQ (Schiffauerova and Thomson, 2006; Chen and Tang, 1992). The X-axis is the quality level which moves from 100% defects on the left to 0% defects on the right (Schiffauerova and Thomson, 2006; Chen and Tang, 1992). The Y-axis represents the quality costs that start from 0 and move towards infinite. With such improvements, the quality level progresses from 100 to 0% defects, indicating a linear increase on the part of CoGQ (Schiffauerova and Thomson, 2006; Chen and Tang, 1992). Similarly, CoPQ begins to decrease sharply, and the total CoQ also potentially drops quite significantly (Schiffauerova and Thomson, 2006;

Chen and Tang, 1992). This statement may present the condition behind this concept: total CoPQ is the lowest, the highest is quality level.

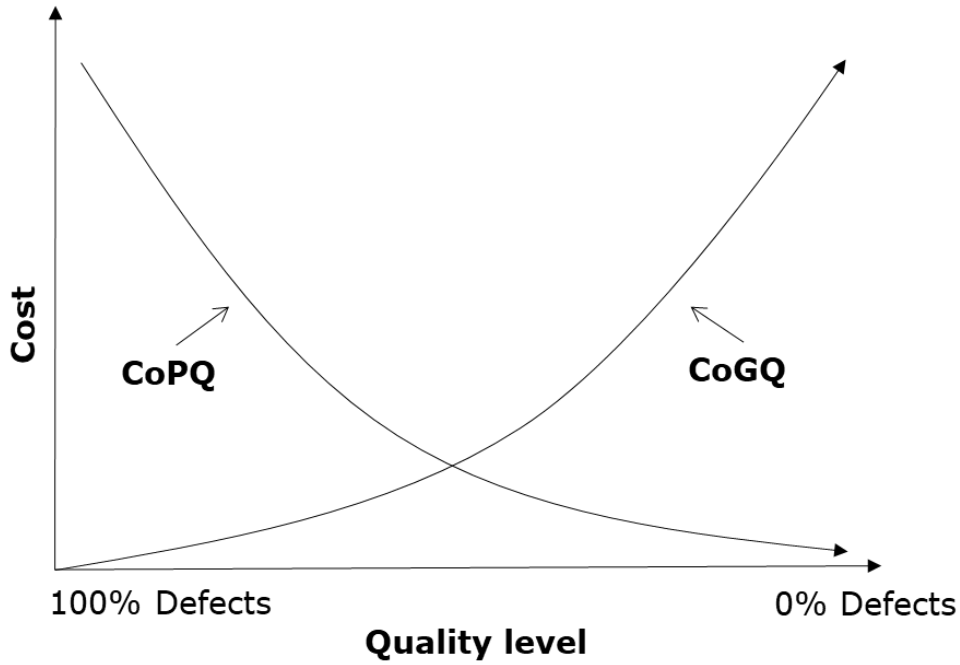


Figure 11: Classical view of the CoQ curve, adapted from Schiffauerova and Thomson (2006)

As a constituent of CoGQ, FMEA is a sub-element of quality assurance which aims to mitigate the potential failures and contribute to make things right first-time, which can clearly be classified under the prevention category (Schmidt, 2013; Xu et al., 2002; Gevirtz, 1994; Webber, 1990). From this viewpoint, investment in deploying FMEA as element of prevention management may reap substantial rewards as it pertains to reducing failure costs (Kiani et al., 2009; Tsai, 1998). This is because the cost benefits resulting from the deployment of FMEA seek to proactively evaluate and mitigate failures prior to their emergence (Lipol and Haq, 2011). Figure 12 displays the schematic representation of the expected benefits of deploying FMEA applications and the impact on the cost of failures and related works. This cost saving would be directly proportional to when the failure is identified and mitigated.

In the context of FMEA, CoQ framework seems able to evaluate the absence of deploying FMEA particularly in the product development domain. In a preventive mode, all FMEA applications work together and simultaneously to identify, analyse and mitigate failures. As being highlighted, FMEA deployment encourages team members to gather and respond to failures at glance in which helps to save such costs due to for example, the potential scraps and excessive of inspections. Therefore, the presence of FMEA deployment would be judged by considering whether failures have been evaluated and addressed or not.

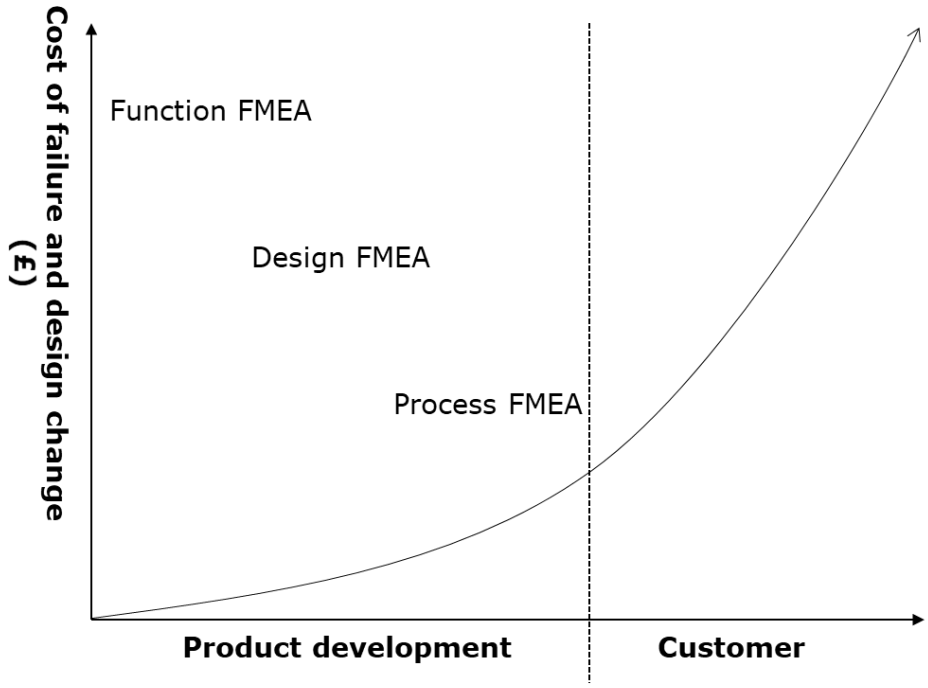


Figure 12: Schematic representation of the expected cost of failures and design changes, and the relation to FMEA deployments, inspired by Lipol and Haq (2011), Kiani et al. (2009) and Tsai (1998)

To measure the performance of the capital invested, the operation of FMEA deployment would be measured as CoGQ by quantifying the cost incurred by its deployment. With reference to the improvement expected at the quality level, the measure that is produced is compared with the potential cost of failures (i.e., as a measure of CoPQ). This contrast appears to

distinguish good from bad FMEA deployments which should, in theory, reflect the impact of its implementation on the quality level and the contrary curve.

Rare studies have considered FMEA to produce CoQ metric. Srivastava (2008) employed FMEA to build CoQ, define and mitigate the external failures as means of customer complaints in pharmaceutical company in India. In Srivastava (2008) work, the associated efforts hours and the cost incurred to resolve these complaints were calculated. This work may emphasise that measuring the performance of FMEA deployment could be informed by the application of CoQ framework.

2.4. Summary of the literature review

This chapter sought to determine the existing background around FMEA implementation, the main reasons for adopting it and the focal literature on FMEA deployment and the related performance measurement. It started with describing the characteristics for implementing FMEA, its applications in the product development process and the drivers for adopting it.

The focal literature on the challenges associated with deploying FMEA have been presented. The studies (i.e., those were made of various systematic engineering methodologies) which sought to address the practical challenges highlighted in implementing FMEA were identified. With regards to the objectives pursued, these studies, however, demonstrate unclear performance of the effects of co-adopting these methodologies on the success of implementing FMEA. This provides the principal rationale for the orientation of this work, which has sought to evaluate these approaches and determine the extent to which they could improve the practical execution of FMEA. To address this important gap in knowledge therefore, this research investigates the hypothesis that the co-adoption of these methodologies outlined in section 2.2.2 and other such managerial factors

reduce the level of difficulty associated with the practical execution of FMEA processes and activities.

In addition, the literature review has shown a paucity of research in the area of combining AD with FMEA methods and the relevant importance for bridging the gap in knowledge between the applications of FMEA and catching the cascaded failures. This research seeks to explore the applicability of AD method to synchronise Functional, Design and Process FMEAs through developing one such example of an integrated framework.

Moreover, the focal literature on the current performance measurement of FMEA deployment suggests limited research on this side of FMEA management. In this light, this research aims to survey the manufacturing industry to observe how FMEA implementation is being assessed.

Further, the subject of estimating the cost of performing FMEA and its related financial impact have been reviewed, including the potential use of CoQ framework in support of this. Most studies from those reviewed focused on the cost estimate of failures to be incorporated with RPN as a means to support this measure. It seems, from the extant literature, that estimating the cost of implementing FMEA has not yet been determined, and accordingly this forms the basis of the investigative direction of this research. This involves creating a metric to estimate the performance of FMEA deployment, which could resolve the trade-offs between the cost of FMEA employment and other costs and performance considerations. Based on this, this research aims to provide initial investigation to understand how the CoQ framework could be used to report the performance of FMEA implementation. This link is crucial since FMEA significantly participates in analysing and preventing the occurrence of failures in products and services.

3. Methodology

The objective of this chapter is to provide an overview of the research methodology and methods utilised in this research. It has been organised as follows: the chapter begins with a brief description of the research strategies, design and the sources of data used. It goes on to clarify the data collection techniques employed and highlights the process involved in conducting this research, as well as the rationale for the applied regression models and other techniques selected to analyse data of this research.

3.1. Research strategy

As directed by the gaps indicated in chapter 2 and the research objectives outlined in section 1.2, this section provides the general overview for conducting this research. The entire project was divided into four distinct research phases, each with their own goals as outlined below:

- **Phase 1:** Investigating the impact of the co-adoption of FMEA with other systematic engineering methods of FTA, FFBD, AHP, QFD, KBS, DAIREC and AD, as well as the effect of the dynamic change in managerial factors of industry membership, engineering experience held and organisational size.

This phase of the research aims to accomplish objective 2. Specifically, this phase focuses on exploring the current challenges for deploying FMEA in practice and provide an understanding of the associated effects of co-adopting the abovementioned approaches on the application of FMEA methods as well as identifying the appropriate method for developing the framework of synchronising FMEA methods. It also aims to articulate the dynamic part of the relationship between the managerial factors outlined in the above and the progress of FMEAs deployment. In executing this phase, the researcher recruited participants with a range of different experiences and from backgrounds and applied a statistical inference model to

determine the impact of the association between the combination of these approaches and the successful applications of FMEAs, also to report the change effect of organisational factors on the well-executed FMEAs (refer to section 3.4.1 for further details).

- **Phase 2:** Review the current performance measurement approaches of FMEAs execution.

This phase aims to meet the requirements of objective 3. It puts emphasis on the process of surveying and quantifying the current measurement systems utilised in practice to evaluate the performance of FMEA deployment. This phase aims to determine the industry targets from deploying FMEAs. By this end, these targets identified in this phase would help to identify the grounds for developing the framework of integrating FMEA methods. Using feedback from industry and the descriptive and graphical data analysis methods, the approaches applied for measuring the performance of FMEA were reported and evaluated (see section 3.4.1).

- **Phase 3:** Development and validating the integrated framework of FMEA methods.

This phase is linked to the achievement of objective 4. It aims to develop a framework for implementing and synchronising FMEA methods, and then validating it via the evaluation by FMEA subject-matter experts. Once the framework had been developed, it was presented to FMEA-related users to gather feedback. These responses were evaluated through the application of a statistical hypothesis test to validate the proposed framework, which has been presented in section 3.4.2.

As an outcome, initial investigations into determining such a cost function model were carried out to provide a quantitative measurement tool that can be used to evaluate the developed framework of integrating FMEAs. However, the host company would not disclose the records to validate the established cost model and therefore, results will be disclosed at a later

date. This thesis, therefore, covers the cost model developed, as presented in section 4.3, instead.

3.2. Research Design

In general terms, research design can be classified into quantitative, qualitative or mixed methods (Creswell, 2017; Saunders, Lewis and Thornhill, 2009). The former applies a numerical approach to investigate the phenomena under investigation (Creswell, 2017). It is more suited for explaining and confirming the relationships between diverse variables that are of interest (Creswell, 2017; Leedy and Ormrod, 2005). Creswell (2017) highlights that this kind of research design is highly relevant in testing a hypothesis and so on. For example, through statistical testing, the data collected is analysed and presented in numerical forms for asserting the validity of the hypotheses being tested (Creswell, 2017). This method employs a sampling approach to generalise the results to a certain population (Creswell, 2017). Quantitative research is inexpensive, and the results yielded are also verifiable and replicable (Robson, 2011). However, it lacks a certain degree of flexibility in terms of being able to modify the research direction (Robson, 2011).

In contrast, qualitative research design focuses on observations, verbal actions and responses to improve understanding and establish different views on the phenomena investigated (Creswell, 2017; Hussey and Hussey, 2003). This kind of approach puts emphasis on details and descriptions, and is typically conducted on a smaller scale (Creswell, 2017; Hussey and Hussey, 2003). Qualitative research design, by its very nature, is time consuming, arguably less accurate and less reliable with the possibility of bias (Robson, 2011). However, it promotes direct contact with participants and can encourage changes in the direction of the research (Robson, 2011).

Mixed methods research design involves combining both quantitative and qualitative approaches to provide a better understanding of the research

problem rather than individual research design (Creswell, 2017). This style of research design enables both quantitative and qualitative methods to be applied at the same time. Depending on the research objectives and questions, both approaches can be also employed in a sequential form; one after the other (Creswell, 2017).

This particular research project followed the quantitative research design in all date-driven phases as follows:

- **Phase 1**: This phase used a quantitative research-based approach that analysed the causal relationship between the level of challenge associated with FMEAs deployment and the complementary approaches and the impact of other managerial factors, as previously outlined-above. This study, therefore, requires quantitative data to explain this relationship and statistically evaluate the correlating effects. It used the survey to gather the relevant data and then applied a statistical regression model to quantitatively analyse the effect of co-adopting other approaches and the impact of managerial factors on the application of FMEA.
- **Phase 2**: Since this study aims to identify the current performance measurement practices of FMEAs deployment and their methods in a measurable approach, quantitative research design was deemed suitable for this purpose. In this phase, the responses collected were quantified to show the most common practice being used for measuring the performance of FMEA deployment.
- **Phase 3**: The objective of this study is to determine whether the combination of AD and DSM is capable to synchronise Functional, Design and Process FMEAs. Therefore, a framework of integrating AD with DSM and FMEA was developed and then validated by following the quantitative approach. The data was collected and, by means of the statistical analysis, quantitively evaluated to validate the proposed framework.

3.3. Data source

To understand the research context of phases 1, 2 & 3, different sources such as books and articles were used to identify the current empirical literature, knowledge gaps and research focus. In addition, a series of formal meetings with people in the host company were held to form the bases of these phases of the research and define the current practice of deploying and measuring the performance of FMEA.

This research principally focuses on managing the implementation of FMEA, in particular the automotive and the aerospace industries. It seeks to contribute to all bodies of knowledge on new product development, system, concurrent, quality and reliability engineering fields. Identifying the research context, therefore, is important as this helps to develop an appropriate data collection method.

3.4. Data collection techniques

Data collection is fundamental in research, since it contributes to providing a better understanding of the phenomena under investigation. Data can be classified as either primary or secondary. The former is concerned with collecting new data. This process requires resources which are time-consuming, and so can make this process somewhat expensive. There are various data collection techniques that can be used to gather data, such as questionnaires, interviews and observations. Secondary data typically relies on utilising information from existing literature and other sources. When using this approach, factors such as the type of information sought, from whom and under which conditions are all considered (Robson, 2011). This research requires both data to achieve the objectives outlined in section 1.2.

This section outlines the data collection techniques that were employed for each individual strategy, as described in section 3.1. It lists the data

collection methods utilised and the construction and validation processes, as well as describing the administrative processes for gathering data and the sampling approaches applied. Finally, this section explains the data analysis approaches that were employed.

3.4.1. Phases 1 & 2 of the research

Due to nature of both phases 1 & 2 of this research requiring more inputs from a variety of different sources and experiences, the data for both phases were collected using the same data collection form and in one process. The sub-sections described below elucidate the procedures involved in collecting the relevant data.

3.4.1.1. Research method

To obtain a dataset for completing phases 1 & 2 of the research, a questionnaire-based data collection approach was adopted to gather information from a wide range of participants. This method was chosen because of the restriction imposed on accessing FMEA relevant data. The questionnaire was also selected because of the nature of these two phases of the research; requiring various inputs from different sources. The questionnaire is a scientific research tool that contains a series of questions which participants are obliged to complete without help and interference (Saunders, Lewis and Thornhill, 2009). The questionnaire is economically useful when collecting a large amount of information from a wide range of people (Saunders, Lewis and Thornhill, 2009).

To achieve the aim of phase 1, the questionnaire was designed to capture the relationship between the co-adoption of FTA, FFBD, AHP, QFD, KBS, DAIREC and AD approaches and the level of challenge associated with deploying FMEA by prompting the respondents to identify methodologies supporting FMEA employment and their effectiveness. Additionally, the questionnaire surveyed the common challenges encountered in deploying FMEA within the organisation by identifying five challenge categories, which

were summarised from the literature review. This enabled the respondents to more precisely state some of the particular challenges in the current practice of FMEA deployment.

Moreover, the questionnaire was also formed to meet the requirements of phase 2 of the research by capturing an in-depth view of the current performance measurement methods used for FMEA execution from participants in an attempt to obtain new insights which, it was envisaged, would provide a useful contribution in trying to bridge the existing gap in the literature. To achieve these aims, the questionnaire was designed in a manner to acquire an in-depth understanding for this phase of the research.

3.4.1.2. Questionnaire construction

The process of constructing the questionnaire went through several iterations and was also scrutinised by the research supervisors until the final version was achieved, which is presented in Appendix A. To simplify the process of data collection, the questionnaire was split into three parts to cover phases 1 & 2. The first two parts collect the data required for phase 1, as presented in section 4.1, while the third part gathers the data required for phase 2, as outlined in section 4.2. An explanation is provided for each of the parts below:

- Part 1: This part quantifies the impact of combining the methods of FTA, FFBD, AHP, QFD, KBS, DAIREC and AD on the implementation of FMEA. To obtain the data on the performance of the execution of approaches listed above, the survey contained Likert-box questions prompting the respondents to identify the level of effectiveness to which the abovementioned approaches were being adopted within the respondents' organisation.
- Part 2: This part captures the current challenges associated with implementing FMEA. This part sets a multiple-choice question for respondents asking them to identify whether they had encountered the following five partial challenges in the deployment of FMEA: excessive

use of resources, applicability, capturing of interaction failures between system, sub-system and components levels, knowledge gap between design and manufacturing and inability to trace failures.

- Part 3: Part 3 records the current measurement methods used to assess the performance of FMEA application. It begins with listing the existing procedures to manage the performance measurement of FMEA deployment encouraging participants to define the present approaches of performance measurement moving on to record the manners in which these methods are applied.

3.4.1.3. Validation of the data collection technique employed

Validity concerns the data collection method employed should be taken into account to certify that they meet the requirements of this research (Robson, 2011; Saunders, Lewis and Thornhill, 2009). The data collection method should be structured so as to reveal the information required to verify the ability to produce high-quality data which will enhance the credibility of findings (Robson, 2011; Saunders, Lewis and Thornhill, 2009). Robson (2011) defines validity as the extent to which the data collection tools can provide a true picture of the phenomena being researched.

Two common approaches are often used to test the validity of the data collection methods and ensure that their items secure the required information: literature reviews and judgment from experts (Saunders, Lewis and Thornhill, 2009). The following sections provide an overview of the practices that were followed to test the validity and reliability of the data collection methods utilised in this research.

3.4.1.3.1. Content validity of the data collection tool employed

In the present study, the relevant literature was reviewed to determine the elements that would form the questionnaire elements. For phase 1, the challenges of deploying FMEA were identified and structured in the questionnaire. In addition, the performance of FTA, FFBD, AHP, QFD, KBS,

DAIREC and AD methodologies were identified as the main constructs. As highlighted in section 2.2.2, these methodologies were proposed to address the limitations of FMEA implementation. For phase 2, the same procedure was followed to capture and add the performance measurement themes and their approaches for evaluating FMEA deployment.

To improve the content of the questionnaire developed for these phases of the research, extra processes were applied. The researcher attended three workshops that were organised by the host company concerning FMEA deployment and its performance measurement; this was done to observe the practical management of FMEA deployment and the relative performance measurement. These observations were used to improve the process of designing the questionnaire. Moreover, other historical records, documented procedures and developed FMEAs obtained from the host company were analysed and used as a source for the development of the questionnaire, which was then built upon these bases. Completing these processes helped to ensure an alignment between the literature and practice and improve the validity of the questionnaire.

Prior to the roll out of the full-fledged research study, pilot interviews were conducted as a pre-test for the ready-made questionnaire. Two groups were selected to complete this process. The first group was a sample of 5 engineers from the host company. Face-to-face interviews were conducted to test the questionnaire design and ascertain the clarity and validity of the questionnaire content. The second group involved in the pilot study was 2 PhD students who provided assistance to determine the time duration involved in completing the questionnaire. This pilot study was beneficial as it improved the process of data collection on a large-scale sample, as the participants' suggestions were revised, and the necessary changes made to the questionnaire.

3.4.1.3.2. Reliability of the data collection tool employed

For phase 1 of the research, Likert scales were developed to gather data on the performance of co-adopting FTA, FFBD, AHP, QFD, KBS, DAIREC and AD methods on the deployment of FMEA. The reliability of these scales in meeting their requirements was assessed. In this research context, reliability refers to the degree of internal consistency between variables included in the questionnaire developed. To ascertain reliability, Cronbach's Alpha test was applied to assess the reliability of phase 1 of the research-related parts embedded in the questionnaire and measure the internal consistency between the independent and dependent variables in these parts.

Cronbach's Alpha test is considered one of the most pervasive approaches for investigating survey reliability (Saunders, Lewis and Thornhill, 2009). More specifically, this test is appropriate for measuring the reliability of a survey with multiple questions requiring a scale-based response (Saunders, Lewis and Thornhill, 2009). The coefficient values of Cronbach's Alpha range between '0' and '1'. '0' denotes no internal consistency between variables and therefore, the questionnaire is unreliable (Saunders, Lewis and Thornhill, 2009). Meanwhile, '1' indicates the opposite confirming reliability (Saunders, Lewis and Thornhill, 2009). The Cronbach Alpha test has been frequently used in the same field; for example, Kumar, Garg and Garg (2009) and Hilton, Balla and Sohal (2008).

3.4.1.4. Administration of the questionnaire

An invitation message containing a link to the online questionnaire was sent to 76 industry professionals between May 3rd 2018 and Aug 24th 2018; 27 responses were received and recorded (35.5%). Of those, only 15 replies yielded valid responses that were used for analysis. In conjunction with the online questionnaire and at the same time, the survey was completed in virtual and face-to-face meetings with 31 additional participants, where 5 responses were disqualified due to incomplete information on the survey.

Overall, this resulted in a sample size of n = 41 with a response rate of 38.3%. The observed response rate is in line with the researcher's expectation – this is also due to the potentially sensitive nature of the information being sought. To assure the anonymity of the participants, coding design was applied. Figure 13 shows a pie chart of the percentages for those groups that participated in this study.



Figure 13: Sample representativeness

3.4.1.5. Sampling

Since the number of respondents was too small to perform a random sampling approach, the resulting dataset forms a convenience sample. Convenience sampling carries the benefits of a short lead time and reduces the associated costs incurred when forming a group of participants (Etikan, Musa and Alkassim, 2016).

The group targeted for the study consists of engineers in design, manufacturing and quality roles in both the automotive and the aerospace industries. It is acknowledged that convenience sampling carries the possibility of self-selection bias. To minimise this issue, one participant was randomly selected from each location or organisation to represent the practice of FMEA.

3.4.1.6. Data analysis

3.4.1.6.1. Phase 1

An ordered probit model was employed to evaluate the effects of the co-adoption of these methodologies outlined above and other managerial factors on the associated challenges for deploying FMEA. This model was used to test the hypothesis formulated in section 2.4. Through this model, the level of challenge for executing FMEA was interrelated to the performance of these methodologies and modes of other managerial factors.

The ordered probit model is a statistical inference test that is considered useful in situations to which outcomes are represented in the form of discrete ordered numerical information (McKelvey and Zavoina, 1975). As the basis for this model, equation (1) shows a linear association between the unobservable variable Y^*_i and the independent variables, with Y^*_i being single latent and continuous variable:

$$Y^*_i = x'_i \beta + \varepsilon_i \qquad (4)$$

Where x'_i is the transpose of a vector of the independent variables for the i^{th} observation, β is a vector of parameters to be estimated (i.e. regression coefficients) measuring the effects of a change in x'_i on Y^*_i, and ε_i is the random error that is assumed to be normally distributed with 0 mean and unit variance $\varepsilon_i \sim$ N (0,1). The unobservable variable Y^*_i is used here to interpret the targeted outcomes of this study.

Since the data required for this phase of the research was obtained from ordinal responses, the ordered probit model was identified as being suitable for this type of study (Baumers, Tuck and Hague, 2011; Chan, Miller and Tcha, 2005). This model has been widely applied to fit the data of an ordinal structure in the same field (see examples from Yang et al. (2011) and Bayo-Moriones and Cerio (2001)). Although there is no ideal approach to conduct

such an analysis, the implementation of the above works could promote the validity and efficiency of the application of the ordered probit model on such studies. Due to the relatively small sample size, this model was also regarded as potentially providing the best way of correlating the interrelated impact of co-adopting other systematic engineering approaches and other managerial factors on FMEA implementation.

This model was chosen over the ordered logistic regression (another technique from the ordinal regression models family), as it is more parsimonious to present accurate predictions of the explained variable. The ordered probit model was found to provide a better goodness of fit to represent the regressions of this study, which in turn could produce more reasonable estimations and results in a better prediction. The likelihood ratio test (*Pseudo-*R^2) was used to appraise the goodness of fit. *Pseudo-*R^2 test is a goodness of fit measure which demonstrates how well the model adopted explains the explanatory variables. This test quantifies the amount of variations in the explained variables that can be imputed to the explanatory variables. *Pseudo-*R^2 values vary between '0' and '1', where '1' indicates a better model fit.

3.4.1.6.2. Phase 2

The findings obtained from the third part of the questionnaire were quantified and analysed by descriptive and graphical data analysis methods. Since this phase is motivated by the need to understand how FMEA deployment performance is measured, these data analysis approaches were selected as appropriate. The findings were presented in graph format and then evaluated with the help of descriptive analysis.

3.4.2. Phase 3 of the research

3.4.2.1. Research method

A novel framework of implementing and synchronising FMEA applications was developed. To practically explore the validity of the proposed framework, a semi-structured questionnaire was formalised to gather experts' feedback and assess the acceptance and performance of the proposed framework by FMEA subject-matter experts. This process seeks to examine the concepts underlying the designed framework, primarily its usefulness, clarity and intuitiveness.

Using expert feedback as a primary validation is a common practice for evaluating such conceptualised frameworks (Subriadi and Najwa, 2020; Almutairi, Salonitis and Al-Ashaab, 2019; Haq and Boddu, 2017; Anvari et al., 2013; Beecham et al., 2005). For example, Subriadi and Najwa (2020) developed an improved framework of FMEA to improve the consistency associated with ranking RPN's components in Information Technology applications. Using set of evaluation measures, they recruited a panel of expert to primarily validate their proposed framework in improving the consistency among RPN's measures. In a similar vein, Anvari et al. (2013) developed an evaluation framework for analysing Lean Manufacturing tools to evaluate their efficacy in real applications. They used expert feedback to validate their framework for analysing the leanness of Lean Manufacturing tools.

These applications suggest that expert feedback can be used as an approach for primary validation. Therefore, this research project used this validation method to primarily validate the proposed framework of integrating FMEA applications. However, this validation technique is often associated with the vagueness and uncertainty in expert judgement (Subriadi and Najwa, 2020). Thus, practical validation is required to ensure that the proposed framework is relevant and can deliver the required

targets: synchronising FMEA applications and therefore, catching the cascading failures.

3.4.2.2. Questionnaire construction

The questionnaire was constructed based on carefully reviewing the literature, attending relevant courses on the implementation of FMEAs and a series of meetings with managers from design, manufacturing and quality departments in the host company. This phase of the research suggested a framework of integrating Functional, Design and Process FMEAs into a working framework. Based on the required functions of the proposed framework, the questionnaire was prepared for evaluating the applicability of the framework from the practice perspective.

As presented in Appendix B, the questionnaire was constructed of three sections. The first part records participants' details to assure the right persons are selected. The second section uses a set of closed questions featuring a Likert-scale with 5 measures, encouraging participants to assess the framework. Beyond these prior sections, open-ended questions were introduced to capture any extra comments suggested by participants, including the potential limitations in the framework and possible improvements based on the perceptions of the participants. Table 5 presents the assessment criterion and associated definitions where the questionnaire was built upon. These assessment criteria are displayed in Likert-scale questions as explained in Table 6. Every individual measure was formed of 5 scales; '1' denotes weak performance gradually moving to the excellent measure of '5'.

Table 5: Assessment criterion of the proposed framework

Assessment Criterion	**Definition**
Ease of Use	The degree which implementing this framework is effortless
Useful for implementing FMEA applications	The degree to which a person believes that using this framework would enhance the implementation of FMEA applications
Providing support	The extent to which the proposed framework can support synchronising FMEA applications
Comprehensiveness	The capability measurement of how comprehensive the framework is to catch the cascaded failures
Applicability	The extent of how likely the user will be able to use and apply the framework

Table 6: Part two of the questionnaire - the measurement instrument

A. To what extent do you agree that the proposed framework is easy to use?

☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
Very easy to use	Easy to use with minor explanations needed	Easy to use but more explanations required	Not easy to use but could be used with intensive explanations	Not very easy to use

B. To what extent do you agree that the proposed framework is useful for implementing FMEAs?

☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
Very useful	Useful	Useful but may need some improvements	Not useful but it could be considered for use	Not very useful

C. To what extent do you agree that the proposed framework is providing support with regards to synchronising FMEAs?

☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
Provide a lot of support	Provide support	Provide some support but there would be a need for other tools	Does not provide enough support but it could be used as an extra tool	Does not support

D. To what extent do you agree that the proposed framework is comprehensive, and will catch/detect the cascaded failures?

☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
Very comprehensive	comprehensive	Fairly comprehensive	Not sufficiently comprehensive	Not comprehensive

E. To what extent do you agree that the proposed framework is applicable?

☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
More applicable	Applicable	Applicable but requires some modifications to the framework	Not applicable unless there will be major modifications to the framework	Not applicable at all

3.4.2.3. Validation of the data collection technique employed

3.4.2.3.1. Content validity of the data collection tool employed

A pilot study was performed to audit the content validity of the developed questionnaire. This study was completed through two meetings which were held in the host company with a sample of 3 engineers. Each person was given the questionnaire to offer feedback on both the content of the survey and the proposed framework of integrating Functional, Design and Process FMEAs. The meeting began with showing the framework developed and followed with discussions on both the framework and the questionnaire. The feedback was reviewed, and any necessary changes required were addressed in both the framework and the questionnaire. This pilot study provided necessary support by ensuring the clarity and validity of the developed questionnaire questions.

3.4.2.3.2. Reliability of the data collection tool employed

Due to the scale-based responses which characterised the designed questionnaire, Cronbach's Alpha test was also conducted. The data collected was tested for internal consistency, and hence, the reliability.

3.4.2.4. Sampling

The panel of experts was chosen based on two particular criteria. The first criterion is to select individuals with such experience in design, manufacturing, and quality. FMEA is a cross-functional team method that relies on a wide range of experience in these different areas of expertise to ensure that product and process failures, as well as their causes and effects, are identified, recorded, and addressed (Liu, 2016; Carlson, 2012; Stamatis, 2003). Engineers must have a high level of particular knowledge and skills for designing and processing the products in question, where these expertise are used to deploy FMEA and achieve its targets (Banghart, Bian and Babski-Reeves, 2016; Liu, 2016; Carlson, 2012; Bluvband and

Grabov, 2009; Stamatis, 2003). Therefore, choosing the appropriate team with the relevant expertise is one of the most critical aspects for deploying FMEAs (Liu, 2016; Carlson, 2012; Stamatis, 2003).

From this point of view and since the aims of this framework are to synchronise Functional, Design and Process FMEA and catch the cascaded failures in between, participants with such expertise are required to evaluate this framework. Because this phase of the research attempts to determine if the suggested framework can synthesise their expertise across product development domains to trace and capture the cascading failures. Meaning that this validation process seeks to investigate whether this proposed framework can help those participants to deploy FMEA applications and chase failures from their backgrounds. For example, this validation process tries to clarify that a design engineer can chase failures up and down from functional and process domains using this suggested framework.

The second criterion is to choose people who have used or continue to utilise FMEAs in their jobs. This criterion seeks candidates who are knowledgeable with the procedures for deploying FMEA. The recruited team should be familiar with the step-by-step instructions for performing FMEA and calculating RPN measures for the failures under consideration, as well as the FMEA analysis' worksheet or equivalent to document the findings of the analysis.

Using these criteria, the host company's experts in the application of FMEAs were invited to recommend people with such expertise on the design, manufacturing and quality fields, as well as knowledge and expertise on FMEAs deployment. As a result, 10 participants, who are experienced in design, manufacturing and quality engineering and FMEA deployment, were purposely sampled from the aerospace industry from both the practical and research-based backgrounds, those who work in the aerospace industry for the improvement of such designs. Furthermore, the researcher identified 2

participants from the automotive industry, who have such expertise on both the manufacturing/quality engineering and FMEA deployment perspectives.

Those participants were contacted both virtually and face-to-face. Due to the sensitivity of the information being disclosed, the participants and their respective employers were anonymised. Table 7 provides details (i.e., profiles) of the participants involved in the study. Considering the exploratory nature of this phase of the research as well as the restrictions imposed to recruit more experts, those participants who took part in this phase of the research are seen to represent the panel of expertise required for evaluating the proposed framework. However, it should be noted that this validation process is not conclusive as this phase of the research requires recruiting further larger sample size of expertise panel, as well as further practical applications.

Due to the objectives of this phase which involves evaluating the proposed framework of combining Functional, Design and Process FMEAs, purposive sampling approach was applied. Purposive sampling is a form of judgemental sampling to which participants are deliberately chosen due to the characteristics they possess (Palinkas et al., 2015). This sampling technique encourages the recruitment of participants that are available and willing to share their experiences (Palinkas et al., 2015). Despite the positive aspects of this sampling approach, however, it can be highly prone to bias since the selection is led by the researcher judgment. To alleviate possible bias, this study tried to apply a chain referral strategy to identify participants. Experts in the host company were asked to suggest key persons, which resulted in most participants (10 individuals) being recruited through this chain referral process.

Table 7: Participants profiles

No	Participant role	Participant expertise	Experience (Years)	Type of organisation	Industry	Company (Coded)	FMEA used
1	Consultant	Manufacturing	> 15	Design	Aerospace	Company A	Design and Process FMEA
2	Quality improvement manager	Manufacturing Quality	> 15	Design Manufacturing Consultancy Research centre	Automotive	Company B	Functional, Design and Process FMEA
3	Producibility lead	Design Producibility	11-15	Design	Aerospace	Company C	Functional, Design and Process FMEA
4	Consultant	Quality Software	> 15	Software	Aerospace Automotive	Company D	Functional, Design and Process FMEA
5	Consultant	Quality Metallurgy	> 15	Consultancy	Aerospace Automotive	Company D	Design and Process FMEA
6	Researcher	Manufacturing	< 5	Research Centre	Aerospace	Company C	Functional, Design and Process FMEA
7	Researcher	Design	6-10	Research Centre	Aerospace	Company C	Functional, Design and Process FMEA
8	Researcher	Manufacturing	< 5	Research Centre	Aerospace	Company C	Functional, Design and Process FMEA
9	Senior Manager	Manufacturing Operations	> 15	Consultancy	Aerospace	Company E	Design and Process FMEA
10	Consultant	Manufacturing Quality	> 15	Design Manufacturing Consultancy Research centre	Automotive	Company B	Design and Process FMEA
11	Sub-system specialist	Design	> 15	Design	Aerospace	Company C	Functional, Design and Process FMEA
12	Integration design engineer	Design	> 15	Design	Aerospace	Company C	Functional, Design and Process FMEA

3.4.2.5. Administration of the questionnaire

One-hour meetings were held physically and virtually with participants to collect responses and validate the framework. The validation process began with a 20-to-30-minute presentation which provided an explanation of the research, its objectives and the proposed framework. The participants were then asked to assess the framework using the assessment criterion presented in Table 6, giving each question a number/rank from 1 to 5.

3.4.2.6. Data analysis

Inspired by Almutairi, Salonitis and Al-Ashaab (2019) and Vinodh and Chintha (2011), one sample t-test was performed to analyse the feedback that was collected from participants. This examined the acceptance level of the proposed framework of synchronising FMEA applications by their perspectives. The t-test is a type of inferential statistical models used to compare means from different groups, as well as testing the null hypotheses. Equation (5) shows the basis for the t-test model; estimating t value as follows:

$$t = \frac{\overline{x} - \mu}{s_{\overline{x}}} \tag{5}$$

Where,

$$s_{\overline{x}} = \frac{s}{\sqrt{n}} \tag{6}$$

Where $\overline{x}$ denotes the sample mean, μ typifies the hypothesised mean and $s_{\overline{x}}$ represents the estimated standard error of the mean. The symbol *s* is the sample standard deviation and *n* is the sample size. In the context of this study, the hypothesised mean was given and assumed by the researcher, for measuring the performance of the proposed framework.

4. Results

Across two sections, this chapter presents the questionnaire-data driven from the investigated sample, related to phases 1 & 2 of the research. Section 4.1 presents the findings of phase 1 of the research investigating the impact of combining FTA, FFBD, AHP, QFD, KBS, DAIREC and AD on FMEA deployment and the effect of a change in other managerial factors that control the perceived challenges for executing FMEA. It begins with the explanation of the process of preparing data for analysis. Following that, this section explains the specified statistical test of the ordered probit model, then delineates the related findings. Section 4.2 demonstrates the findings of phase 2 of the research, which explores the current measurement methods applied in the automotive and the aerospace industries to evaluate the performance of FMEA execution. As an outcome of phase 2 of the research, the sub-sequent section (section 4.3) displays the process of building the cost model suggested for measuring the performance of FMEA deployment.

4.1. Phase 1 of the research: results on the impact of co-adopting other tools on the performance of FMEA deployment

Various approaches were proposed to tackle the practical challenges of executing FMEA, outlined above. The literature review determined that the field of reliability and quality engineering methodologies have so far been exposed to limited empirical research on the effects of co-adopting these methodologies, specified above, on the deployment of FMEA, in particularly in the applications of the automotive and the aerospace industries. To address this important gap in knowledge, this phase of the research examined the hypothesis that the co-adoption of methodologies, such as those outlined in the above, reduce the level of challenge associated with the practical execution of FMEA. Other managerial factors of industry

membership, engineering experience held, and organisational size were also covered in the analysis to understand the relative effects on FMEA implementation. This is critical to validate these approaches and the extent to which could boost the practical execution of FMEA.

To test this hypothesis, this study presented the empirical investigation of the level of challenge (*LC*) associated with FMEA deployment as perceived by practitioners. The ordered probit model was applied to empirically analyse the correlations between *LC* and the performance of combining these methodologies and provide understanding of how each individual element of these tools and other factors outlined above can enhance the practice of FMEA.

4.1.1. Data preparation

4.1.1.1. Construction of the dependent variable

Level of challenge (*LC*) is defined as the dependent variable for this study. As reported by respondents, *LC* reflects the overall challenge for implementing FMEA in engineering systems. This metric was designed to correlate the performance of each methodology and the change in each factor, outlined above, and determine the potential impacts on the application of FMEA. Inspired by previous work analysing the challenges associated with manufacturing technology adoption (Baumers, Tuck and Hague, 2011), *LC* was constructed as the sum of the current observed partial challenges in the deployment of FMEA. These issues are: excessive use of resources, applicability, capturing of interaction failures between system, sub-system and components levels, knowledge gap between design and manufacturing and inability to trace failures.

As far as this research is concerned, the literature has considered these challenges of FMEA deployment are with the same level of importance. This phase applied a scheme assuming each individual FMEA challenge is modular and with the same impact. The elements flowing into *LC* were

obtained from the multiple-choice question, as highlighted in question 5 in Appendix A, asking respondents to identify whether they had encountered the above partial challenges. Binary 'yes/no' questions were generated for each response to perform the analysis. The value of *LC* was then obtained as a score from the summation of these binary elements and can thus take six discrete values ranging from '0' to '5'. This approach is summarised in Table 8 with full description of the collected data.

Table 8: Summary of the independent and dependent variables

Variable name	Symbol	Description	Information type	Data source and remarks
Fault Tree Analysis	*FTA_PERF*	Performance value coded from Likert-scale	Ordered discrete	Questionnaire
Functional Flow Boundary Diagram	*FFBD_PERF*			
Analytical Hierarchical Process	*AHP_PERF*			
Quality Function Deployment	*QFD_PERF*			
Knowledge-Based System	*KBS_PERF*			
Define, Analysis, Improve, Recommend, Evaluate and Control	*DAIREC_PERF*			
Axiomatic Design	*AD_PERF*			
Experience Level	*EXP*	Coded as follows: *EXP* = 0, if the number of experiences =<9 *EXP* = 1, if the number of experiences >9 and =<15 *EXP* = 2, if the number of experiences >15 and =<23 *EXP* = 3, if the number of experiences >23 and =<30 *EXP* = 4, if the number of experiences >30	Continuous	LinkedIn profiles and face-to-face questions

Organisational size	*SIZE*	Coded as follows: *SIZE* = 0, if the number of employees <= 20000 *SIZE* = 1, if the number of employees >20000 and =<50000 *SIZE* = 2, if the number of employees >50000 and =<100000 *SIZE* = 3, if the number of employees >100000 and =<250000 *SIZE* = 4, if the number of employees >250000		Annual reports of businesses
Industry membership	*MEM*	Industry membership values coded from participants fields of work	Binary	LinkedIn profiles and face-to-face questions
Level of challenge to deploy FMEA (the dependent variable)	*LC*	Score variable consisting of the following challenges: Excessive use of resources Applicability Capture interaction failures between system, sub-system and components levels The knowledge gap between design and manufacturing phases Inability to trace risks	Ordered discrete	Ques-tionnaire, composed from multiple questions

4.1.1.2. Construction of the independent variables

The independent variables capture the performance of FTA, FFBD, AHP, QFD, KBS, DAIREC and AD approaches that support or complement FMEA in its deployment. The following seven multinomial discrete variables reflecting the approach performance results were specified, each taking six possible values, ranging from '0' to '5': *FTA_PERF*, *FFBD_PERF*, *AHP_PERF*, *QFD_PERF*, *KBS_PERF*, *DAIREC_PERF* and *AD_PERF*. The coding method used is presented in Table 8.

Beyond the surveyed types of complementary approaches, the model included three additional variables to assess the impact of such organisational factors on *LC*. Industry membership (*MEM*) was included to represent the effects of industry characteristics, entering as a binary variable with '0' denoting aerospace membership and '1' denoting automotive membership. Organisational size (*SIZE*), in terms of employee numbers in the respondent's organisation and experience level (*EXP*), measuring the respondents' work experience in their role in years, were included to represent the resources required for deploying FMEA. Both variables entered the model in coded discrete form by converting continuous numerical information in logarithmic fashion. The coding scheme is also summarised in Table 8.

4.1.2. Model specification for analysis

As being pointed out in section 3.4.1.6.1, the ordered probit model was implemented to elucidate the impact of the dynamic change in the independent variables on the perceived level of challenge (*LC*). In its implementation of the ordered probit model, this study follows the applications process to execute this model by Baumers, Tuck and Hague (2011) and Chan, Miller and Tcha (2005). For this study, the establishment of this model is presented as follows:

$$LC^*_i = x'_i \beta + \varepsilon_i \qquad (7)$$

In the extent of this study, LC^*_i indicates the single latent and continuous variable, which reports the value of *LC.* It should be noted however, that the interpretation of the relationship between the observable discrete variable LC_i, as a counterpart to the unobservable continuous variable LC^*_i, is not straightforward. The correspondence between LC_i and LC^*_i is determined by equation (8), where a set of threshold values α_k serves as estimable unknown parameters. As illustrated in Figure 14, these parameters define the limits of the observed categories ($LC_i = k$), such that:

$$LC_i = k \;\; if \;\; \alpha_{k-1} < LC^*_i < \alpha_k \tag{8}$$

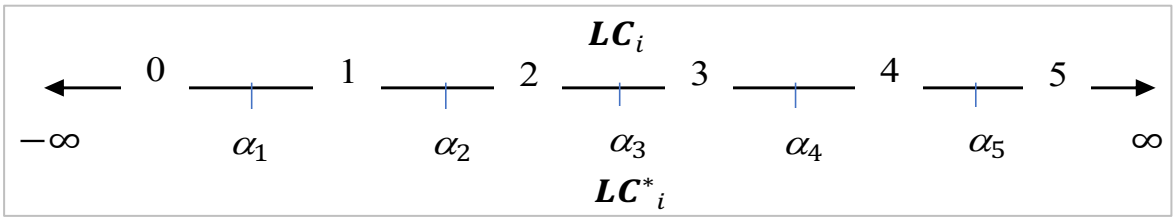


Figure 14: The correspondence between LC_i and LC^*_i

Thus, for the given k^{th} category of LC_i and in a situation where $k \in \{0,1,2,3,4,5\}$ can be written as follows:

$$LC_i = \begin{cases} \mathrm{k} = 0, & if \quad -\infty < LC^*_i < \alpha_1 \\ \mathrm{k} = 1, & if \quad \alpha_1 < LC^*_i < \alpha_2 \\ \mathrm{k} = 2, & if \quad \alpha_2 < LC^*_i < \alpha_3 \\ \mathrm{k} = 3, & if \quad \alpha_3 < LC^*_i < \alpha_4 \\ \mathrm{k} = 4, & if \quad \alpha_4 < LC^*_i < \alpha_5 \\ \mathrm{k} = 5, & if \quad \alpha_5 < LC^*_i < \infty \end{cases} \tag{9}$$

Therefore, by substituting (7) in (8):

$$LC_i = k, \;\; if \quad \alpha_{k-1} < x'_i \beta + \varepsilon_i < \alpha_k \tag{10}$$

And by substituting (7) into (9):

$$LC_i = \begin{cases} \mathrm{k} = 0, & if \quad -\infty < x'_i\,\beta + \varepsilon_i < \alpha_1 \\ \mathrm{k} = 1, & if \quad \alpha_1 < x'_i\,\beta + \varepsilon_i < \alpha_2 \\ \mathrm{k} = 2, & if \quad \alpha_2 < x'_i\,\beta + \varepsilon_i < \alpha_3 \\ \mathrm{k} = 3, & if \quad \alpha_3 < x'_i\,\beta + \varepsilon_i < \alpha_4 \\ \mathrm{k} = 4, & if \quad \alpha_4 < x'_i\,\beta + \varepsilon_i < \alpha_5 \\ \mathrm{k} = 5, & if \quad \alpha_5 < x'_i\,\beta + \varepsilon_i < \infty \end{cases} \tag{11}$$

Thus, the probability of observing LC_i for the k^{th} category can be determined as follows:

$$\Pr\,(LC_i = k) = \Pr\,(\alpha_{k-1} < x'_i\,\beta + \varepsilon_i < \alpha_k) \tag{12}$$

Which can be readjusted to give:

$$\Pr(LC_i = k) = \Pr(\alpha_{k-1} - x'_i\,\beta < \varepsilon_i < \alpha_k - x'_i\,\beta) \tag{13}$$

Which in turn, can be rearranged as follows:

$$\Pr(LC_i = k) = \Pr(\varepsilon_i < \alpha_k - x'_i\,\beta) - \Pr\,(\varepsilon_i < \alpha_{k-1} - x'_i\,\beta) \tag{14}$$

The normal distribution ε_i can be estimated by its cumulative distribution function $\Phi(z)$, which determines the cumulative probability of observing a given z-value (Baumers, Tuck and Hague, 2011; Aldrich, Nelson and Adler, 1984), such that:

$$\Phi(z) = \int_{-\infty}^{z} \Phi(t)\,dt \tag{15}$$

Where,

$$\phi(t) = \frac{e^{\frac{-t^2}{2}}}{\sqrt{2\pi}} \tag{16}$$

Therefore, equation (14) can be re-written as follows:

$$\Pr\,(LC_i = k) = \Phi(\alpha_k - x'_i\,\beta) - \Phi(\alpha_{k-1} - x'_i\,\beta) \tag{17}$$

The full set of probabilities for all k^{th} categories can be rearranged and re-written as follows:

$$\Pr(LC_i = k) = \begin{cases} \Pr(k=0), & if \quad \Phi(\alpha_1 - x'_i\beta) - \Phi(-\infty - x'_i\beta) \\ \Pr(k=1), & if \quad \Phi(\alpha_2 - x'_i\beta) - \Phi(\alpha_1 - x'_i\beta) \\ \Pr(k=2), & if \quad \Phi(\alpha_3 - x'_i\beta) - \Phi(\alpha_2 - x'_i\beta) \\ \Pr(k=3), & if \quad \Phi(\alpha_4 - x'_i\beta) - \Phi(\alpha_3 - x'_i\beta) \\ \Pr(k=4), & if \quad \Phi(\alpha_5 - x'_i\beta) - \Phi(\alpha_4 - x'_i\beta) \\ \Pr(k=5), & if \quad \Phi(\infty - x'_i\beta) - \Phi(\alpha_5 - x'_i\beta) \end{cases} \quad (18)$$

The estimation of α_k and β values can be achieved by Maximum Likelihood Estimation (l) (Cameron, 1988; Aldrich, Nelson and Adler, 1984). Following Jackman (2000), the likelihood contribution l for each i^{th} observation can be derived as follows:

$$l_i = \prod_{k=1}^{K} \Pr(LC_i = k|x'_i)^{Z_{ik}} \quad (19)$$

Where Z_{ik} is used for the purpose of computing the indicator function $Z_{ik} = \mathbf{1}(LC_i = k)$, for $k = 1,..,S$. This allows the statement of the likelihood contribution as follows:

$$l_i = \prod_{k=1}^{s} [\Phi(\alpha_k - x'_i\beta) - \Phi(\alpha_{k-1} - x'_i\beta)]^{Z_{ik}} \quad (20)$$

Aggregating the likelihood contributions over the sample, the likelihood function (L) of parameters α and β can thus be written as:

$$L(\alpha, \beta) = \prod_{i=1}^{n} \prod_{k=1}^{K} [\Phi(\alpha_k - x'_i\beta) - \Phi(\alpha_{k-1} - x'_i\beta)]^{Z_{ik}} \quad (21)$$

Which can be simplified by taking logarithms:

$$\ln L(\alpha, \beta) = \sum_{i=1}^{n} \sum_{k=1}^{K} z_{ik} [\Phi(\alpha_k - x'_i\beta) - \Phi(\alpha_{k-1} - x'_i\beta)] \quad (22)$$

Equation (22) is maximised by the means of Maximum Likelihood Estimation, which is reported to produce appropriate convergence results (McKelvey and Zavoina, 1975).

4.1.3. Results

4.1.3.1. Descriptive statistics

Reflecting a discrete measure on a scale, a value of *LC* = '0' indicates that there is no challenge in deploying FMEA and a value of *LC* = '5' implies that deploying FMEA is highly challenging. As shown in the histogram in Figure 15, the *LC* values observed in the sample appear to be approximately normally distributed.

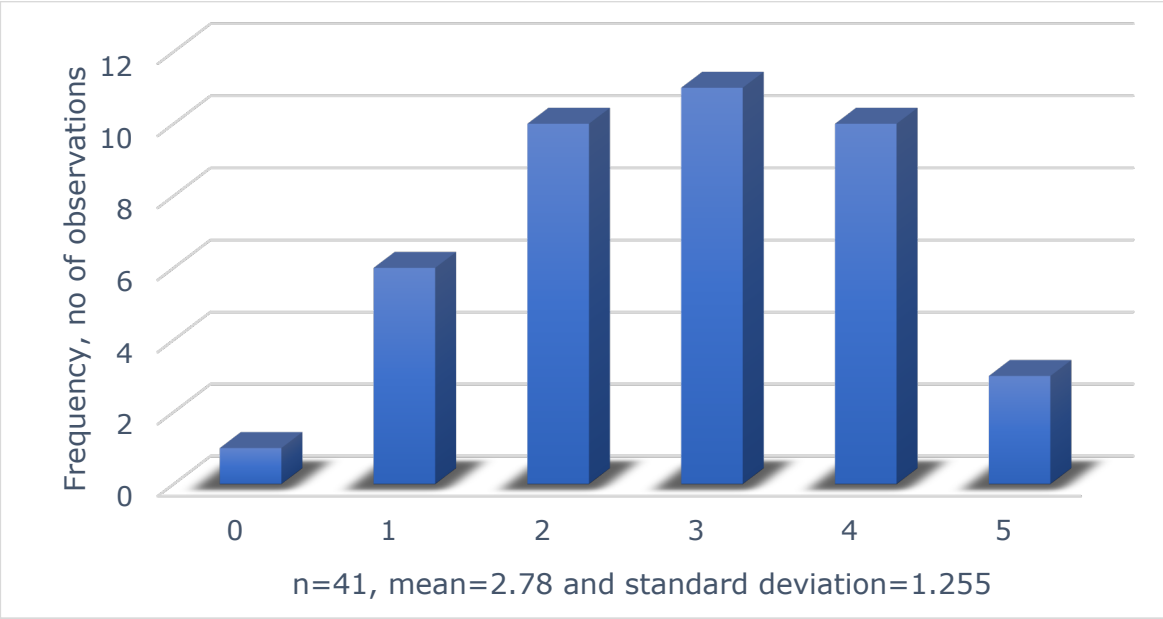


Figure 15: Sample distribution of *LC*

Figure 16 displays the performance responses for the seven approaches (*FTA_PERF*, *FFBED_PERF*, *AHP_PERF*, *QFD_PERF*, *KBS_PERF*, *DAIREC_PERF* and *AD_PERF*). As can be seen, a zero-performance result was reported for all seven approaches, ranging from approximately 15% of the sample for QFD to over 80% of the sample for AD. High levels of performance were also reported for all seven approaches ranging from approximately 17% of the sample for AD to approximately 37% of the sample for FFBD.

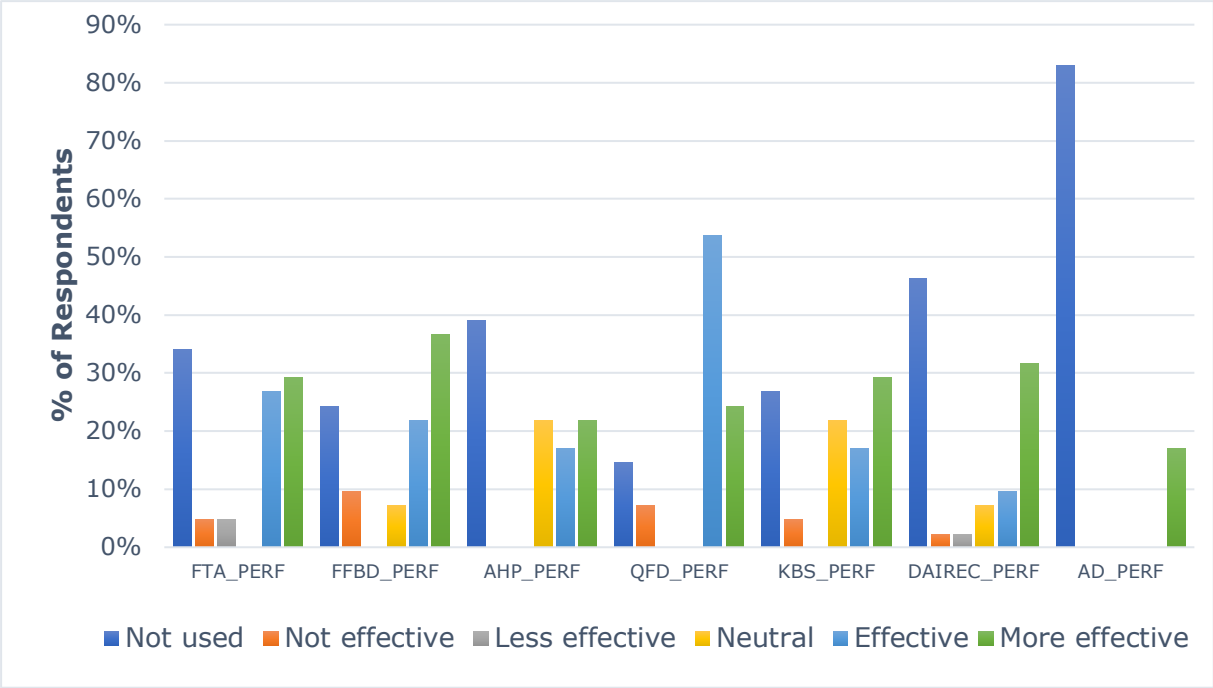


Figure 16: Participants responses, approaches performance

Table 9 displays the full correlation matrix for both the dependent and independent variables. As expected, most of the independent variables show overall negative correlations with *LC*. In particular, it was found that *FTA_PERF*, *DAIREC_PERF* and *AD_PERF* are strongly negatively correlated with *LC* (ρ = -0.600, ρ = -0.466 and ρ = -0.599 respectively). It is noteworthy that *EXP* shows a weak positive correlation with *LC*, while *QFD_PERF* surprisingly indicates a strong positive association with *LC*. The means and standard deviations for the dependant and all independent variables are included in Table 9.

Table 9: Summery of the descriptive statistics

	Mean	Standard deviation	Minimum	Maximum	*FTA_PERF*	*FFBD_PERF*	*AHP_PERF*	*QFD_PERF*	*KBS_PERF*	*DAIREC_PERF*	*AD_PERF*	*EXP*	*SIZE*	*MEM*	*LC*
FTA_PERF	2.683	2.184	0	5	1.000										
FFBD_PERF	3.024	2.091	0	5	0.072	1.000									
AHP_PERF	2.439	2.086	0	5	0.245	0.141	1.000								
QFD_PERF	3.439	1.732	0	5	-0.524	-0.065	-0.276	1.000							
KBS_PERF	2.853	2.007	0	5	0.035	0.209	0.225	-0.154	1.000						
DAIREC_PERF	2.268	2.292	0	5	0.197	0.395	0.236	-0.213	0.128	1.000					
AD_PERF	0.854	1.905	0	5	0.337	0.089	0.124	-0.685	0.132	0.032	1.000				
EXP	1.561	1.163	0	4	-0.213	-0.058	-0.073	0.197	-0.167	-0.114	0.004	1.000			
SIZE	1.780	1.275	0	4	-0.044	0.078	0.124	-0.276	-0.112	0.056	0.237	0.018	1.000		
MEM	0.536	0.505	0	1	-0.046	-0.178	-0.206	0.067	-0.069	-0.192	0.162	0.283	0.269	1.000	
LC	2.780	1.255	0	5	-0.600	-0.303	-0.245	0.689	-0.162	-0.466	-0.599	0.172	-0.174	-0.046	1.000

4.1.3.2. The Cronbach's Alpha test results

Likert scale-based responses obtained from the questionnaire were measured for reliability using the Cronbach's Alpha test. Appreciating that Alpha value differs between '1' (i.e., perfect reliable) and '0' (i.e., unreliable), the value that is greater than 0.5 is considered acceptable (Gliem and Gliem, 2003).

The Alpha coefficients were computed using STATA (v.16) for both the independent and dependent variables. Table 10 summarises the Cronbach's Alpha values for all variables included in this study. For this model, all Alpha values are within the acceptable range. The overall score is also covered in the satisfactory ground, indicating a good reliability of the driven data for further analysis.

Table 10: Cronbach's Alpha values for phase 1 of the research

Variables	**No. of items**	**Alpha value**
FTA_PERF	6	0.6712
FFBD_PERF	6	0.6940
AHP_PERF	6	0.6824
QFD_PERF	6	0.6367
KBS_PERF	6	0.7052
DAIREC_PERF	6	0.6779
AD_PERF	6	0.6766
SIZE	5	0.7241
EXP	5	0.7041
MEM	2	0.7224
LC	5	0.6275
The overall Cronbach's Alpha coefficient		0.7060

4.1.3.3. Ordered probit model results

Table 11 represents the ordered probit model results, obtained by using the statistics package STATA (v.16). A Chi-square test produced a value of 57.03 with a P-value > Chi^2 = 0.0000, indicating that this specified ordered probit model is statistically significant. Chi-Square test is used to investigate the significance of the regression analysis model by comparing the observed sample distribution with the expected probability distribution.

A likelihood ratio test (*Pseudo*-R^2) was used to measure the goodness of fit of the observed variables, that is by quantifying the extent to which all variables included in the ordered probit model can describe *LC*. The obtained *Pseudo*-R^2 value for this model is 0.4335. As outlined above in section 3.4.1.6.1, *Pseudo*-R^2 value presents the amount of variations in the independent variables to describe the explanatory variable (i.e., level of challenge in this study). The *Pseudo*-R^2 values vary between '1', indicating better prediction of the explanatory variable, and '0' suggesting the opposite. However, the executed ordered probit model in this study produced unacceptable value (*Pseudo*-R^2=0.4335). This means that the specified model may not be able to accurately predict the explanatory variable (i.e., level of challenge in this study). As noted by Hemmert et al. (2018), the *Pseudo*-R^2 values are susceptible to the study design and sample characteristics. Using 274 published articles around logistic regression models for meta-analysis and simulated data, their study suggests that the *Pseudo*-R^2 value is significantly influenced by the sample size, number of explained variables, and number of categories of the explanatory variable and its distribution asymmetry.

Furthermore, there is no a generally acceptable range value for *Pseudo*-R^2 value for ordinal regression models (Veall and Zimmermann, 1992; Agnew, and Huguley, 1989; Brym, Gillespie and Lenton, 1989). Another issue with the ordinal regression models is the unavailability of the latent variable (i.e., in this study: LC^*_i) could contribute to the low *Pseudo*-R^2 value, which

lacks the ground to compare the explained variables with the explanatory variable, according to Hagle and Mitchell (1992).

In the case of the current study, it is assumed that the low *Pseudo*-R^2 value (0.4335) is commensurate with the relatively small sample size used in this phase of the research as well as the limited range of the explained variables included in the ordered probit model. In addition, the exploratory character of this study encouraged to use this model with low *Pseudo*-R^2 value to have a better understanding of the impact of integrating different methods with the deployment of FMEA, given that it will not provide conclusive results. However, this study lays out the foundation for future research, which requires to employ a larger sample size and larger range of the explained variables. Moreover, the ordered probit model applied in this study offers a better *Pseudo*-R^2 value (0.4335) compared to other applications of the same model like Liu and Koirala (2012) with *Pseudo*-R^2=0.032 and Chan, Miller and Tcha (2005) with *Pseudo*-R^2=0.188.

To determine whether the differences between threshold mean values (α_k) are statistically significant and distinct, a confidence interval overlapping analysis was used to compare the boundary values of the confidence intervals coupled with all threshold parameters. The confidence interval overlapping is an approach for determining the significant differences between groups (Payton, Greenstone and Schenker, 2003; Schenker and Gentleman, 2001). At 95% significant level, Figure 17 displays that this model produced overlapping between confidence intervals associated with all threshold parameters. This may imply that these parameters are not statistically significant and therefore, they are not distinct. However, it is imperative to clarify that the differences between those threshold parameters might still be significant.

Table 11: The ordered probit model estimation results

Sample size: 41
Degree of freedom: 9
LR Chi^2: 57.03
P-value > Chi^2: 0.0000
Pseudo R^2: 0.4335
Log-likelihood: -37.26

Variables	**Coefficients**	**Standard deviation**	**Signifi -cance**	**[95% Conf. Interval]**
FTA_PERF	-0.249	0.109	**	-
FFBD_PERF	-0.158	0.103	-	-
AHP_PERF	-0.043	0.105	-	-
QFD_PERF	0.466	0.204	**	-
KBS_PERF	0.007	0.101	-	-
DAIREC_PERF	-0.293	0.099	***	-
AD_PERF	-0.477	0.182	***	-
EXP	0.186	0.178	-	-
SIZE	0.123	0.185	-	-
MEM	-0.798	0.467	*	-
α_1	-6.32	1.572	-	-9.425 -3.226
α_2	-2.902	1.191	-	-5.246 -0.558
α_3	-0.604	1.169	-	-2.895 1.686
α_4	0.704	1.161	-	-1.574 2.977
α_5	2.355	1.157	-	0.087 4.623

Note:

(*) indicates the significance of variable is at the 10% level
(**) indicates the significance of variable is at the 5% level
(***) indicates the significance of variable is at the 1% level
α_1, α_2, α_3, α_4 and α_5 are threshold parameters



Figure 17: Boxplot diagram of the width of the confidence intervals for threshold parameters, at 95% confidence level

In an attempt to satisfy the condition of the confidence interval overlapping, the original model was redesigned by minimising the scale of both the dependent and independent variables. Among various adjusted scenarios, the model was formed to a scale of 4 measures for both the dependent and most the independent variables (*FTA_PERF*, *FFBD_PERF*, *AHP_PERF*, *QFD_PERF*, *KBS_PERF*, *DAIREC_PERF*, *AD_PERF*, *EXP* and *SIZE*). The applied coding approach for the optimised model, called reduced model, is presented in Table 12.

Table 12: Summary of the reduced model of the independent and dependent variables

Variable name	Symbol	Description	Information type	Data source and remarks
Fault Tree Analysis	*FTA_m*	Taking *FTA_perf* as illustrative to represent all variables listed, the coding as follows: *FTA_m* = 0, if *FTA_perf* = 0 *FTA_m* = 1, if *FTA_perf* = 1 & 2 *FTA_m* = 2, if *FTA_perf* = 3 & 4 *FTA_m* = 3, if *FTA_perf* = 5	Ordered discrete	Original formed Likert-scales
Functional Flow Boundary Diagram	*FFBD_m*			
Analytical Hierarchical Process	*AHP_m*			
Quality Function Deployment	*QFD_m*			
Knowledge-Based System	*KBS_m*			
Define, Analysis, Improve, Recommend, Evaluate and Control	*DAIRE C_m*			
Axiomatic Design	*AD_m*			
Experience Level	*EXP_m*	Recoded as follows: *EXP_m* = 0, if *EXP* = 0 & 1 *EXP_m* = 1, if *EXP* = 2 *EXP_m* = 2, if *EXP* = 3 *EXP_m* = 3, if *EXP* = 4	Continuous	
Organisational size	*SIZE_m*	Recoded as follows: *SIZE_m* = 0, if *SIZE* = 0 & 1 *SIZE_m* = 1, if *SIZE* = 2 *SIZE_m* = 2, if *SIZE* = 3 *SIZE_m* = 3, if *SIZE* = 4		

Industry membership (Kept same)	*MEM*	Industry membership values coded from participants fields of work	Binary	LinkedIn profiles and face-to-face questions
Level of challenge to deploy FMEA (dependent variable)	*LC_m*	Recoded as follows: *LC_m* = 0, if *LC* = 0 & 1 *LC_m* = 1, if *LC* = 2 *LC_m* = 2, if *LC* = 3 *LC_m* = 3, if *LC* = 4 & 5	Ordered discrete	Original formed Likert-scales

Table 13 presents the results of the model parameters obtained from the execution of the reduced probit model at 90% significant level. This model still addresses overlapping between confidence intervals coupled with all threshold parameters as shown in Figure 18; however, the decision was made to retain this model since it produced narrower overlapping intervals and a better *Pseudo* R^2 value with approximately 5%. In addition, this model was made of fewer regressand and regressor's categories, which may carry meaningful effects with reduced margin error levels.

Table 13: The reduced ordered probit model estimation results

Sample size: 41 Degree of freedom: 9 LR Chi^2: 51.41 P-value > Chi^2: 0.0000 Pseudo R^2: 0.4599 Log-likelihood: -30.18				
Variables	**Coefficients**	**Standard deviation**	**Signifi -cance**	**[90% Conf. Interval]**
FTA_m	-0.41	0.208	**	-
FFBD_m	-0.284	0.204	-	-
AHP_m	-0.017	0.196	-	-
QFD_m	0.927	0.36	**	-
KBS_m	-0.062	0.203	-	-
DAIREC_m	-0.426	0.182	**	-
AD_m	-0.71	0.288	**	-
EXP_m	0.007	0.237	-	-
SIZE_m	0.136	0.271	-	-
MEM	-0.471	0.49	-	-
α_1	-2.761	1.214	-	-4.759 -0.763
α_2	-0.603	1.154	-	-2.502 1.295
α_3	0.725	1.139	-	-1.148 2.599
Note: (*) indicates the significance of variable is at the 10% level (**) indicates the significance of variable is at the 5% level (***) indicates the significance of variable is at the 1% level α_1, α_2 and α_3 are threshold parameters				

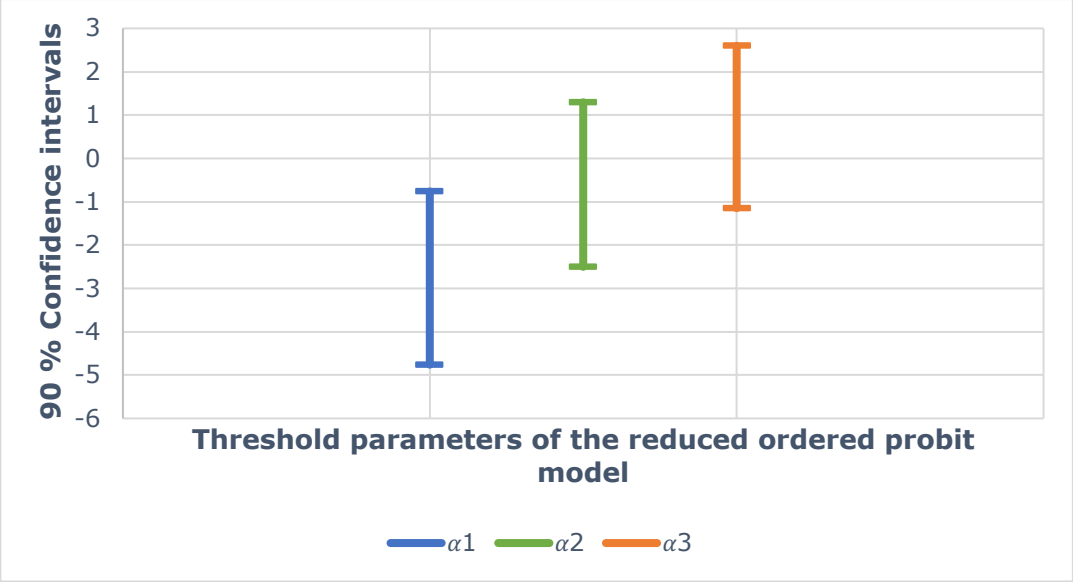


Figure 18: Boxplot diagram of the width of the confidence intervals for threshold parameters, at 90% confidence level

Using the ordered probit model, the positive coefficients denote a larger probability for the membership to the maximum level of *LC_m* (i.e., *LC_m* = 3), whereas vice versa the negative coefficients indicate larger probability for the membership to the minimum level of *LC_m* (i.e., *LC_m* = 0). This being indicated, the interpretation of coefficients yielded by an ordered probit model requires further analysis to investigate the marginal effects and the predicted probabilities.

As can be seen, the *FTA_m*, *QFD_m*, *DAIREC_m* and *AD_m* variables are statistically significant. The *FTA_m* variable (-0.41) suggests a larger probability for the membership to the lowest category of the perceived level of challenge (*LC*), as represented by *LC_m* = 0. This means that FTA method has the largest positive influence on *LC* reduction by offering an effective method to decompose system functions and identify the coupled failure modes. Likewise, both the *DAIREC_m* and *AD_m* variables have the equal relationship to the smallest category of *LC*. The similarity between the coefficients estimated for the *DAIREC_m* variable (-0.426) and *AD_m* variable (-0.710) is noteworthy, since both approaches have the same positive impact and role in improving FMEA deployment (i.e., synchronising

FMEA procedures). Compared to *DAIREC_m*, the *AD_m* variable has a relatively greater positive impact on *LC_m* reduction. However, the *QFD_m* variable (0.927) indicates a positive relationship to the highest category of *LC_m*; this suggests an adverse impact of co-adopting QFD on *LC*.

The next step in the analysis of the ordered probit model is the investigation of the marginal effects for each independent variable on the membership to all *LC_m* categories. Marginal effects analysis provides further insights and a useful measure for the degree of influence of the independent variables on *LC_m* (Chan, Miller and Tcha, 2005).

The marginal effects presented in Table 14 were estimated at the means of the independent variables. As a result of a one-unit increase in the independent variables, this analysis allows to assess the overall changes in the probability of observing *LC_m* categories at a particular level. Thus, the results shown in Table 14 indicate that if the *FTA_m* variable increases by one unit, the probability of observing *LC_m* = 0 increases by more than 1%. The negative impacts in the top two categories of *LC_m* (-7.148% and -9.199 %) show clearly that the co-adoption of FTA method is likely to reduce the level of challenge associated with FMEA deployment.

The impacts of the *DAIREC_m* and *AD_m* variables on *LC_m* indicate that the combination of DAIREC and AD approaches in the practice of deploying FMEA also contribute to the reduction of *LC*. Both variables increase the probability to reduce *LC_m* = 2 by 9.554% and 15.93% respectively, while the probabilities of observing *LC_m* = 0 for both variables increase by less than 3%.

The effect of an increase in the *QFD_m* variable by one unit rises the chance of observing the intermediate level of challenge (*LC_m* = 2) by 20.97%. Running counter to this, the probability of observing *LC_m* = 0 resulting from a change in the *QFD_m* variable decreases to 3.29%.

The probability of observing the intermediate value of the level of challenge (*LC_m* = 2) remarkably decreases by 10.15% as a result of a change in industry membership (*MEM)*. Overall, it is noteworthy that the change in all independent variables appears to increase or decrease the probability of observing the high level of challenge (*LC_m* = 3), whereas it appears to have a far lower effect when the level of perceived challenge is low (*LC_m* = 0).

Table 14: Summary of the marginal effects

	Categories of *LC_m* for deploying FMEA			
Variables	**3**	**2**	**1**	**0**
*FTA_m***	-7.148	-9.199	14.89	1.455
FFBD_m	-4.495	-6.365	10.30	1.007
AHP_m	-0.294	-0.379	0.61	0.06
*QFD_m***	16.15	20.79	-33.65	-3.29
KBS_m	-1.084	-1.395	-2.226	-0.221
*DAIREC_m***	-7.423	-9.554	15.46	1.511
*AD_m***	-12.38	-15.93	25.79	2.521
EXP_m	0.121	0.155	-0.25	-0.024
SIZE_m	2.375	3.056	-4.947	-0.483
MEM	-8.443	-10.15	16.92	1.669

Note:

For expositional purposes, all coefficients were multiplied by 100 therefore, values presented above is in the form of percentage point effects. Values across rows may not equal to 0 due to rounding errors.

(*) indicates the significance of variable is at the 10% level

(**) indicates the significance of variable is at the 5% level

(***) indicates the significance of variable is at the 1% level

Finally, the *FTA_m* and *AD_m* variables are chosen for further exploration due to their large influences on *LC_m*. This was performed by calculating the predicted probabilities of the associations between all categories of *LC_m* and *FTA_m*/*AD_m*. The predicted probabilities provide a good indicator with the objective to shed light on the actual levels with which the different levels of FTA and AD performances are represented in *LC_m* categories (Chan, Miller and Tcha, 2005). Table 15 presents the predicted

probabilities for the memberships of all *LC_m* categories across the different discrete values of the independent variables of *FTA_m* and *AD_m*, held at their mean values.

Table 15: Summary of the predicted probabilities of all *LC_m* categories

		The predicted probabilities for *LC_m* categories			
Variables	**Value**	**3**	**2**	**1**	**0**
FTA_m	**0**	65.36	26.82	7.729	0.074
	1	7.575	37.59	52.63	2.196
	2	22.57	26.78	39.71	10.92
	3	10.17	18.05	52.24	46.52
AD_m	**0**	38.54	29.49	28.14	3.818
	1	-	-	-	-
	2	-	-	-	-
	3	0.787	4.893	14.52	79.79

Note:

For exposition, all coefficients were multiplied by 100 therefore, values presented above are in the form of percentage points. Values across rows may not equal to 0 due to rounding errors.

Table 15 indicates that the *FTA_m* and *AD_m* variables appear to have an influence on how the level of challenge associated with FMEA deployment is distributed. Obviously, when FTA performance is reported as high, the bulk of the distribution of *LC_m* is in the low category (*LC_m* = 0). This pattern is repeated even more pronouncedly for the *AD_m* variable, for which the predicted probabilities could only be obtained for the extreme values of the *AD_m* variable. These results manifest the actual

effectiveness of co-adopting both FTA and AD approaches on the deployment of FMEA.

4.2. Phase 2 of the research: results on the current methods applied for measuring the performance of FMEA deployment

The motivation for this phase of the research stemmed from the lack of existing studies on the measurement systems currently employed to validate the performance of FMEA application, as well as exploring the targets usually required by industry to use for developing the framework of integrating FMEA application proposed in this research project. This study statistically explored the current status of measuring the performance of FMEA. The findings obtained from the questionnaire were quantified and presented in graphical format with the help of Microsoft Excel, and the graphs produced were then evaluated using descriptive analysis. This section is divided into two segments: the current metrics applied for measuring the performance of FMEA employment and the ways for implementing these metrics.

4.2.1. Results

4.2.1.1. Current metrics used to measure the performance of FMEA practice

As perceived by participants through the responses obtained from the developed questionnaire in section 3.4.1.2, Figure 19 presents the current performance measurement approaches used for assessing FMEA implementation in the aerospace and the automotive industries. With 80.5% of the responses, the index of mitigating failures was classified as the most frequently applied approach, followed by both the metrics of determining the capability of FMEA practice to identify failure modes and documenting the knowledge/actions of the analysed failures with a rate of 68.3% of the responses. Evaluating the performance of the resources invested for deploying FMEA and quantifying the cost of corrective actions

were classified as the least used approaches in the sample surveyed. In order to understand how these approaches are being applied, further questions were asked and are presented in the next section.

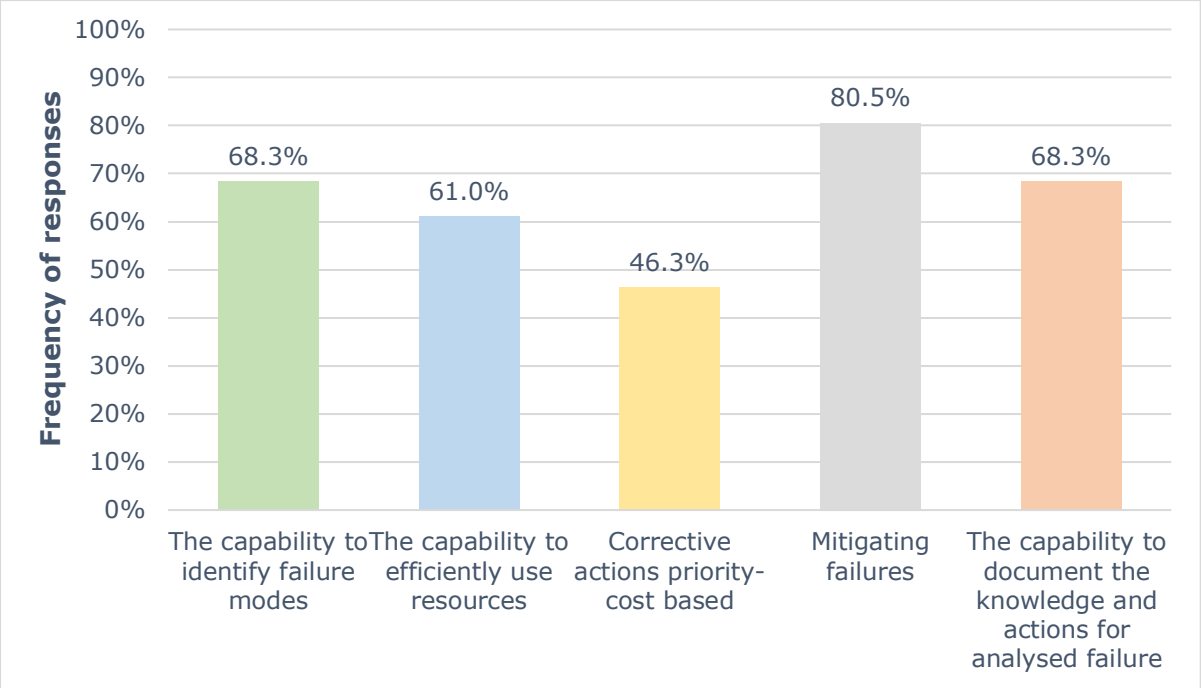


Figure 19: Metrics used to measure FMEA employment performance

4.2.1.2. Methods for implementing the metrics used

This study had been extended to shed light on the ways of employing the measurement themes presented as outlined above. Figure 20 highlights that the themes identified are executed on either subjective or objective measures. However, none of the respondents elaborated on the process involved in deploying these measures, which might be due to confidentiality requirements. According to Gibbs et al. (2005), subjective measures are usually influenced by the personnel opinions/judgment of how the worker, machine or tool performs, while in contrast, objective measures are those that are quantitatively based.

As shown in Figure 20, most approaches adapted for measuring the performance of FMEA deployment are based on subjective evaluations. For the index of determining the capability of FMEA to identify failure modes,

73% of those surveyed employed subjective measures to perform this metric, whereas 15% of participants used objective measures. The remaining 12% chose not to comment on this question.

Both subjective and objective measures were equally used with the same rates (43%) to report the metric of mitigating failures. For the metric of determining the capability of the executed FMEA to efficiently use the assigned resource, over half of those who responded (57%), applied subjective measures to complete this task, while 27% of respondents used objective bases.

In contrast, 42% of participants surveyed exercised an objective assessment to evaluate the cost of the corrective-driven actions. For measuring the performance of FMEA to document the knowledge/actions of the analysed failures, over half of the surveyed sample (52%) applied this metric subjectively.

This part of the research helped to identify the common approaches used to estimate the performance of FMEA deployment in industry. These targets were used in this research project to build the framework of integrating FMEAs, presented in the next chapter. Moreover, the findings of this phase of the research indicate that current performance measurement of FMEA deployment is frequently managed in industry by subjective measures. This suggests the demand for a computable metric, which would help to certify the outputs of FMEA execution and avoid the bias in the measurement results. In this phase of the research, the cost model developed for estimating the performance of FMEA execution has been investigated. This cost model merged various cost elements of the activities required to complete FMEA deployment, which are managed by the number of the analysed functions and the associated failure modes. On the basis of CoQ framework, this cost model was designed to correlate the cost of executing FMEA with the cost of failures to highlight the impact of FMEA deployment

and show the cost saving. The next section elaborates on this cost model in further detail.

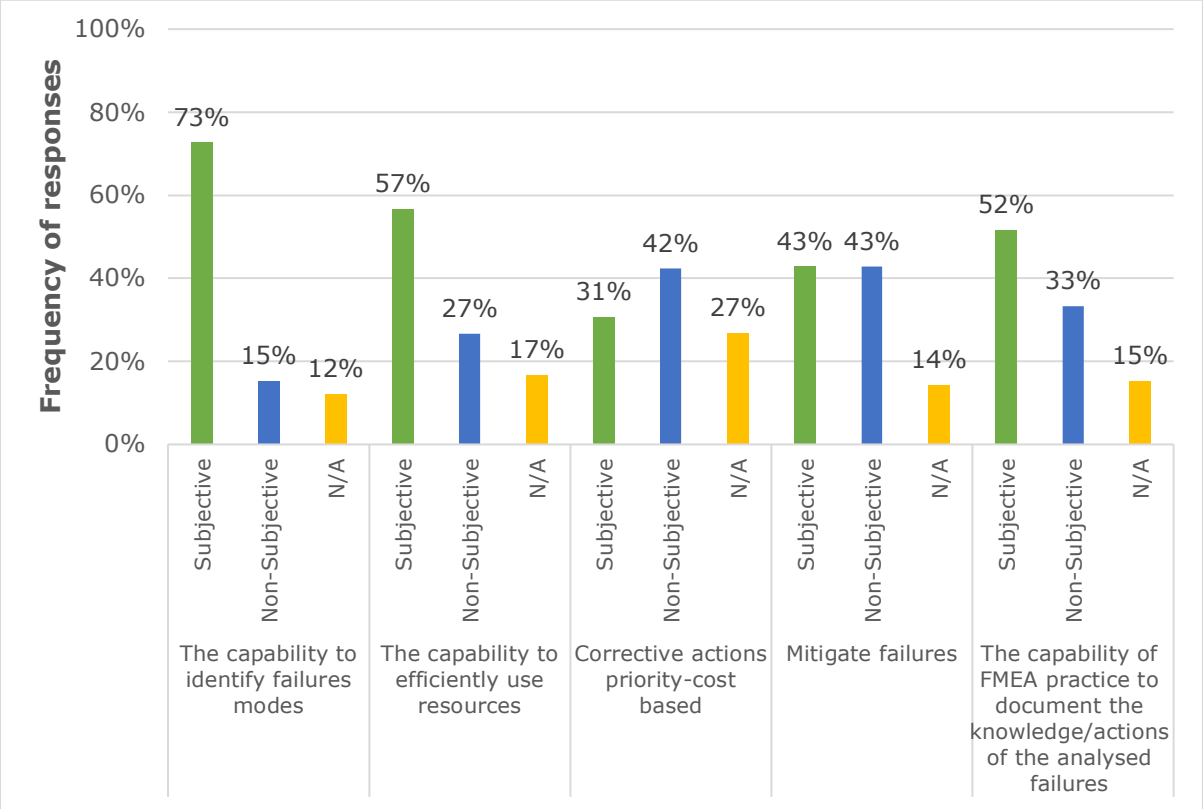


Figure 20: The approaches for implementing the metrics used

4.3. The proposed cost model

The associated benefits of implementing FMEA likely originate from the ability to recognise and mitigate failures in advance, making them less costly to address (Lipol and Haq, 2011). Therefore, the performance of FMEA execution should be measured to present the key achievements, as well as providing proof of advancements in any extended FMEA work (Pollock, 2005). The extant literature has demonstrated a dearth of studies devoted to estimating the value of deploying FMEA. Existing cost models have focused on the estimation of the cost of mitigating actions and design changes (Von Ahsen, 2008) and the cost of failure (Tazi, Châtelet and Bouzidi, 2017; Von Ahsen, 2008; Kmenta and Ishii, 2004; Rhee and Ishii, 2003), while the cost estimation of deploying FMEA and its impact itself have been ignored.

Derived from the previous section, the subjectivity of the measures identified motivate research for a quantitative indicator that could estimate the performance of FMEA deployment with an overarching goal for addressing the limitations suggested in the literature and enabling organisations to reveal the impact of implementing FMEA. On cost bases, this section explains how CoQ architecture provides a framework to measure the performance of FMEA deployment. It goes on to elucidate a conceptualised cost model designed to compute the cost of executing FMEA.

CoQ framework maps the inverse relationship between different costs of good and poor quality practices; for example, the cost of deploying FMEA is spent to reduce or prevent poor quality from occurring. The proposed cost model is considered as a novel approach and was influenced by work proposed by Stevenson et al. (2017), who developed a cost model to empirically quantify the impact of part consolidation (PC) associated with additive manufacturing. Their cost model seeks to chase the cost of PC over the development and production stages in a such additive manufacturing

application. The cost model proposed in this phase of the research follows the similar procedure of Stevenson et al. (2017) to investigate the impact of deploying FMEA in product development process.

4.3.1. Development of the FMEA cost model

Since the overall goals for deploying FMEA is to improve the reliability and quality of products as well as save money, these goals could be addressed in the following cost model, presented in Table 17, to investigate the impact of FMEA deployment on business performance by emphasising the capability of FMEA deployment in mitigating and reducing the cost of failures. This cost model may serve as an approach to evaluate the level of reliability in deploying FMEA, by quantifying the number of failures been addressed by FMEA deployment.

The cost model proposed follows Activity-Based Costing approach (ABC) to estimate the cost of executing FMEA. ABC quantifies the individual cost of each activity involved for delivering products or services (Hassan et al., 2010). On the basis of the CoQ framework described in section 2.3.3, the cost of deploying FMEA generates the illustration of CoGQ; the cost of minimising or preventing failures (symbolised: $CoGQ_{FMEA}$). Meanwhile, the other part of CoPQ is characterised as failure cost, which refers to all costs incurred by the failure (termed: $CoPQ_{Failures}$).

As discussed in section 2.1.2, FMEA is deployed in three distinct applications within the product development process; Functional, Design and Process FMEAs. For simplicity, this work is limited to an individual FMEA, which was imposed due to time and resources restrictions. The cost elements of the developed cost model were identified from the work of Carlson (2012). As shown in Figure 3, the workflow of undertaking FMEA is drawn from FMEA preparation to FMEA review in the form of a process map to define the activities involved in implementing FMEA practice and hence, outlining the cost elements of FMEA deployment.

This model deconstructs the cost into five features associated with the activities of $CoGQ_{FMEA}$, which are grouped into four cost categories: FMEA preparation, analysis, failure prevention and review, as expressed in Table 16. The cost of resources consumed by each activity in FMEA implementation is amalgamated to form the total cost of $CoGQ_{FMEA}$. As is the source for the most existing cost models suggested for estimating failure cost and for simplicity, the model of Rhee and Ishii (2003) was chosen to obtain $CoPQ_{Failures}$. The material cost of failures prevention was deemed out of scope. This is because this cost item is ill-structured as it is difficult to determine (Baumers and Tuck, 2019); since the prevention process generally goes through intervention processes including redesigning, retesting, re-inspecting and so on.

Table 16: Cost categories of the cost model proposed

Cost category	The associated activities
FMEA preparation	• Identification of functional requirements • Associated failure modes/causes/ effect/possible control actions identifications
FMEA analysis	• RPNs determinations
Failure prevention	• Failures detection/mitigation
FMEA Review	• Review

4.3.1.1. Definition of the cost elements as a cost per unit

To guide the cost model, two allocation bases were identified to manage and differentiate the understanding of the suggested model. They were defined as units used to quantify the degree of FMEA execution performance. These allocation bases are the number of functional requirements (marked: $N_{Functions}$) and failure modes (labelled: $N_{Failures}$). The first unit denotes the number of functions being analysed within the

execution process of FMEA. The second refers to the total number of related failure modes. Table 17 presents the proposed cost model and all notations required to calculate the final $CoGQ_{FMEA}$. These notations are driven by the required time to preform each activity, number of workers and worker rate. For example, two tasks are required prior to implementing FMEA; determining the functional requirements concerned and the associated failure modes, causes, effects and possible control actions. As proposed in this model, the cost of each task is computed via identification time ($T_{Identification}$), number of workers (N_{workers}) and worker cost/hour (C_{worker}). The same procedure is applied to the other cost categories, where the cost of each activity is estimated through similar cost elements. It is assumed that all activities are performed once and expressed as cost rates.

Table 17: Cost elements of the cost model proposed for measuring the performance of FMEA deployment

Cost category	Associated activities	Cost elements	Allocation bases (units)	Specifications (cost unit)
FMEA preparation	Identification of functional requirements identification	Identification time ($T_{Identification_R}$) No. of workers (N_{workers}) Worker cost/hour (C_{worker})	No. of functional requirements ($N_{Functions}$)	$a = \left(\frac{T_{Identification_R}}{N_{\text{workers}}} \times C_{\text{worker}}\right)$ $a = \left[\cancel{hrs} \times \frac{£}{\cancel{hrs}}\right]$
	Identification of the associated failure modes, causes, effects and possible control actions	Identification time ($T_{Identification_F}$) No. of workers (N_{workers}) Worker cost/hour (C_{worker})	No. of failure modes ($N_{Failures}$)	$b = \left(\frac{T_{Identification_F}}{N_{\text{workers}}} \times C_{\text{worker}}\right)$
FMEA analysis	RPNs determinations	Assessment time ($T_{Assessment}$) No. of workers (N_{workers}) Worker cost/hour (C_{worker})		$c = \left(\frac{T_{Assessment}}{N_{\text{workers}}} \times C_{\text{worker}}\right)$
Failure prevention	Failures detection and mitigation	Prevention time ($T_{Prevention}$) No. of workers (N_{workers}) Worker cost/hour (C_{worker})		$d = \left(\frac{T_{Prevention}}{N_{\text{workers}}} \times C_{\text{worker}}\right)$
FMEA Review	Review	Review time (T_{Review}) No. of workers (N_{workers}) Worker cost/hour (C_{worker})	No. of functional requirements ($N_{Functions}$)	$e = \left(\frac{T_{Review}}{N_{\text{workers}}} \times C_{\text{worker}}\right)$

To determine the potential impact of FMEA deployment on a business, the net benefits of executing FMEA are estimated and compared by equation (25) using the allocation bases ($N_{Functions}$ and $N_{Failures}$), by the notations described in Table 17. Equation (23) is geared by the number of units ($N_{Functions}$ and $N_{Failures}$) to obtain $CoGQ_{FMEA}$. On the other hand, equation (24) estimates $CoPQ_{Failures}$, which is driven by ($N_{Failures}$). The total costs for

both $CoGQ_{FMEA}$ and $CoPQ_{Failures}$ are calculated by the total number of these units.

$CoGQ_{FMEA}$ is obtained as follows:

$$\boldsymbol{CoGQ_{FMEA}} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{N_{Functional}}}(\boldsymbol{a_i} + \boldsymbol{e_i}) + \sum_{\boldsymbol{j=1}}^{\boldsymbol{N_{Failure}}}\left(\boldsymbol{b_j} + \boldsymbol{c_j} + \boldsymbol{d_j}\right) \quad (23)$$

Where $CoPQ_{Failures}$ can be adopted from Rhee and Ishii (2003) model as follows:

$$\boldsymbol{CoPQ_{Failures}} = \sum_{\boldsymbol{j=1}}^{\boldsymbol{N_{Failures}}} \boldsymbol{p_j c_j} \quad (24)$$

Where $\boldsymbol{p}$ denotes the probability of the occurrence of the failure and $\boldsymbol{c}$ refers to the cost associated with that failure. By determining both costs, equation (25) calculates the total of CoQ-related FMEA (CoQ_{FMEA}) as follows:

$$\boldsymbol{\Delta CoQ_{FMEA}} = \boldsymbol{CoGQ_{FMEA}} + \boldsymbol{CoPQ_{Failures}} \quad (25)$$

As shown in Figure 21, the increase in spending on FMEA implementation ($CoGQ_{FMEA}$) would theoretically contribute to a decrease in the cost of failures ($CoPQ_{Failures}$), which likely leads to a reduction in the quality level featuring internal and external failures. This may indicate a negative correlation between both $CoGQ_{FMEA}$ and $CoPQ_{Failures}$. It should be noted, however, that $CoPQ_{Failures}$ is expected to be far higher than $CoPQ_{Failures}$. To afford a representative model, other factors associated with $CoGQ_{FMEA}$ should be taken into account to obtain this estimate, such as the cost of materials for correcting failures and improving the design features concerned.

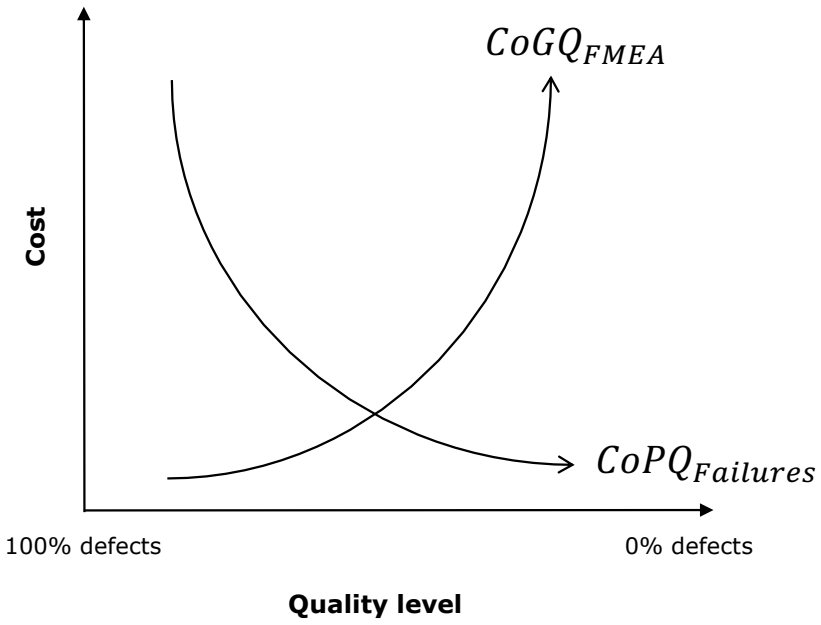


Figure 21: The expected theoretical view of CoQ curve

5. The proposed framework of synchronising Functional, Design and Process FMEAs

Phase 1 of the research identified AD methodology as a suitable element for integrating FMEAs. Moreover, phase 2 of the research identified three common goals for deploying FMEA: the capability to identify failure modes, mitigating failures and document the knowledge of the analysed failures. Meaning that the framework should be able to help and meet these targets. AD was used to develop the proposed framework of synchronising Functional, Design and Process FMEAs. These common goals above mentioned also were considered in the process of developing the framework. Across two sections, section 5.1 demonstrates a detailed investigation of the requirements for developing the targeted framework. Section 5.2 presents the findings of the validation process of the proposed framework.

5.1. Phase 3 of the research: the proposed framework

FMEA has been determined as a time-consuming methodology for its inability to capture and trace the cascaded failures, those failures escape between Functional, Design and Process FMEAs (Xiao et al., 2011; Kmenta and Ishii, 2004). Yet, FMEA on its own lacks a synchronised structure to transform and hook these failures. To maximise the benefits of applying FMEA, the different tasks of FMEA must be synchronised to effectively trace and capture failures, as well as handling such derived improvements in each area as shown in Figure 22 (Henshall, Campean and Rutter, 2014; Soufhwee et al., 2013; Carlson, 2012; Xiao et al., 2011; Popović, Vasić and Petrović, 2010; Teng et al., 2006; Kmenta and Ishii, 2004). A close look

into the relevant literature reveals there is limited research to investigate this requirement.

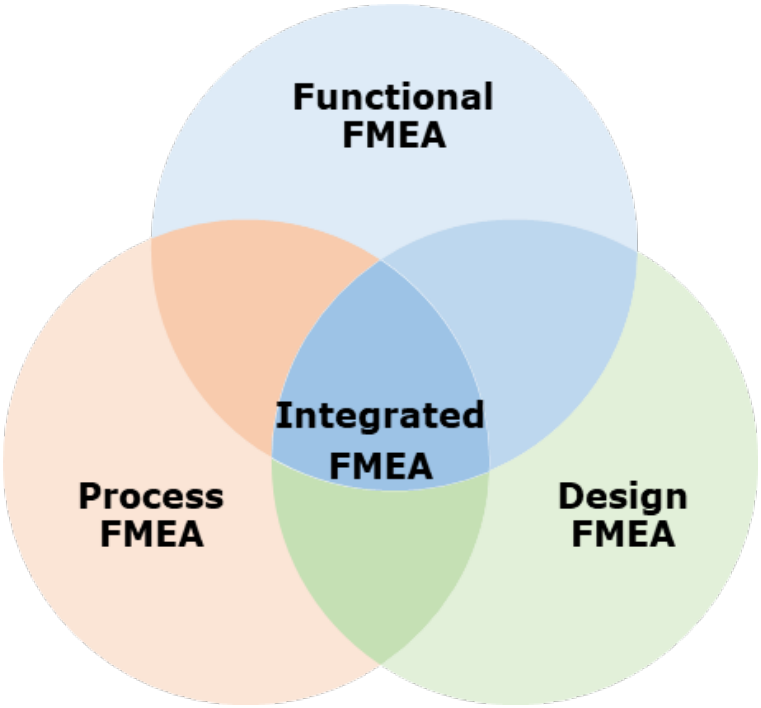


Figure 22: Proposed model of synchronising FMEA applications

Adhering to the objective outlined in section 1.2, and the findings described in the previous chapter, this phase of the research was aimed at developing a conceptualised framework for improving the practice of FMEA and integrating its applications in the product development process. This proposed model, named AD-DSM-FMEA framework, was furthered with complementary validation through the feedback collected from the field related individuals. The responses were then fed into the t-test model to assess the developed framework.

AD method is recognised as a tool for identifying the design sequence (Park et al., 2021; Goo et al., 2019; Shao et al., 2016; Suh, 2001). By using the domains, hierarchical structures, zigzagging and the independence axiom, AD method can decompose systems into sub-systems and components, and synthesis these elements across to the process domain (Park et al., 2021; Goo et al., 2019; Shao et al., 2016; Suh, 2001). Thus, this can

identify nodes where design elements are connected, resulting in determining the independence between these elements (Park et al., 2021; Goo et al., 2019; Shao et al., 2016; Suh, 2001). Tracking the design flow and those nodes are important for identifying the impact of such failures in a design feature on others connected elements and therefore, capturing the cascading failures between these elements (Henshall, Campean and Rutter, 2014; Carlson, 2012). Therefore, this research mainly selected AD method to synchronise the Functional, Design and Process FMEAs and therefore, trace and capture the cascading failures between these domains. Since the scope of the framework proposed in this research is to improve the new product development process, AD method was selected. AD method has been extensively used to develop new designs/products, where there is a lack of details and via its elements, new designs can be developed (Park et al., 2021; Goo et al., 2019; Shao et al., 2016; Salonitis, 2016; Tang, Zhang and Dai, 2009; Suh, 2001).

AD was found to enhance the applications of FMEA in catching the cascaded failures. For example, Sadeghi et al. (2013) developed a framework combining both AD and FMEA methods. AD method is used in their approach to determine the functional requirements (FRs) associated with reliability issues and map these requirements to the attributed design parameters (DPs). These interactions identified by AD method in their framework are evaluated by the application of FMEA. This means that the combination of both AD and FMEA methods is used to trace and capture the cascading failures between functional and design domains; represented by FRs and DPs. A case study of a power take-off (PTO) system was used to validate this framework. The validation process shows that the co-adoption of both methodologies can better catch the cascading failures between functional and design domains and therefore, improving the reliability of a such design (Sadeghi et al., 2013).

In addition, Arcidiacono and Campatelli (2004) shared the same view, where their model of co-adopting AD approach with FMEA and FTA methods

helped to catch the cascading failures between functional and design domains, as well as saved the 50% of the resources that was usually utilized in deploying FMEA. However, these works are limited to capturing the cascading failures between functional and design domains. This means that these models only focused on the integration of Functional and Design FMEAs. Therefore, this research seeks to expand the scope of these works and explore the capability of AD method in integrating Functional with Design and Process FMEAs as well as capturing the cascading failures between these applications of FMEA.

Still, Figure 16 shows that AD method is not commonly used in the industry. Therefore, it can be argued that AD method is not applicable in practice. This concern has been justified by Kumar and Tandon (2019) and Frey et al. (2007), who argue that satisfying the independence axiom featured the application of AD method particularly at component level is sometimes difficult to achieve due to the associated cost and level of system integration. Another justification was given by Park et al. (2021) and Guenov and Barker (2005), who clarify that it is difficult to determine the physical link between design parameters (DPs) using AD method.

However, these challenges were considered in the development of the framework proposed in this research by integrating Design Structure Matrix (DSM) approach with AD method. In the case that the system in question cannot meet the requirement of maintaining the independence between functional requirements (FRs) at certain levels, then DSM is used to analyse those FRs as well as those related DPs, which are considered coupled. DSM has been identified as an effective approach for evaluating the interaction between the coupled design features and improving design process flow by determining the physical relationship between these features and then clustering them into related groups for further integration and improvements (Jefferson, Ratchev and Crossley, 2014; Eppinger and Browning, 2012; Tang, Zhang and Dai, 2009; Guenov and Barker, 2005; Steward, 1981).

5.1.1. AD-DSM-FMEA framework

Figure 23 presents the theoretical framework of the integrated AD-DSM-FMEA. It comprises four stages, made of a set of loops, and organised to synchronise Functional, Design and Process FMEAs – thereby enabling the cascaded failures to be captured. AD procedures are mainly implemented to facilitate the process of decomposing the system examined and to link FMEA applications. DSM method is also combined to provide full coverage for managing the coupling issue between design elements. The term 'framework' has been used broadly in the engineering design domain within different contexts and meanings, as noted by Pepe et al. (2011) and Arcidiacono and Campatelli (2004). For example, in the context of the new product development, the notion of a framework is used as means of guidance comprising a set of steps joined together to support the investigation's efforts for improving the design processes (Pepe et al., 2011).

The proposed framework is formed of 13 steps, which are grouped into four stages: abstraction level definition, detailed level definition, system analysis and next level definition. Each stage acts towards synchronising FMEAs, departing from defining the analysis scope of FMEA deployment and the introduction of the top-level requirements of the product system and leading to establishing the related design features and process variables. Once that objective is complete, the framework evaluates the associated failures, next if any, introducing and assessing the next system level. The following sub-sections explain each stage in detail.

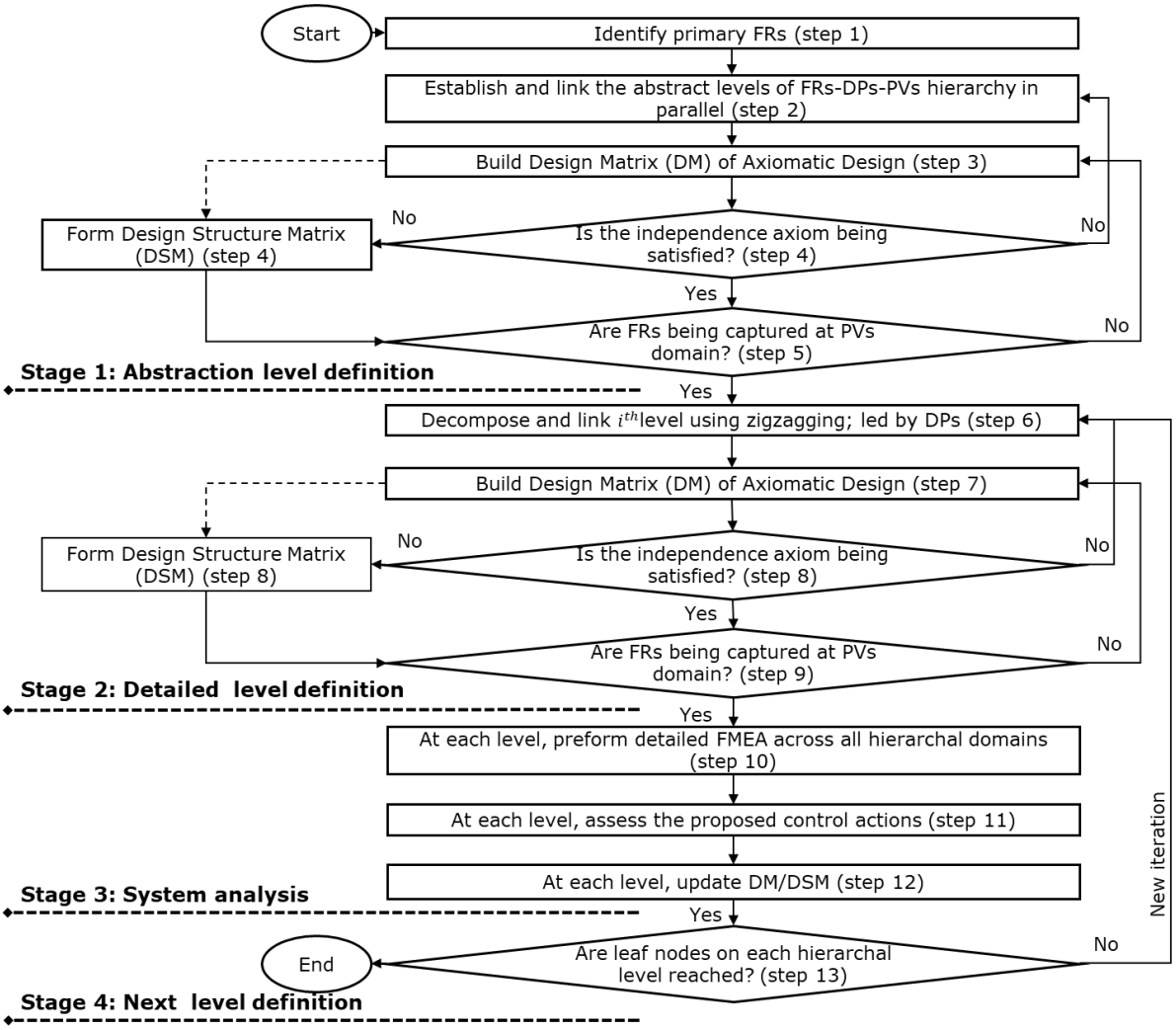


Figure 23: The proposed conceptual framework of integrated AD-DSM-FMEA

5.1.1.1. Stage one: abstraction level definition

This stage describes the process of identifying the scope of FMEA analysis and establishing the first level hierarchy of functional, design and process domains. It strives to answer the question "*What must the system have in order to meet customer needs*?''. To craft the AD hierarchy and set up the scope of FMEA analysis, the 1st step identifies the primary functional requirements (FRs), design parameters (DPs) and process variables (PVs) of the system in question. The 2nd step is to establish and link the abstraction level of functional, design and process domains in a parallel way to form the system taxonomy. Theoretically, this step horizontally

decomposes FRs into DPs, then to the corresponding PVs. As illustrated in Figure 24, this step develops the overall picture and conceptualisation of the design and its embodiment.

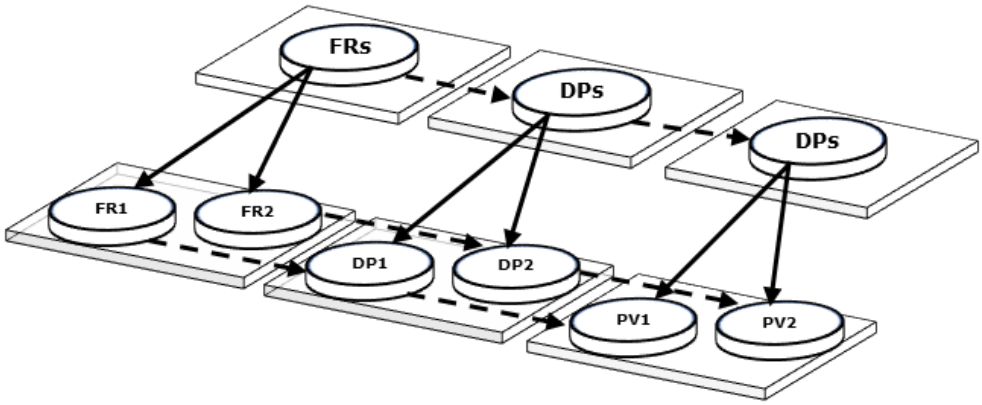


Figure 24: Representative model of the abstraction level hierarchy

Once the first two steps are complete, the 3rd step involves building the Design Matrix (DM) and represents the link between all functional, design and process domains. For the first two domains, DM must be either diagonal or triangular to ensure a consensus with the independence axiom (Suh, 2001). As shown in Figure 25, building DM serves as a method of checking and numerically representing consistency between all domains (Suh, 2001). The 4th step determines whether the DM that has been developed can satisfy the independence axiom, as it aims to manage the communication between all domains.

In the event that the level of consistency required falls short and the defined design has violated the independence axiom, the 2nd step will be re-examined to re-design the identified level for uncoupling design. However, meeting the requirements of the independence FRs might be unachievable, as highlighted by Kumar and Tandon (2019) and Frey et al. (2007). Therefore, the alternative route of incorporating Design Structure Matrix (DSM) method is introduced to overtake and complete the process at this stage, as well as modelling the coupled design. Any move towards

using DSM method will be judged by the capability of the design, which has been introduced, to meet the independence axiom.

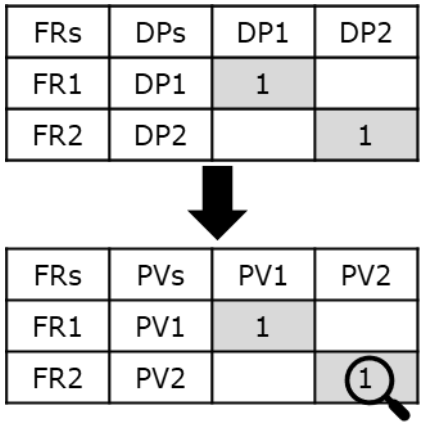


Figure 25: Representative model of the developed DM

In either situation, whether satisfying or failing to satisfy the independence axiom, the 5th step in this stage investigates whether FRs have been transformed and captured in the process domain, and whether the related PVs have been allocated. Otherwise, the assembled DM in the 3rd step will be reviewed and re-formed to horizontally transform FRs into PVs. On the whole, the output from this stage evolves from abstract to detailed concepts as presented in the next stage.

5.1.1.2. Stage two: detailed level definition

In this stage, the abstraction level hierarchy is extended and detailed, and this attempts to respond to the question "*How does the system work to accomplish the expectations?*''. By means of decomposition tree and zigzagging of AD, the 6th step in this framework decomposes the abstraction level of all constructed functional, design and process domains into the lower levels and interconnects them. This process is led by the primary DPs to define the next level of FRs and the corresponding PVs. In other words, the recognised FRs are correlated to the related DPs and PVs, so as to conceptualise the design and introduce the next FRs, DPs and PVs. Vertically and horizontally, this step synthesises the abstraction level of DPs

in both directions, towards determining the next level elements; as presented in Figure 26.

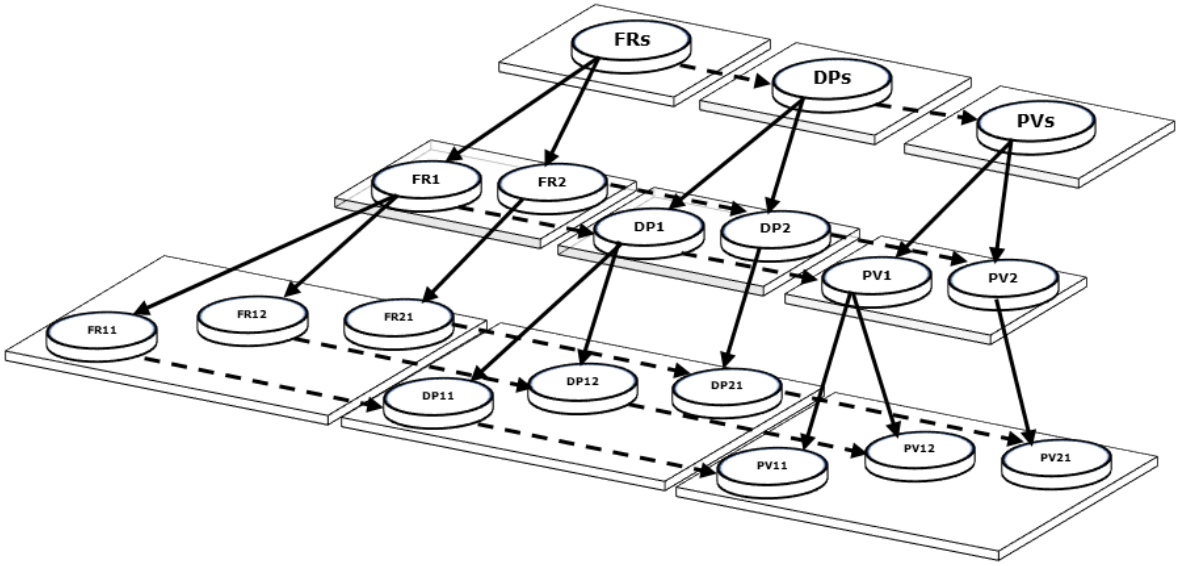


Figure 26: Representative model of the 2nd level hierarchy

The 7th, 8th and 9th steps follow the same process as described in the 3rd, 4th and 5th steps respectively, presented in stage one. Having the abstraction level being decomposed, step 7 builds DM to numerically chase the transformation process and present the whole picture of the integration between the decomposed domains.

Next, step 8 assesses the capability of the decomposed domains to ascertain whether the defined system level can fulfil the requirements of the independence axiom. As an alternative, the proposed framework demands two actions at this juncture: either, going back to step 6 and re-decomposing the design elements given towards meeting the condition of this axiom, or establishing DSM as a substitute route to cover and treat the coupling issues between the elements of the decomposed domains.

Finally, step 9 evaluates the system level introduced to ensure the decomposed FRs have being captured at the PVs' domain and the associated PVs have been assigned, otherwise step 7 will be evaluated and improved to transform FRs into the PVs' domain. Generally, this stage

provides a scoping procedure for executing FMEA and presents the design elements, ensuring they are interconnected in a way that simplifies the process for synchronising Functional, Design and Process FMEAs, which is discussed in the next stage.

5.1.1.3. Stage three: system analysis

This stage involves the process of evaluating the defined hierarchy and seeks to answer the question "*How will the defined system proactively improve?*''. FMEA deployment is brought here to proactively evaluate the design elements, derived from the above stages, and mitigate the associated failures. Step 10 is to apply a detailed FMEA across all the AD domains introduced and to evaluate the potential failure modes associated with all features of the system levels decomposed. In addition, this step determines RPNs; for prioritising and improving the severity and likelihood of failures. Through the constructed hierarchy of all domains, this step addresses the linkage between Functional, Design and Process FMEAs simultaneously in one package.

Having performed FMEA with control actions being determined, steps 11 and 12 in this framework assess the proposed actions and update the DM/DSM respectively: following the FMEA cycle as displayed in Figure 27. The proposed control actions will be traced and evaluated with a new cycle of FMEA to ensure the effectiveness of these actions for reducing the impact or mitigating failures, as well as validating the determined RPNs have been minimised. Once the control actions have been approved, the DM/DSM developed will be updated to demonstrate the design improvements for further investigations that will be covered by the next stage.

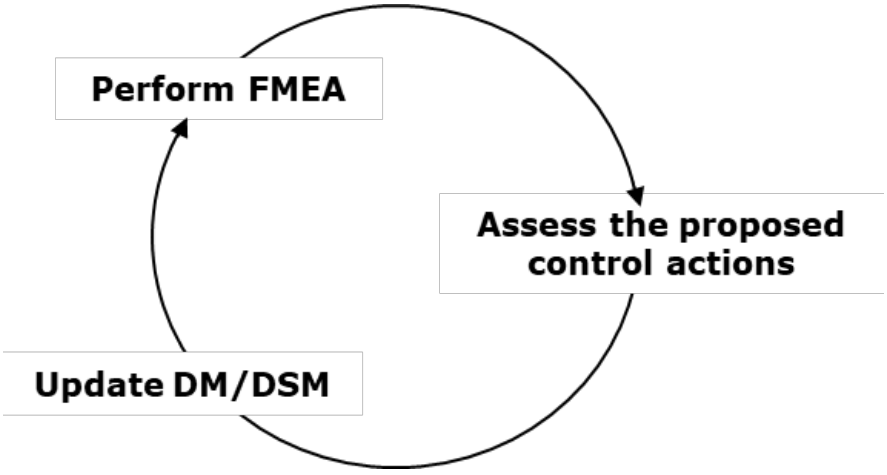


Figure 27: FMEA cycle

5.1.1.4. Stage four: next level definition

To continue evolving system analysis, this stage regulates the process of defining the next level of the hierarchy initiated in stage two. It also serves as a determination criterion that either communicates back with stage two to decompose the next level hierarchy of all AD domains, or informs the end of the framework process. This stage is constructed to ensure that the defined hierarchy is achieved and improved by ensuring that all leaf nodes in each hierarchal level are treated. 'Leaf' represents the last item in each tree of all AD hierarchy as presented in Figure 28.

Through the use of expert information, for example engineers' expertise and reference to design manuals, the hierarchy introduced will be appraised to assure that the design introduced has been understood and proactively investigated. The next steps involve going back to stage two and starting a new iteration to create the next lower level FRs and the associated DPs/PVs. Through the application of FMEA, horizontal correlations between the levels of FRs, DPs and PVs that have been introduced will then be generated and improved. This link and integration are managed by the DM/DSM constructed to explore and represent the correlations between Functional and Design FMEAs over to Process FMEA. At this end point, it would help to detect and control the underlying root causes of failures, as

this could help to inform that all hierarchical leaf nodes are completed. To provide boundaries to the framework's focus and better enable evaluation of its success, this next level definition stage can be limited to the acute elements related to product safety and performance.

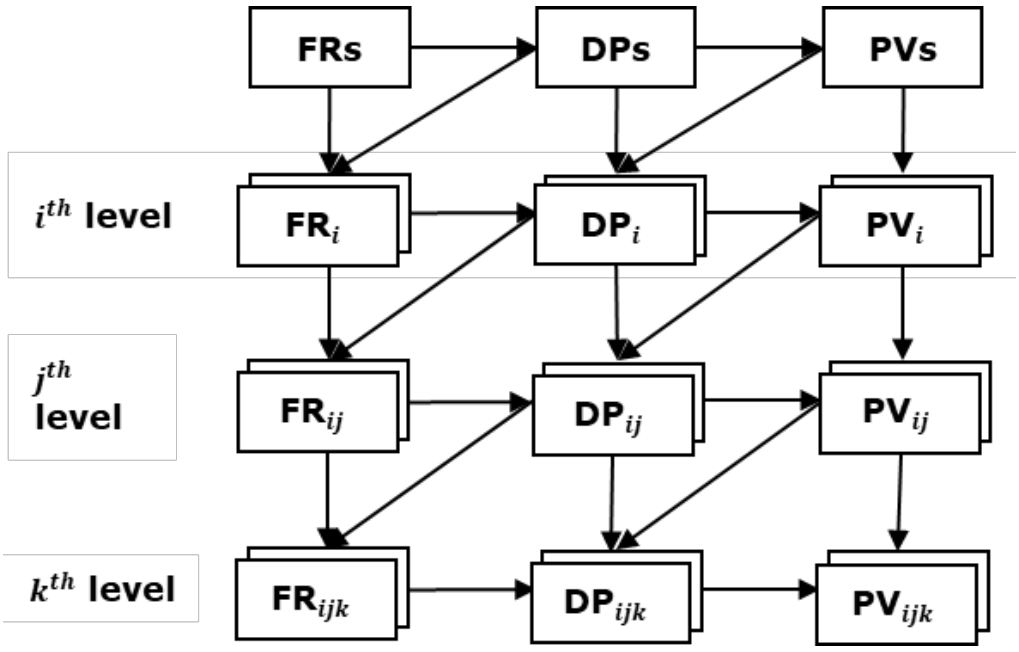


Figure 28: Representative model of hierarchical leaf

5.2. The process of validating the framework developed for integrating FMEAs

Led by the gap in the literature, the integrated AD-DSM-FMEA framework was designed to incorporate Functional, Design and Process FMEAs into an integrated working architecture and streamline the workflow of FMEA deployment. This framework was validated by 12 related recruits from both industry and research-based perspectives. The one sample t-test was applied to empirically evaluate these responses collected. To assess the acceptance level of the proposed framework, this phase of the research investigates various hypothesised mean trials for each evaluation measure in the assessment criterion, as presented in Table 6. The summary of the descriptive statistics is demonstrated in Table 18.

Table 18: Summary of the descriptive statistics of the applied t-test model

Measure sample	Sample size (n)	Sample mean $(\overline{x})$	Standard error $(s_{\overline{x}})$	Standard deviation $(s_{\overline{x}})$	Min	Max	[95% Confidence interval]
A	12	2.75	0.18	0.62	2	4	2.355 3.144
B	12	4.67	0.28	0.98	2	5	3.041 4.292
C	12	3.75	0.22	0.75	2	5	3.271 4.229
D	12	3.58	0.23	0.79	2	5	3.079 4.087
E	12	3.83	0.27	0.93	2	5	3.237 4.429

5.2.1. The Cronbach's Alpha test results

Because this model consists of scale-based responses, the relevant reliability was investigated by the application of Cronbach's Alpha test to check the internal consistency between these responses. Using STATA (v.16), the Alpha coefficients for all measures including the overall score were found to be greater than the acceptable limit of 0.5 as illustrated in

Table 19 below. These results reveal the confidence in the results of this model.

Table 19: Cronbach's Alpha values for phase 3 of the research

Measure	No. of items	Alpha value
A	5	0.9311
B	5	0.876
C	5	0.8971
D	5	0.9181
E	5	0.8867
The overall Cronbach's Alpha coefficient		0.9207

5.2.2. The t-test model results

For the means of all samples, Table 20 presents the t-test results for the three distinct hypothesised mean trials. The chosen significance level (*p*-value) for this model is 0.05. The proposed model can be interpreted as follows:

- The *p*-value of more than 5% (*p*-value > 0.05) indicates weak evidence against the null hypothesis (H0: $\mu = \overline{x}$), so the researcher fails to reject the null hypothesis and the alternative hypothesis (H0: $\mu \neq \overline{x}$) is being rejected.
- The *p*-value of less than 5% (*p*-value < 0.05) indicates strong evidence against the null hypothesis (H0: $\mu = \overline{x}$), so the null hypothesis is rejected and the alternative hypothesis (H0: $\mu \neq \overline{x}$) is being accepted.

For the first trial, the hypothesised mean was set to equal 4, which means that 80% of the opinions are in favour of successful application of the proposed framework in practice to achieve the target required for each

measure (*A*, *B*, *C*, *D* and *E*) at the 95% confidence interval. On this basis, the t-test was specified using statistics package STATA (v.16) for all criterion measures at the 95% confidence interval. At μ = 4, the *p*-values for samples *B*, *C* and *E* (*p* = 0.13, 0.13 and 0.27 respectively) are statistically insignificant and therefore, this model failed to reject the null hypothesises for *B*, *C* and *E* samples while the null hypothesises for *A* and *D* samples were rejected. This demonstrates that the participants believe that the proposed framework is useful, providing support to synchronise FMEAs and practically applicable. Figure 29 presents the participants' responses to each individual measure scale. A high level of performance (4) was reported for measures *B*, *C*, *D* and *E*, which indicates that most responses point to the framework being practically feasible and adoptable.

Among various trials, the hypothesised mean of the second trial was given as 3.5 to test the others measures; *A* and *D*. At this trial, the t-test model results suggest only measure *D* has satisfied the null hypothesis with a *p*-value of 0.36, which means the model failed to reject the null hypothesis (μ = 3.5). This signifies that 70% of the opinions suggest that the proposed framework is quite comprehensive in terms of its ability to catch and detect failures that could occur and cascade over the product development stages.

At the hypothesised mean of 3, the third trial has confirmed the consensus of measure *A* with *p*-value being just above 5% to the null hypothesis of equal 3. This demonstrates that the t-test model rejected the alternative hypothesis (μ = 3). These findings indicate that the participants believe that this proposed framework would be easy to use if it was supported with further explanations.

Table 20: The t-test model results for the three trials

		Measure sample	*t* value	*p*-value
Trial 1: Reporting that 80% of the opinions are in favour of successful implementation of the proposed framework.		*A*	-6.96	0.00
		B	-1.17	0.13
		C	-1.15	0.13
Null hypothesis	H0: $\mu = 4$	*D*	-1.82	0.04
Alternative hypothesis	H0: $\mu \neq 4$	*E*	-0.62	0.27
Trial 2: Reporting that 70% of the opinions are in favour of successful implementation of the proposed framework.		*A*	-4.18	0.00
		B	-	-
		C	-	-
Null hypothesis	H0: $\mu = 3.5$	*D*	0.36	0.36
Alternative hypothesis	H0: $\mu \neq 3.5$	*E*	-	-
Trial 3: Reporting that 60% of the opinions are in favour of successful implementation of the proposed framework.		*A*	-1.14	0.09
		B	-	-
		C	-	-
Null hypothesis	H0: $\mu = 3$	*D*	-	-
Alternative hypothesis	H0: $\mu \neq 3$	*E*	-	-

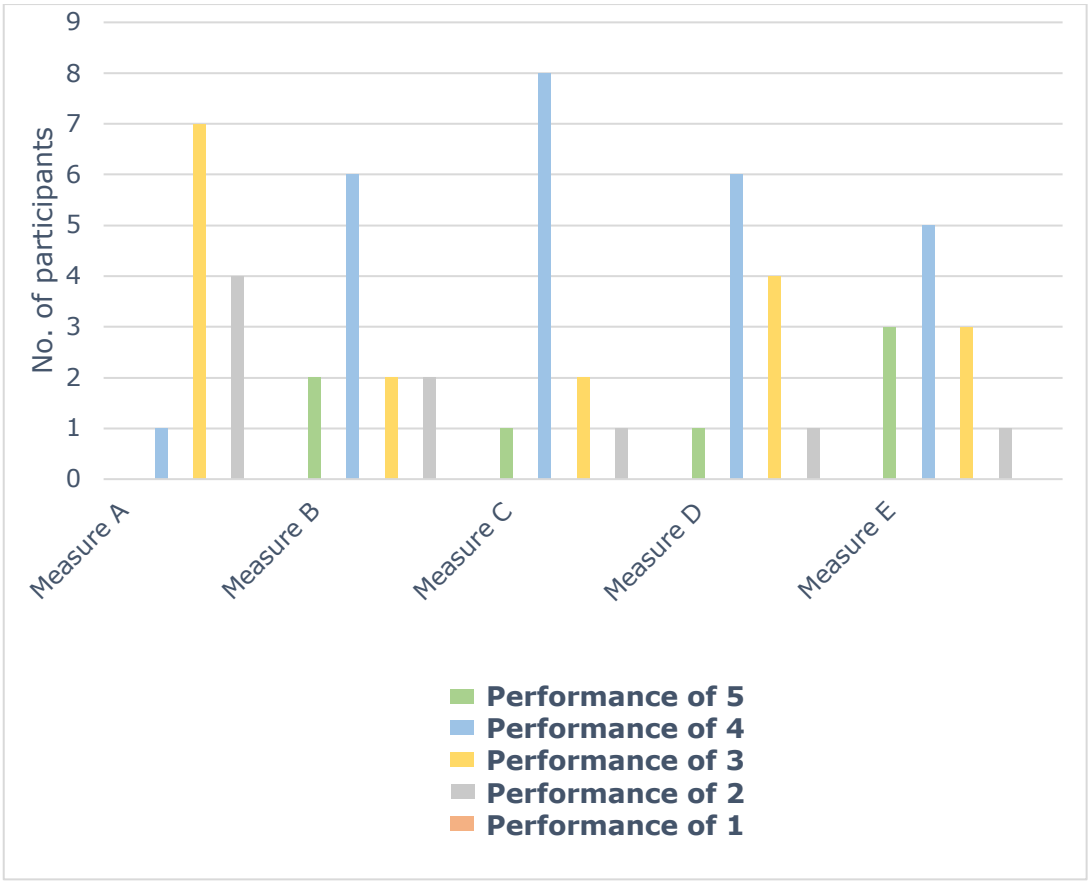


Figure 29: Participants' responses to all measures

6. Discussion

As presented in chapters 4 and 5, this chapter discusses and interprets the research findings in the context of the existing literature, also reviews the proposed frameworks proposed in this research. In terms of structure, two themes are presented to will form the basis of this chapter. The first theme represents all discussions and reviews linked to FMEA deployment with the second theme focusing on all considerations around the performance measurement of FMEA deployment.

6.1. FMEA deployment

6.1.1. Phase 1 of the research

The traditional mode of FMEA implementation involves a bottom-up analysis of failure behaviour and is independently performed during the product development stages (Emovon et al., 2015; Carlson, 2012; Stamatis, 2003). This results in difficulties for determining where to search for failure modes and how to pursue their effects, which makes it difficult to achieve sufficient depth of analysis resulting in a generally time-consuming process.

This phase of the research sought to achieve the aim of objective 2 by determining the impact of combining FTA, FFBD, AHP, QFD, KBS, DAIERC and AD methodologies suggested to address the current limitations of FMEA deployment, as well as the effect of dynamic alteration in managerial factors on the application of FMEA. Through the application of the survey-based responses and the ordered probit model, this phase employed a unique quantitative indicator to measure the performance of integrating these methodologies abovementioned and the impact of other organisational factors (i.e., represented by *EXP*, *SIZE* and *MEM* variables) on the application of FMEA. The empirical results presented in section 4.1 provide useful insights into the methods and factors that may potentially

lead to successful application of FMEA in the automotive and the aerospace industries.

For example, the co-adoption of FTA method was identified as a supporting element in the employment of FMEA, allowing a top-down decomposition of engineering systems. To address this issue, a structured framework for combining FTA and FMEA approaches was established and employed to evaluate the development of a metal additive manufacturing system (Peeters, Basten and Tinga, 2018). Likewise, Han and Zhang (2013), Yu et al. (2011), Bluvband, Polak and Grabov (2005) and Arcidiacono and Campatelli (2004) also suggest this concept of combining FTA and FMEA into a hybrid methodology to tackle the limitations involved with both methods. However, the true impact of this integrated approach requires further investigation as this example has only been assessed to a limited extent, where the focus was on the applicability of the suggestions.

Notwithstanding the above, the results presented in this phase do provide a new quantitative indication of the extent to which the co-adoption of FTA method can assist in the deployment of FMEA. This is confirmed by the negative coefficient of the *FTA_m* variable (-0.41) which was obtained by the executed ordered probit model (presented in Table 13), suggesting that FTA implementation may be able to efficiently guide and lead the application of FMEA to the component level which happens to be the system's deepest. This can be seen through the hierarchical trees developed; allowing the identification of the top functional failure modes, followed by an extension of these failure modes down to a detailed level. This process creates a robust, logical hierarchy which can be used to better understand the underlying failure mechanism. Together with the model results observed (see section 4.1.3.3), this indicates that the co-adoption of FTA approach in the deployment of FMEA can have a positive impact in terms of reducing the analysis of such systems with a level of integrations, which would save resources and ensure an effective application of FMEA (García Márquez et al., 2012; Lee et al., 1986).

Informed by the perceived level of challenge (*LC*), the predicted probabilities results illustrated in Figure 30 provide an additional insight into the link between both *LC* associated with FMEA deployment and the performance of combining FTA method. These results also suggest the significant effect that the co-adoption of FTA method has on the application of FMEA. For example, where FTA implementation is at its highest performance (shown in Figure 30.d), this brings *LC* associated with FMEA deployment down into the lowest category (*LC_m* = 0). Arcidiacono and Campatelli (2004) have drawn similar conclusions, noting that where FTA and AD combined with FMEA, a 50% saving in resources utilised in implementing FMEA was achieved.

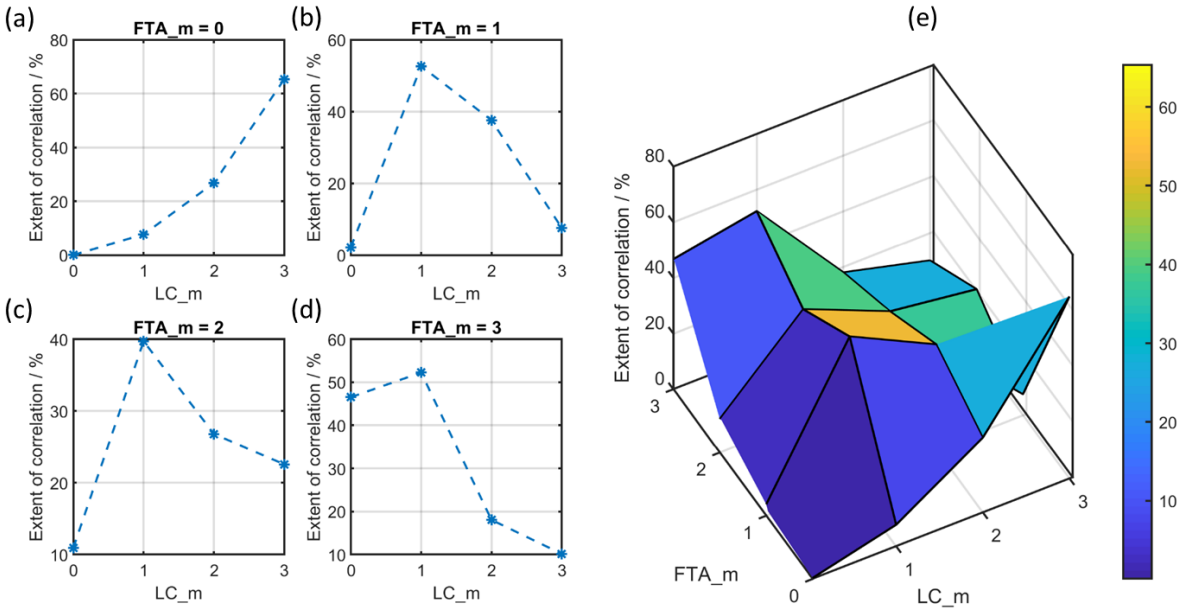


Figure 30: The predicted probabilities of *FTA_m* performances: (a) *FTA_m* = 0, (b) *FTA_m* = 1, (c) *FTA_m* = 2, (d) *FTA_m* = 3 and (e) overall performance of *FTA_m*

In addition, synchronisation issues between FMEA applications can be controlled using AD approach, which is highlighted by the model results presented in Table 13. Indeed, the review of the relevant literature suggests a dearth of research linked to the use of AD method in synchronising all FMEA procedures. However, the results obtained in this

study appear to be encouraging in terms of highlighting the ability of AD method to perform this task. The ability of AD method to resolve FMEA synchronisation issues in this regard has also been documented by others (Sadeghi et al., 2013; Arcidiacono and Campatelli, 2004; Mohsen and Cekecek, 2000).

The potential of AD approach is also noted in this study's results with the negative coefficient of the *AD_m* variable obtained by the ordered probit model executed (-0.71). Figure 31 highlights that the co-adoption of AD approach affects *LC_m* relatively strongly. This means that AD method adoption could synchronise the applications of Functional, Design and Process FMEAs, as it is able to perform the role of system decomposition (i.e., through decomposition tree and design matrix) and interconnects FMEA procedures (i.e., through domains and zigzagging approaches). This is a key point as AD implementation may facilitate clear modelling of the effects of the failure modes identified and detection of the cascaded failures at diverse product development stages. As previously mentioned, these are areas where FMEA is currently underdeveloped and quite inefficient.

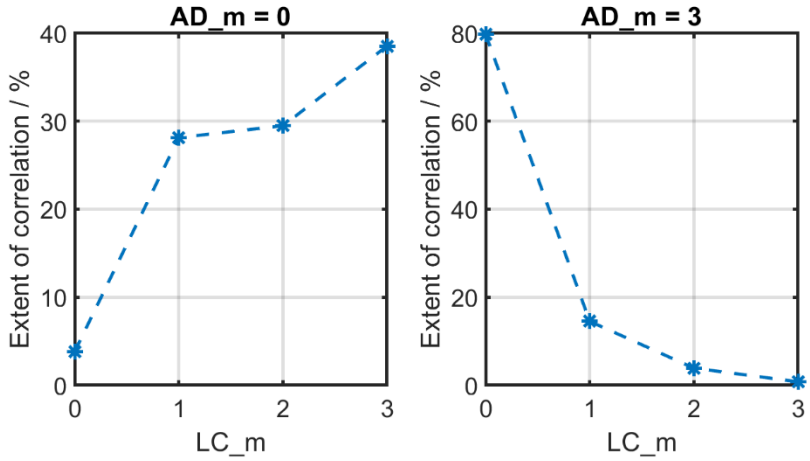


Figure 31: The predicted probabilities of *AD_m* performances: (a) *AD_m* = 0 and (b) *AD_m* = 3. Note: the relevant overall performance cannot be obtained due to the missing data for the intermediate categories of *AD_m*

Another area examined in this phase of the research involved assessing the impact of co-adopting QFD approach with the application of FMEA. Gu, Cheng and Qiu (2019), Shaker, Shahin and Jahanyan (2019), Hassan et al. (2009) and Ginn et al. (1998) contend that co-adopting QFD approach could improve FMEA deployment by synchronising its procedures. However, the extent to which this integration could improve FMEA deployment has yet not been clearly understood.

This phase of the research sought to shed further light on this notion and has examined the associated impact of co-adopting QFD method with the deployment of FMEA. As highlighted in Table 13, the *QFD_m* variable was identified as statistically significant and not reducing *LC_m*, due to its positive association with *LC_m* (0.927). It can be argued that QFD implementation works in a similar manner to AD approach by potentially interlinking FMEA procedures by applying various characteristics matrices (Gonçalves-Coelho, Mourão and Pereira, 2005). Although this may be true to an extent, others, such as Gonçalves-Coelho, Mourão and Pereira (2005) and Suh (2001), assert that QFD method is not effective for modelling new designs (the aim of this phase of the research). It should also be noted that QFD implementation is viewed as a time-consuming methodology and is therefore impractical for treating large information within systems typically characterised by huge interrelationship matrices (Hari, Kasser and Weiss, 2006; Chan, 2005; Prasad, 1998).

Soufhwee et al. (2013) proposed adapting DAIREC method to improve FMEA practice and synchronise Design with Process FMEAs. To test the validity of this proposal, the present research has evaluated the impact of combining DAIREC approach with FMEA deployment. Table 13 illustrates that the *DAIREC_m* variable (-0.426) was determined as having a positive impact on the application of FMEA. However, when compared to AD, this approach was found to be less effective for synchronising FMEA applications (*AD_m* variable (-0.71)).

According to Soufhwee et al. (2013), DAIREC method follows a lean six sigma approach, which relies on brainstorming to gather data on the potential failures that cascade between both Design and Process FMEAs. To improve the performance of this methodology on the application of FMEA, historical data can be used to predict the potential failures which would play a key role in reducing the need to brainstorm, thus saving time and costs (Lee et al., 2013).

Other frameworks for improving FMEA deployment through combining/co-adoption have also been proposed such as FFBD approach (Korayem and Iravani, 2008; White et al., 2007; Sharma, Kumar and Kumar, 2005), AHP method (Battirola Filho et al., 2017; Tang, Wang and Wang, 2007) and KBS technique (Renu et al., 2016; Augustine et al., 2012). These additional approaches were also analysed during this initial phase of the research to verify their impact on the implementation of FMEA.

Based on the *FFBD_m*, *AHP_m* and *KBS_m* variables illustrated in Table 13, these methods were identified as statistically insignificant in terms of their effect on *LC* linked to FMEA deployment (represented on the *LC_m* variable). This is because the coefficients associated with these variables were numerically small to influence *LC*. This might also be due to the small sample size used in this study and the fact that some products involve integrated systems, per se, present significant challenges for determining system integrations and managing large scale information, and that FFBD and AHP methodologies appear to have little impact in their original forms.

As for the *KBS_m* variable, its statistical insignificance could be attributed to the fact that implementing KBS involves developing a set of rules to generate and utilise knowledge from diverse sources (e.g., in this study: Functional to Design and then to Process FMEAs). Considering that KBS method may be beneficial for automating the process of FMEA as presented by Price and Taylor (2002) and Hata and Kimura (2003), this method would lead to higher costs for the overall FMEA deployment. This is because of

the requirements of such training and dedicating a specialised team to run and monitor the application of the KBS developed (Wirth et al., 1996).

As regards evaluating the impact of the change in other managerial factors, this study has investigated the effect of experience level (*EXP*), organisational size (*SIZE*) and industry membership (*MEM*) on the successful application of FMEA. These factors have been selected as they are believed to have a certain influence on the progress of FMEA deployment (Banghart, Bian and Babski-Reeves, 2016; Carlson, 2012; Bluvband and Grabov, 2009). However, it is worth noting that there is a paucity of research linked to the impact of these factors on FMEA application.

In this phase of the research, these managerial factors (represented by the *EXP_m, SIZE_m and MEM* variables) were found to be statistically insignificant. This may be due to insufficient information about the attributes of those people involved (i.e., their skills and knowledge) representing the understanding of FMEA-tasked employees around the evaluated system and the related extent of knowledge, as well as the skills for using FMEA.

This raises a key concern, which is that the manufacturing process and relevant historic information should be known to an extent prior to carrying out FMEA analysis. Where those involved in FMEA deployment are experienced, this would make the process of gathering data on the FMEA process far easier; an indicator that team experience (i.e., represented in *EXP_m*) is a key variable in determining the relevant impact on the performance of FMEA deployment. Factors such as *EXP* and *SIZE* are therefore considered essential in terms of being to evaluate the impact on FMEA implementation. This issue will be borne in mind for future work.

Based on the discussion so far, it can be inferred that FMEA deployment has been recognised as being impractical in systems associated with a high degree of systems integration (Peeters, Basten and Tinga, 2018; Henshall,

Campean and Rutter, 2014; Soufhwee et al., 2013; Yu et al., 2011; Abbas and Vachtsevanos, 2009; Walker et al., 2009). Therefore, the *MEM* variable (demonstrating the level of system integration) is expected to show a significant impact on the performance of FMEA employment. Table 13 contrariwise demonstrates that the *MEM* variable is statistically insignificant to affect the performance of FMEA implementation. However, to provide more credible, robust data, more details are required on the number of system components needed to execute FMEA effectively, as well as in-depth analysis preferred for executing FMEA. These measures would most likely yield more significant results highlighting the impact of various factors. These measures would be considered in the future direction of this research.

6.1.2. Phase 3 of the research

FMEAs interlinked within the product development process is required to achieve a number of objectives, such as identifying and capturing the cascaded failures (Henshall, Campean and Rutter, 2014; Carlson, 2012) and transforming functional requirements (FRs) into the process domain (Teng et al., 2006). In addition, it allows one to look at failures from both generic and downstream perspectives. As a result, that interlinking could provide orientation to ensure the failures identified are traceable and thus, making and correlating the appropriate control actions for the related causes (Teng et al., 2006).

It is considered that a proper decomposition and link between the functional, design and process domains of a product development will easily lead to a good quality of FMEA interlinkage and reduction in the associated execution costs (Henshall, Campean and Rutter, 2014; Teng et al., 2006). A sound FMEA interlinkage, as proposed by Teng et al. (2006) and Mohsen and Cekecek (2000), involves creating a taxonomy for a particular system to scope FMEA analysis and reduce the complication of the given design, as is provided by an approach such as AD (Suh, 1998).

Underpinned by the decomposition tree and zigzagging, AD implementation plays an important role in controlling the decomposition and transformation of FRs into the design and process domains at each level and between each domain (Suh, 2001; Mohsen and Cekecek, 2000). Well-developed AD generates an aggregated hierarchy of the functional, design and process domains, which addresses a good overview of the product structure, as well as accessible learning and understanding (Suh, 2001; Engelhardt, 2000). This overview is required for evaluating systems coupled with quantities of information, such as in the case of aeroengines, which could effectively lead to tracing the cascaded failures and, most importantly, identifying their root causes (Frey et al., 2007). The hierarchy combined these domains could provide an additional indication to ensure FRs are traceable to a certain level (Suh, 2001; Engelhardt, 2000). This element of traceability would show that the system design and process in question is fully determined and controlled (Suh, 2001; Engelhardt, 2000).

In support of Mohsen and Cekecek's (2000) proposal, extension to Arcidiacono and Campatelli's (2004) proposal and suggestions originating from phase 1 of the research to further the investigation into the construction of a model involving AD for integrating FMEA models, phase 3 of the research developed and validated the proposed framework that co-adopted AD, DSM and FMEA with the overall aim for synchronising Functional, Design and Process FMEAs. This phase of the research was aimed at addressing objective 3.

Both the works of Jefferson, Ratchev and Crossley (2014) and Guenov and Barker (2005) share several key features of this proposed framework. However, the addition feature in this established framework is the involvement of FMEA method. This framework might be deemed specifically beneficial for supporting the successful application of AD by evaluating and mitigating the risks underlined and by maximising the reliability of design. However, it is aimed at developing a means for managing FMEAs' synchronicity within the product development process.

This framework was validated via the field-related feedback and application of the t-test model, as outlined in section 5.2. The findings reveal that the proposed framework could improve the implementation of FMEA and synchronise Functional, Design and Process FMEAs. The transformation processes across the functional, design and process domains could help to correlate the related features through the hierarchal structure developed. Figure 32 shows the overall evaluation of the framework designed, with each of the criterion used are discussed below in further detail.

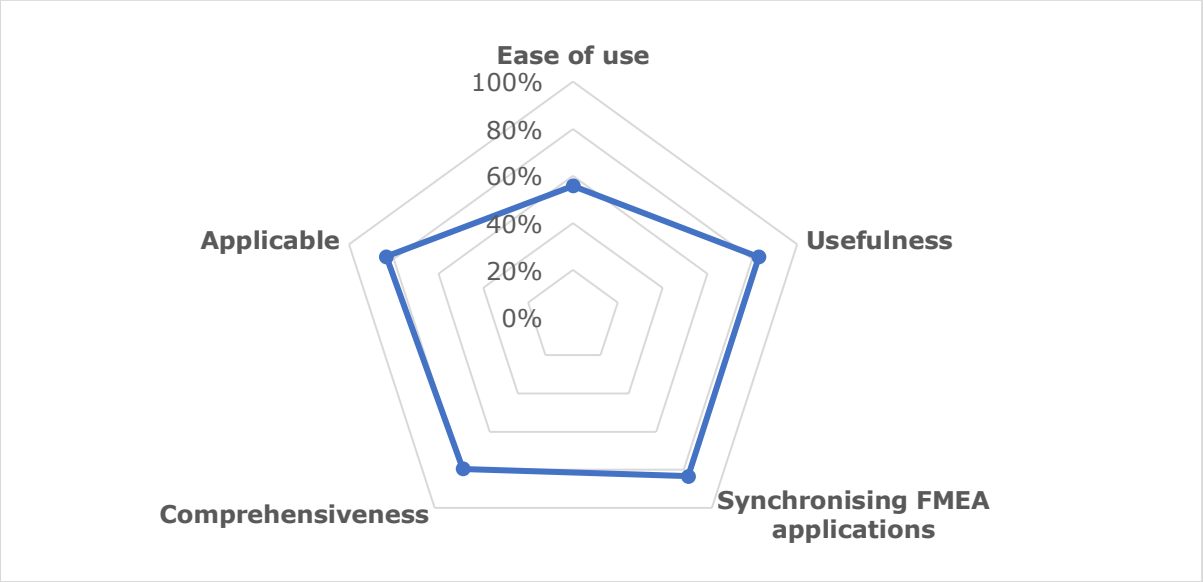


Figure 32: The overall evaluation of the proposed AD-DSM-FMEA framework

- **Ease of use:**

This feature measures the degree to which this framework is effortless. According to almost 60% of the participants, the t-test model executed shows that this framework is, to some extent, easy to use with more explanation required to understand this framework. To clarify the target of this measure, the proposed framework should be validated through case works to which all framework steps should be presented in a way can be understood by participants. This is a potential future direction for this research.

- **Usefulness:**

This measure is concerned with the extent to which the participants recruited believe this framework is effective for improving the implementation of FMEA. The results of the t-test model applied indicate that this framework is practical (by approximately 80% of the responses) and could help practitioners to deploy FMEA. Compared to the traditional FMEA form, this framework could decompose the system functions into sub-functions and correlate them to design features, then identify the associated failure modes, causes and control actions.

- **Synchronising FMEA applications**

This criterion assesses the capability of the established framework to synchronise FMEA procedures. The participants consider that the framework constitutes a good methodology for synchronising FMEA, as reported by the t-test model (i.e., according to almost 80% of the feedback gathered). This measure supports the findings obtained from phase 1 of the research (presented in section 4.1.3.3), which indicate the same outputs – namely, that AD could promote the link between FMEA applications (Functional, Design and Process FMEAs). This would make it easier to merge the disparate processes of FMEA and thus, target the failures highlighted more effectively.

Arcidiacono and Campatelli (2004) have developed a systematised model to enhance the application of FMEA for improving the reliability of diesel engine. Besides FTA approach, AD method was mainly incorporated to form Arcidiacono and Campatelli's (2004) model. When deployed, this model was found to reduce the time normally required to undertake FMEA by 50%. As being noticed however, that the authors' model is only limited to Functional and Design FMEAs. Therefore, extending this model to cover the link to Process FMEA could even save more resources as to which can correlate the design failures to their process attributes. The model results presented

in this research suggest that the developed framework of AD-DSM-FMEA could offer such an extension, which in turn could save more resources.

- **Comprehensiveness:**

This involved measuring the ability of the proposed framework to trace and cascade failures to their sources over FMEA applications. The model results manifest that this framework can chase the cascaded failures, according to almost 80% of those surveyed. This observation is supported by the findings shown in phase 1 of the research.

As presented in Table 13, the *AD_m* variable was identified as statistically significant in reducing the level of challenge (*LC*) associated with FMEA implementation, indication that AD method could improve the application of FMEA. This could be seen through the transformation processes of FRs, DPs and PVs across the functional, design and process domains (Teng et al., 2006; Arcidiacono and Campatelli, 2004; Mohsen and Cekecek, 2000), that feature in the proposed framework. AD approach is believed to provide an effective tool for transmitting and capturing FRs, DPs and PVs throughout the structured trees (Suh, 2001; Mohsen and Cekecek, 2000). The structured trees are identified as being more effective for modelling and understanding the effects of failures (Peeters, Basten and Tinga, 2018; Han and Zhang, 2013; Yu et al., 2011; Ferdous et al., 2009; Arcidiacono and Campatelli, 2004). From this point, the framework proposed in this research is believed to provide valuable extension to the proposals suggested by Kmenta and Ishii (2004) and Cooper (2015).

- **Applicable:**

This measure evaluates the applicability of this framework in real applications. The proposed framework was largely recognised as being practical according to almost 80% of the responses. It can be argued that the application of AD method in real life applications is impossible due to the practical concern over the requirement of this method to maintain the independent functional requirements within designs (Kumar and Tandon, 2019; Frey et al., 2007). However, this issue was acknowledged during the framework development, whereby DSM method was included in the framework to consider the coupling issues within the design elements. DSM is a well-known approach for processing connected design elements (Jefferson, Ratchev and Crossley, 2014; Eppinger and Browning, 2012; Tang, Zhang and Dai, 2009; Guenov and Barker, 2005; Steward, 1981).

6.2. Performance measurement of FMEA

6.2.1. Phase 2 of the research

The purpose of this theme was to highlight the current ways of measuring the performance of FMEA deployment in the automotive and the aerospace industries. The focal literature on the current performance measurement of FMEA deployment suggests a paucity in research devoted to this side of FMEA management. To achieve the goal identified in objective 3, this phase of the research has therefore, surveyed the manufacturing industry to observe how FMEA implementation is being assessed.

As reported in section 4.2.1.1, the findings obtained from phase 2 of the research demonstrate that 80.5% of the participants measure the capability of FMEA employment to mitigate failures subjectivity and objectivity. The popularity of this approach is probably linked to the ultimate goal of FMEA implementation which is to generate action plans to detect, prevent or reduce the impact of failures (Chang and Cheng, 2011; Chin et al., 2009; Sharma, Kumar and Kumar, 2005). Knowing the number of mitigated failures been detected, prevented or reduced helps to more accurately determine the overall performance and efficacy of FMEA implementation; a view which is shared by others (Campean, Henshall and Rutter, 2013; Yang, Basem and El-Haik, 2003). Having such a measure in place can be beneficial as it is particularly evident in the design and reliability of products as an indicator of quality control (Haughey, 2017; Krasich, 2007).

The next most frequently used approach was the practice of subjective measure for estimating the capability of the preformed FMEA to identify failure modes according to 68.3% of the responses. There is always a possibility of failures being uncovered within the FMEA process; therefore, it is important to measure the performance of any such FMEA implemented to ensure that all failures are detected. As suggested by Estorilio and Posso

(2010), this particular measure can be used as a tool for pursuing the quality issues occurred during the product development. However, it is worth mentioning that this particular technique should be used quantitatively so that the performance of FMEA deployment can be reported numerically (Pollock, 2005). This is evidenced by the approaches adopted by Yang et al. (2015) and Shebl, Franklin and Barber (2012), where the capability of FMEA practice to identify failure modes was quantitively evaluated by reporting the number of the residual failure modes.

In a similar vein, subjective assessment was reported as the most commonly approach applied to gauge the performance of FMEA execution in terms of documenting the knowledge and actions of the failures analysed. Subjective judging of the usefulness of the knowledge recorded, resulting from the FMEA developed, is considered a valuable sign for measuring the performance of FMEA deployment (Pollock, 2005).

Generally, the accumulated knowledge and experiences linked to design and process failures are retained as they can provide valuable information for future product and process designs and relevant assessments (Teoh and Case, 2004). Depending on the type and quality of information retained, this can provide lessons which can be used for continuous improvement. For example, FMEA documents usually contain full understanding of the occurred failures including the related causes, associated effects and control actions. So, it not only helps to improve and predict better future processes, but it can also be used to correlate data linked to failures, making it easier to spot them before they occur. The perceived benefits garnered by this measure may go beyond its original target to evaluate the blended experiences and skills of the team tasked to perform FMEA (Pollock, 2005).

Subjective measures have been frequently reported to evaluate the efficiency of resources used for FMEA deployment. FMEA is a risks discovery process that requires a significant team effort and length of time to meet

targets (Peeters, Basten and Tinga, 2018; Estorilio and Posso, 2010; Wetterneck et al., 2004). Using subjective measures in this context, therefore, may not be sufficiently representative to quantify these resources recruited and may lead to some bias in the results. Thus, the switch to a quantitative measure seems to be more appropriate as it can estimate and enumerate the business impact, which could be clearly highlighted by the cost saving associated with performing FMEA (Cooper, 2015; Pollock, 2005). This would also appeal to the project stakeholders (Epstein and Roy, 2001). This finding indicates the need for a model that should estimate the value of FMEA deployment. To do so, a model for estimating the rewards of executing FMEA was developed and is presented in the next section. However, it was not possible to validate this model because the host company did not give permission for its data to be published due to confidentiality requirements. Therefore, the next section focuses primarily on describing the potential link to the relevant literature.

6.2.2. The proposed cost model

As detailed in section 2.3.2, there is no consensus on the sensible and measurable financial impact of FMEA employment on design and manufacturing processes, and no evidence has been provided. Most research has focused on the cost estimation of failures and the associated lifecycle impact (Tazi, Châtelet and Bouzidi, 2017; Von Ahsen, 2008; Kmenta and Ishii, 2004; Rhee and Ishii, 2003). However, the cost model being proposed in this study seeks to provide an alternative dimension by investigating the efficiency of the resources invested for implementing FMEA as well as assessing its impact on the business. This model would be also expected to support the suggestion of Pollock (2005), by determining the cost saving led by FMEA execution.

Moreover, various frameworks have been proposed to broaden FMEA practice and address the challenges associated with it. These are described, for instance, in Peeters, Basten and Tinga (2018) and Arcidiacono and

Campatelli (2004), as well as the framework of AD-DSM-FMEA presented in section 5.1. Validating these frameworks will help to highlight the improvements sought. Considering that the proposed cost model is a theoretical framework that demands further validation, it would provide an index to compare the differences between the traditional FMEA and the proposed models on account for highlighting the contribution to the traditional practice of FMEA.

The proposed cost model was structured in a way to pursue and count the mitigated failures (i.e., as represented by the allocation base of $N_{Failures}$ and the quality level adopted in CoQ curve). This model should objectively inform the most frequently used approach (mitigating failures) identified in phase 2 of the research for measuring the performance of FMEA deployment. This cost model might also contribute to estimate the general CoGQ involved in delivering products. As per the CoQ curve presented in Figure 21, this model compares the cost of FMEA execution with a number of failures been detected/prevented in terms of the quality level achieved.

The cost obtained by the proposed model might also provide management departments with information on product and process failures, as well as the activities involved in preventing failures. In this connection, quantifying the cost of FMEA execution would be used to help transfer lessons learned to the next stages - for example, addressing such improvements and perhaps such shortcomings in the FMEA practice experienced.

The proposed cost model may go further in being able to classify the design iterations into positive and negative, which would be observed by the framework adjusted for both CoGQ and CoPQ. Ballard (2000) mentions that both iterations can be distinguished by the value generation to the whole design process and waste reduction in general. In this sense, the developed cost model would (in theory) potentially offer another criterion for classifying design iterations.

In general, those responsible for FMEA deployment can discern the potential deficiencies raised in the design process, and then identify the best options to challenge these flaws (Carlson, 2012; Chang and Cheng, 2011; Chin et al., 2009; Sharma, Kumar and Kumar, 2005; Stamatis, 2003). Through $CoGQ_{FMEA}$, control actions including corrective plans (identified by FMEA implementation to tackle design deficiencies and improve the design process) would be hypothetically classified as a positive iteration. On the other side, all activities involved in addressing $CoPQ_{Failures}$ would be theoretically considered as negative iteration.

7. Conclusion

The unique impact characterised to FMEA implementation has encouraged the large automotive and the aerospace companies to stipulate it as a required course in the product development operations for assessing and mitigating potential failures that could occur in products and processes. While the extant literature has demonstrated various proposals including the co-adoption of FTA, FFBD, AHP, QFD, KBS, DAIERC and AD methods for improving the deployment of FMEA, the fact remains that there is, hitherto, a lack of sufficiently robust quantification of the impacts required by this combination of these approaches to improve the practice of FMEA. Hence this research has sought to present a systematic analysis of the influence of these proposals and other managerial factors on the application of FMEA. It has also provided a review of the current FMEA-related performance measurement systems in both the automotive and the aerospace industries. Finally, this research has proposed innovative techniques for managing the deployment of FMEA and for measurement of its performance.

In terms of structure, this chapter has been organised into four sections. The first presents summaries of the research aim and objectives, along with the key findings and the extent to which the research objectives have been achieved. The next section highlights the research contributions and practical implications arising from this research. Prior to outlining the future work as suggested by this research, the sub-sequent section summaries the limitations and recommendations of this research.

7.1. Achievements of the research aim and objectives

This research has attempted to address the following four objectives:

1. Review the state-of-art of FMEA deployment and measurement.
2. Survey the current practical challenges for deploying FMEA and the impact of combining other systematic engineering methods, also the influence of other managerial factors on the progress of executing FMEA methods.
3. Survey the current industrial practice for measuring the performance of FMEAs implementation.
4. Develop and validate the integrated framework of synchronising FMEA methods.

The following sub-sections summarise how each objective has been fulfilled. Besides objective 1, which has been covered in the literature review (chapter 2), the other three objectives outlined above have been attempted using the three research phases highlighted below.

- **Phase 1:** Investigating the impact of the co-adoption of FMEA with other systematic engineering methods of FTA, FFBD, AHP, QFD, KBS, DAIREC and AD, as well as the effect of the dynamic change in managerial factors of industry membership, engineering experience held and organisational size (demonstrating objective 2 as shown in chapter 4, section 4.1).
- **Phase 2:** Review the current performance measurement approaches of FMEAs execution (presenting objective 3 as described in chapter 4, section 4.2).
- **Phase 3:** Development and validation the integrated framework of FMEA applications (displaying objective 4 as demonstrated in chapter 5).

7.1.1. Objective 1

This objective sought to review the state-of-art for executing FMEA and measuring its performance. To achieve this, the research evaluated the relevant literature on managing FMEA deployment and the related performance measurement. Previous studies from books, related journals, conference papers and online sources were reviewed to highlight where attempts had been made for advancing and synchronising FMEA procedures, as well as identifying the metrics applied for assessing the performance of FMEA implementation.

Research on FMEA employment has shown three main challenges: excessive use of resources, deployment difficulty and data availability. A review of the existing literature has also revealed limited empirical research on the impact of co-adopting other systematic engineering methodologies as well as the influence of other managerial factors on FMEA deployment. Moreover, it has been noted that the synchronicity issue between Functional, Design and Process FMEAs has not been adequately addressed in the literature reviewed.

The literature review on the current performance measurement of FMEA deployment has shown quite a narrow range of, and focus on work devoted to this element of FMEA deployment, where it seems clear that further work and investigation is meritorious in this domain, especially as it relates to the automotive and the aerospace industries linked to this study. Furthermore, the existing cost models have failed to account for the cost of deploying FMEA and its sub-sequent impact on products and processes per se.

7.1.2. Objective 2

As addressed by phase 1 of the research, this objective aimed to evaluate the current industrial practices for implementing FMEA and acquire an in-depth understanding of the performance of co-adopting other systematic

engineering methods for FMEA applications. Using the survey-based data collection method, this study recruited 41 participants from disparate backgrounds in the automotive and the aerospace industries and developed a score-based metric for estimating the level of challenge (*LC*) associated with FMEA deployment. An ordered probit model was then executed to determine the association between *LC* and the co-adoption of other methodologies and the change in organisational factors coupled with FMEA employment.

The model results produced in this study have improved the understanding of the impact of integrating these systematic engineering methodologies and the alteration in other organisational factors on FMEA implementation. This is an encouraging development, given the dearth of existing literature focusing on the benefits of co-adopting FTA and AD methods with FMEA execution. From the literature identified, which addressed this issue, those studies only showed that the combination of AD and FTA methodologies could potentially improve, to some extent, the progress of FMEA deployment. The results obtained from this study have revealed that the co-adoption of FTA and AD methods with FMEA application is negatively associated with the perceived level of challenge (*LC*). Therefore, this study infers that co-adopting FTA and AD approaches improves FMEA practices.

7.1.3. Objective 3

As reported in phase 2 of the research, this study surveyed the practical measurement techniques applied for evaluating the performance of FMEA employment. 41 completed questionnaires were collected from engineers in the automotive and the aerospace industries, respectively. These responses were evaluated using descriptive and graphical analysis methods. The findings demonstrate that the performance of FMEA deployment has been measured subjectively in the most part. The findings from this research drove the focus to develop a quantitative technique (i.e., informed by the cost model developed).

This cost model merged various cost elements of the activities required to complete FMEA deployment, managed and contingent on the number of the functions being analysed and the associated failure modes. On the basis of CoQ concept, this cost model was designed to correlate the cost of executing FMEA with the cost of failures; the aim being to highlight the impact of FMEA deployment and the cost saving. However, some difficulties were encountered in terms of being able to collect the relevant data as imposed by the host company due to confidentiality constrains on the data required, linked to failures and the associated costs (i.e., sensitive information). There was also a lack of records for documenting the cost of implementing FMEA. This means that the cost model needs further testing to demonstrate its applicability; something which will be considered for future work.

7.1.4. Objective 4

The traditional approach of FMEA shows a deficiency in managing the synchronicity between Functional, Design and Process FMEAs and being able to catch the cascading failures. The intent, therefore, behind this objective was to search for the requirements to integrate FMEA procedures into a systematic architecture (i.e., an overarching framework) focusing on displaying a series of coherent interlinked FMEAs across product development stages. As suggested by the findings drawn from objective 2 and 3, a novel AD-DSM-FMEA framework was established and presented in phase 3 of the research to achieve the 4^{th} objective. This framework was developed based on the extensions of AD and DSM approaches. AD procedures were mainly adopted to manage the activities of decomposing the questioned system and interlink the related FMEAs, and DSM was combined to facilitate the interaction among design elements.

This objective also sought to validate the proposed framework for integrating FMEA procedures. As highlighted in phase 3 of the research, this framework was validated via 12 field-related individuals from different

backgrounds using questionnaire-based responses. The framework was introduced to a select number of individuals with experience of FMEA so as to gain feedback. By applying the t-test analysis approach, the findings of this study suggest that this framework is understood and useful for implementing FMEA. However, some further efforts are required to understand the framework more clearly, which can be promoted by a relative practical validation. In addition, the findings obtained from the t-test model applied indicate that the framework is applicable in this context, able to coordinate the synchronicity process linked to FMEAs implementation and sufficiently comprehensive to catch the cascading failures. On the whole, the validation study implies the feasibility of the proposed framework in practice with a success rate of minimum of 60%.

7.2. Research contributions and implications

7.2.1. Contributions to the body of knowledge

This research project has made a number of significant contributions to the field of the new product development, system, concurrent, quality and reliability engineering. As presented in objective 2, the major contribution of this research project is to provide an empirical investigation of the impact of the initiatives identified and undertaken to improve the deployment of FMEA, as well as the influence of other managerial factors on FMEA implementation. On this basis, this study has presented a methodological depth analysis of the impact of combining FTA, FFBD, AHP, QFD, KBS, DAIREC and AD methods and the effect of industrial membership (*MEM*), experience level held (*EXP*) and organisational size (*SIZE*) that could affect the challenge associated with implementing FMEA.

To the best of the author's knowledge, these aspects have not been previously subject to examination elsewhere. Therefore, this project outcome can be regarded as significant since it helped to bring together and evaluate various experiences from different backgrounds and

industries to validate the co-adoption of FTA, FFBD, AHP, QFD, KBS, DAIREC and AD methodologies, and determine the extent to which these methodologies could improve the practice of FMEA. In addition, this project presents analysis to improve the understanding on the association between the well-applied FMEA and the managerial factors of the level of experience for the team members involved and level of details required to apply FMEA.

Another contribution is the application of the statistical inference of the ordered probit model in the body of FMEA knowledge. The ordered probit model used in this research manifests a novel and practical model for measuring the performance of FMEA in any such development and any application. The designed model, informed by the level of challenge (*LC*), can be furthered, and applied to evaluate the performance of toolkits used in the field of the new product development, system, concurrent, quality and reliability engineering.

Due to the limited research in the methods applied for measuring the performance of FMEA execution, this project investigated the practical techniques employed to undertake this task (as addressed by objective 3). This research element provides understanding on the modes that are available to the automotive and the aerospace industries for evaluating the performance of FMEA application. This has shed light on the demand for a quantifiable estimate to improve this practice which has been investigated in this project via the proposed cost model. However, it is clear at this stage, that this model requires further refinement and validation.

Furthermore, this project proposed a synchronised framework for interlinking the applications of FMEA (as demonstrated in objective 4), using one of these methodologies investigated above in objective 2 (i.e., AD method). It endeavoured to develop a hybrid risk assessment tool, which mainly consists of AD, DSM and FMEA methods. The combination of AD and DSM approaches offers a structured method for systemically identifying and cascading failures, causes and the potential effects in the

product development domains, with FMEA providing the framework to analyse system/component and process failures. This research element constitutes a relatively new area, which has emerged due to the lack of research in the current literature on integrating Functional, Design and Process FMEAs. It has also highlighted the gap in utilising both AD and DSM methods to synchronise FMEA applications. This work contributes to the fields of the new product development and concurrent engineering literature, and addresses the compatibility between all the outlined methodologies and the relevant ability to streamline the operations associated with the deployment of FMEA, thereby reducing the associated cost.

7.2.2. Practical implications

The outcomes of this project are of value to the practitioner within the respective automotive/aerospace communities by showing that the level of challenge (*LC*) involved in deploying FMEA appears to be independent of organisational parameters. In addition, such co-adoption of complementary methodologies can help reduce the challenges encountered with the execution of FMEA, outlined in the above. Accordingly, this work is deemed beneficial for both the aerospace and automotive communities as it can serve as a guide in selecting the correct and complementary tool(s) for effective deployment of FMEA as well as being able to highlight the impact of other managerial factors on implementing FMEA for further improvements.

Moreover, the proposed framework of combining FMEA applications with other engineering approaches brings a new perspective for interlinking the product development domains, which has the potential to contribute towards minimising the manufacturing disruptions and downtime. By validating and improving this framework, this framework is expected to catch the cascading failures within the product development process and hence, contribute to reduce the cost of failures. This framework is also

practically relevant as an aid for the practitioners in catching and reducing the impact of the cascaded failures between the application of FMEAs.

7.3. Research limitations and recommendations

This research, like many others, has limitations that provide potential for future investigations, refinements, and improvements. For objective 2, it can be expected that the narrow range of the independent variables included in the ordered probit model executed might limit the generalisability for the scope of the findings of this research, as does the small sample size. Thus, this study may not be fully representative of the industrial FMEA practice.

Although objective 3 has presented the current approaches for measuring the performance of FMEA implementation, the respondents involved in the research did not provide much insights on the techniques, or indeed the strategies, used to apply these approaches. Although this objective has presented interesting insights into the current practice for managing this task, it is recommended that this investigation be broadened to further expose the methods for applying these approaches and to seek more understanding of this task. It should also seek to clarify the usefulness of these approaches to estimate the relevant performance and the impact of these measures over the entire FMEA process.

Within objective 4, the validation process of the framework developed for combining Functional, Design, and Process FMEAs highlighted many restrictions that may define the research agenda in the future. Because of the covid-19 pandemic and the associated measures, this research project was restricted to recruit larger field experts to validate the proposed framework. However, in the future, a larger expert panel size is planned to be used. The validation process was also limited to a subjective evaluation methodology, which may limit the generalisation and utilisation of the proposed framework. Therefore, it is recommended that the proposed

framework not only be validated on a larger subjective base, but also be applied to a real working case to facilitate interpretation of the underlying concepts in a more practical, user-friendly form. Moreover, the proposed framework may be constrained for evaluating the reliability of a system, that is characterised by an increasing component detail. However, the proposed framework is theoretically viewed as a means of developing the picture for managing the link between the different FMEA applications.

7.4. Future work

The overview of the research findings, discussions and limitations suggests the agenda for future work. Firstly, objective 2 could be developed by acquiring more details regarding product integration, the characteristics of people involved (i.e., skills and knowledge) and worker cost related to FMEA users, as well as examining other factors such as the number of mitigated failures. It would also be worthwhile to apply this work to a larger sample size to improve the understanding of the associations between *LC* categories and the independent variables included in the analysis. This sample size would be of more than 100, as suggested by Williams, Onsman and Brown (2010), Hair et al. (1998), Tanaka (1987) and Anderson and Gerbing (1984).

Secondly, further investigation using the content analysis and interview methodologies could be used to support objective 3 to more deeply investigate the present approaches implemented for evaluating the performance of FMEA execution and the associated impact. Apart from the automotive and the aerospace industries, this study would be instructive to cover a larger range of industries. They could potentially benefit as FMEA has been a constituent element of modern quality and reliability management within various industries.

From a cost angle, this research has also built a theoretical cost model for quantifying the performance of FMEA employment, as addressed in

objective 3. This model introduces a methodology to compute the resources required to apply FMEA. However, this cost model should be validated to ensure that the underlaying concepts and all cost elements involved can present meaningful results. These results should inform the performance of FMEA deployment and justify whether employing FMEA helps to reduce the impact of failures and the associated cost. Furthermore, it is recommended to improve the developed cost model to take account of all costs incurred by preventing failures, which may include re-designing, re-testing and re-inspecting activities.

If this cost model is shown to work effectively, it might be useful for computing the impact of FMEA implementation; by establishing a quantitative correlation between FMEA (i.e., illustrated as element of cost of good quality) and failures (i.e., illustrated as element of correlation between FMEA (i.e., illustrated as element of cost of poor quality). Together with measuring the performance of FMEA employment, this cost model would provide part of the information on the quality-related costs required to inform the implementation of quality costing systems. This would facilitate a comprehensive audit of FMEA implementation performance and other CoGQ behaviours, and so are able to recognise improvements in the application being queried or investigated.

Finally, recruiting larger expert panels for objective 4 is considered as a primary step in evaluating the developed framework of integrating FMEA procedures. Then, the framework should be practically validated in real-life scenarios to ensure the greater applicability of this framework which, in turn, would help to enhance its employment in a real-life setting. For more practical adaptation, this objective also requires further investigations to illustrate the scalability of the proposed framework. This would serve as a major contribution in making this framework more relevant to practitioners in industry. One key element which may help in this regard would be to integrate this proposed framework with Model-Based System engineering tools or dedicated FMEA software to deliver the potential benefits of this

framework on account of the interactions across the domains and system levels, and the consequent volume of data that might be involved.

8. References

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9. Appendix

Appendix A. The questionnaire – Phase 1 & 2 of the research

The communication method with interviewee:

☐ The structured interview questionnaire.
☐ E-mail.
☐ Telephone.
☐ Skype.

Questions:

1. Which of the following approaches do you use to decompose system details (i.e. required system functions and failure modes)?

   ☐ Fault Tree Analysis (FTA).
   ☐ Functional Flow Block Diagrams (FFBD).
   ☐ The Analytical Hierarchical Process (AHP).
   ☐ Others, please specify?
   ……

2. How effective do you think this approach is in identifying system details? Why?

   Please rate the effectiveness of this approach in identifying system details.

	NOT EFFECTIVE	LESS EFFECTIVE	NEUTRAL	EFFECTIVE	MORE EFFECTIVE	N/A
FAULT TREE ANALYSIS (FTA)	☐	☐	☐	☐	☐	☐
FUNCTIONAL FLOW BLOCK DIAGRAMS (FFBD)	☐	☐	☐	☐	☐	☐
THE ANALYTICAL HIERARCHICAL PROCESS (AHP)	☐	☐	☐	☐	☐	☐
OTHERS	☐	☐	☐	☐	☐	☐

……

3. Which of the following approaches do you use to synchronise Functional, Design & Process FMEA procedures?

☐ Quality Function Deployment (QFD).
☐ Knowledge-Based System (KBS).
☐ Define, Analysis, Improve, Recommend, Evaluate and Control (DAIREC).
☐ Axiomatic Design (AD).
☐ Others, please specify.
……

4. How effective do you think this approach is in capturing the cascaded risks within the product development phases? Why?

Please rate the effectiveness of this approach in capturing the cascaded risks within the product development phases.

	NOT EFFECTIVE	LESS EFFECTIVE	NEUTRAL	EFFECTIVE	MORE EFFECTIVE	N/A
QUALITY FUNCTION DEPLOYMENT (QFD)	☐	☐	☐	☐	☐	☐
KNOWLEDGE-BASED SYSTEM (KBS)	☐	☐	☐	☐	☐	☐
DEFINE, ANALYSIS, IMPROVE, RECOMMEND, EVALUATE AND CONTROL (DAIREC)	☐	☐	☐	☐	☐	☐
AXIOMATIC DESIGN (AD)	☐	☐	☐	☐	☐	☐
OTHERS	☐	☐	☐	☐	☐	☐

……

5. What are the challenges that you face to deploy FMEA in integrated systems?

☐ Excessive use of resources.
☐ Applicability.
☐ Capture interaction failures between system, sub-system and components levels.
☐ The knowledge gap between design and manufacturing phases.
☐ Inability to trace failures.
☐ Others, please specify.
……

6. What are the approaches that you use to measure the effectiveness/performance of FMEA?

☐ The capability to identify failure modes.
☐ The capability to efficiently use resources.
☐ Corrective actions priority-cost based.
☐ Mitigating failures.
☐ The capability to document the knowledge and actions for failure analysed.
☐ Others, please specify.
……

7. Please describe the metrics used and their methods to perform.

Approach	Metric	Method	N/A
The capability to identify failure modes	☐ Subjective ☐ Objective		☐
The capability to efficiently use resources	☐ Subjective ☐ Objective		☐
Corrective actions priority-cost based	☐ Subjective ☐ Objective		☐
Mitigating failures	☐ Subjective ☐ Objective		
The capability to document the knowledge and actions for failure analysed	☐ Subjective ☐ Objective		☐
Others	☐ Subjective ☐ Objective		☐

Please use the below lines if needed.

……

……

……

……

……

……

Thanks for collaboration

Appendix B. The questionnaire – Phase 3 of the research

The communication method with interviewee

☐ The structured interview questionnaire.
☐ E-mail.
☐ Telephone.
☐ Skype.

Part one: Personal background

(*please tick the appropriate option from the following*)

1.1. What is your role in your Organisation?

- Senior Manager ☐
- Project Manager ☐
- Consultant ☐
- Researcher ☐
- Others (Please specify) ☐

.....

1.2. What is your expertise?

- Design Engineering ☐
- Manufacturing Engineering ☐
- Quality Engineering ☐
- Others (Please specify) ☐

.....

1.3. Years of experience:

- Less than 5 years ☐
- 6 to 10 years ☐
- 11 to 15 years ☐
- More than 15 years ☐

1.4. Type of Organisation:

E. Design ☐
F. Manufacturing ☐
G. Consultancy ☐
H. Research centre ☐
I. Others (Please specify) ☐

.....

Part two: Framework evaluation

(*please tick the appropriate option from the following: by choosing only one answer for each question*)

To what extent do you agree that the proposed framework is:

2.1.	**Easy to use**	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
		Very easy to use	Easy to use with minor explanation needed	Easy to use but more explanation required	Not easy to use but could be used with intensive explanations	Not very easy to use
2.2.	**Useful for implementing FMEAs**	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
		Very useful	Useful	Useful but may need some improvements	Not useful but it could be considered for use	Not very useful
2.3.	**Providing support with regards to synchronising FMEAs**	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
		Provide a lot of support	Provide support	Provide some support but there would be a need for other tools	Does not provide enough support but it could be used as an extra tool	Does not support
2.4.	**Comprehen-sive, and will catch/detect the cascaded failures**	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
		Very comprehen-sive	Comprehen-sive	Fairly comprehensive	Not sufficiently comprehen-sive	Not comprehen-sive
2.5.	**Applicable**	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
		More applicable	Applicable	Applicable but require some modifications to the framework	Not applicable unless there will be major modifications to the framework	Not applicable at all

Part three: Additional comments

3.1. What are the limitations of the proposed framework?

……

……

……

……

3.2. In your view, how can this framework be further improved?

……

……

……

……

3.3. Are there any other comments you would like to provide?

……

……

……

……

Thanks for cooperation!

Appendix C. Phase 1 of the research – The independent variables components: methodologies and factors.

The following table presents the data characteristics included to run the ordered probit model and the other postestimation values to achieve the aim of phase 1 of this research.

Observation	*LC*	*FTA_PERF*	*FFBD_PERF*	*AHP_PERF*	*QFD_PERF*	*KBS_PERF*	*DAIREC_PERF*	*AD_PERF*	*EXP*	*SIZE*	*MEM*
	Discrete	Discrete	Discrete	Discrete	Discrete	Discrete	Discrete	Discrete	Continuous	Continuous	Binary
1	4	0	5	0	5	0	0	0	25	43,224	1
2	2	5	0	3	4	1	1	0	20	9500	0
3	4	0	0	3	5	0	0	0	14	30000	1
4	3	4	5	5	4	0	5	0	10	237,000	1
5	4	0	5	0	5	4	0	0	16	26,004	1
6	4	5	3	0	5	0	4	0	42	9 989	1
7	4	0	5	5	4	5	5	0	8	153,000	0
8	4	4	0	0	4	0	0	0	10	137,250	1
9	3	5	1	5	4	5	0	0	21	3205	0
10	5	0	1	5	4	5	0	0	11	61117	0
11	3	0	0	0	4	5	5	0	26	37,543	1
12	4	4	0	3	4	3	0	0	11	237,000	1
13	5	0	0	4	4	4	0	0	43	54,500	1
14	5	0	0	0	4	0	0	0	20	3,205	0
15	2	5	5	3	4	5	5	0	19	3,205	0
16	3	4	3	0	0	3	0	0	7	105,000	0
17	2	4	5	5	1	3	5	0	29	61117	0
18	3	1	4	4	4	5	5	0	21	85000	0
19	4	5	4	3	5	5	0	0	9	9,500	0
20	2	4	5	4	4	3	5	0	8	3,205	0
21	1	5	5	5	1	5	0	5	13	43,224	1
22	3	4	0	0	4	3	0	0	8	173,000	1
23	3	4	4	0	5	0	0	0	13	54500	0
24	4	0	5	0	5	5	5	0	14	48,000	0

25	3	0	5	3	4	4	0	0	26	237,000	1
26	2	4	3	3	4	4	4	0	28	237,000	1
27	2	4	4	3	4	3	4	0	15	237,000	1
28	1	5	4	4	0	5	4	5	11	37,543	1
29	1	5	1	5	0	0	5	0	8	61117	0
30	3	0	0	0	4	3	0	0	15	9,500	1
31	2	5	4	4	4	5	3	0	15	43,224	1
32	1	5	5	0	0	5	0	5	20	173,000	1
33	1	4	4	3	1	4	3	5	18	153,000	0
34	2	2	5	0	4	3	5	0	5	3,205	0
35	2	0	5	4	5	3	2	0	29	211,915	1
36	1	5	5	5	0	1	5	5	17	133671	0
37	3	1	0	0	4	0	0	5	21	237,000	1
38	2	2	5	0	4	0	5	0	20	655,700	1
39	4	0	4	5	5	0	0	0	27	153,000	0
40	3	0	4	0	5	4	3	0	8	61117	0
41	0	5	1	4	0	4	5	5	6	237,000	1

Appendix D. STATA codes – Phase 1 of the research

The following codes expression show the sequence of actions performed to prepare data for analysis including the codes for obtaining the results of the ordered probit model, the related marginal effects and the predicated probabilities values. The presented codes are to run the reduced ordered probit model shown in Table 13.

1. To optimise the dependent variable: LC

1.1. gen LC_m = 0 if LC == 0 | LC == 1

1.2. replace LC_m = 1 if LC == 2

1.3. replace LC_m = 2 if LC == 3

1.4. replace LC_m =3 if LC == 4 | LC == 5

2. To optimise the independent variables

********** FTA **********

2.1. gen FTA_m = 0 if FTA_PERF == 0

2.2. replace FTA_m = 1 if FTA_PERF == 1 | FTA_PERF == 2

2.3. replace FTA_m = 2 if FTA_PERF == 3 | FTA_PERF == 4

2.4. replace FTA_m = 3 if FTA_PERF == 5

********** FFBD **********

2.5. gen FFBD_m = 0 if FFBD_PERF == 0

2.6. replace FFBD_m = 1 if FFBD_PERF == 1 | FFBD_PERF == 2

2.7. replace FFBD_m = 2 if FFBD_PERF == 3 | FFBD_PERF == 4

2.8. replace FFBD_m = 3 FFBD_PERF == 5

********** AHP **********

2.9. gen AHP_m = 0 if AHP_PERF == 0

2.10. replace AHP_m = 1 if AHP_PERF == 1 | AHP_PERF == 2

2.11. replace AHP_m = 2 if AHP_PERF == 3 | AHP_PERF == 4

2.12. replace AHP_m = 3 if AHP_PERF == 5

********** QFD **********

2.13. gen QFD_m = 0 if QFD_PERF == 0

2.14. replace QFD_m = 1 if QFD_PERF == 1 | QFD_PERF == 2

2.15. replace QFD_m = 2 if QFD_PERF == 3 | QFD_PERF == 4

2.16. replace QFD_m = 3 if QFD_PERF == 5

********** KBS **********

2.17. gen KBS_m = 0 if KBS_PERF == 0

2.18. replace KBS_m = 1 if KBS_PERF == 1 | KBS_PERF == 2

2.19. replace KBS_m = 2 if KBS_PERF == 3 | KBS_PERF == 4

2.20. replace KBS_m = 3 if KBS_PERF == 5

********** DAIREC **********

2.21. gen DAIREC_m = 0 if DAIREC_PERF == 0

2.22. replace DAIREC_m = 1 if DAIREC_PERF == 1 | DAIREC_PERF == 2

2.23. replace DAIREC_m = 2 if DAIREC_PERF == 3 | DAIREC_PERF == 4

2.24. replace DAIREC_m = 3 if DAIREC_PERF == 5

********** AD **********

2.25. gen AD_m = 0 if AD_PERF == 0

2.26. replace AD_m = 1 if AD_PERF == 1 | AD_PERF == 2

2.27. replace AD_m = 2 if AD_PERF == 3 | AD_PERF == 4

2.28. replace AD_m = 3 if AD_PERF == 5

********** EXP **********

2.29. gen EXP_m = 0 if EXP == 0 |EXP == 1

2.30. replace EXP_m = 1 if EXP == 2

2.31. replace EXP_m = 2 if EXP == 3

2.32. replace EXP_m = 3 if EXP == 4

********** SIZE **********

2.33. gen SIZE_m = 0 if SIZE == 0 |SIZE == 1

2.34. replace SIZE_m = 1 if SIZE == 2

2.35. replace SIZE_m = 2 if SIZE == 3

2.36. replace SIZE_m = 3 if SIZE == 4

3. To run the ordered probit model

3.1. global ylist LC_m

3.2. global xlist FTA_m FFBD_m AHP_m QFD_m KBS_m DAIREC_m AD_m EXP_m SIZE_m MEM

3.3. describe $ylist $xlist

3.4. summarise $ylist $xlist

3.5. tabulate $ylist

3.6. oprobit $ylist $xlist, level (90)

4. To obtain the marginal effects at means

4.1. mfx, predict (outcome (0))

4.2. mfx, predict (outcome (1))

4.3. mfx, predict (outcome (2))

4.4. mfx, predict (outcome (3))

5. To obtain the predicted probabilities at means

5.1. predict p1, pr outcome (0)

5.2. predict p2, pr outcome (1)

5.3. predict p3, pr outcome (2)

5.4. predict p4, pr outcome (3)

5.5. summarise p1 p2 p3 p4

5.6. tabstat p1 p2 p3 p4, by (FTA_m)

5.7. tabstat p1 p2 p3 p4, by (AD_m)