Failure Mode Avoidance: A risk management approach to obtain New Product Development projects Right-First-Time

by

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Thesis

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Declarations

Parts of this research have been previously published by the author in the following:

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Abstract

The focus of this research is to develop right-first-time new projects and underlying new products using the principles of Failure Mode Avoidance. The Failure Mode Avoidance currently focuses on producing a right-first-time product via a paradigm shift from the material stages to information stages of NPD process. It is primarily a risk management strategy implemented in the NPD process with a special focus on avoidance and mitigation response methods. The Failure Mode Avoidance refers to an ideal state where it is presumed that all potential failure modes and corresponding causes can be identified and prevented right early in the information based phases of NPD process. The current FMA frameworks including BEQIC FMA framework and MFMA (Manufacturing FMA) framework are heavily focused on engineering design and manufacturing processes respectively in isolation and lacks a holistic approach to achieve a right-first-time NPD project as an output of the NPD process. Furthermore, these framework focuses only on the robustness improvement in engineering design and fails to include mistake prevention, which is equally essential when dealing with avoidance of failure modes in the NPD process. Thus, this research aims to address these gaps via the development of an analytical and holistic NPD FMA framework that focuses on minimizing 'asymmetry' in the NPD process via avoiding and mitigating risks arising due to potential failures and helps facilitate development of right-first-time new projects as well as products. The proposed framework is applied in a real-life company environment for the validation of approach.

Acronyms

AHP Analytical Hierarchical Process.

ANOVA Analysis of Variance.

BEQIC Bradford Engineering Quality Improvement Centre.

BoM Bill of materials.

ERVD election based on relative value distances.

FLOP Faiure in Launch, Operations and Premise.

FMA Failure Mode Avoidance.

FMEA Failure Modes and Effects Analysis.

GDPR General Data Protection Regulation.

IAT Interface Analysis Table.

IoT Internet of Things.

MCDM Multi-criteria Decision Making.

NPD New Product Development.

OWA Ordered Weighted Averaging.

PC-FMEA Profitability Cost FMEA.

PoC Proof of Concept.

R&D Research and development.

RM Risk Management.

RPN Risk Priority Number.

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Chapter 1

Introduction

1.1 Background

1.1.1 Definitions and scope

A new project delivers a tangible or an intangible product upon its completion [Jacobson, Ivar, 2000]. Thus, the end result of a project is a product, which is crafted by different people involved within the project. The people involved are guided by a template called 'process' that dictates the steps needed to deliver a project. In other words, people involved in a new project adapt a given process to produce a product for which the project has been set (refer figure 1.1 and figure 1.2).

A process generally consists of several process steps, each of which corresponds to several stages in a project. Each stage of a project delivers one or more items. Throughout this thesis, the terms including project, product, people, process and item will be used in the context of the new product development.

The New product development (NPD) is a complete process of introducing a new product to the market [Edgett, 2015]. The NPD process consists of several

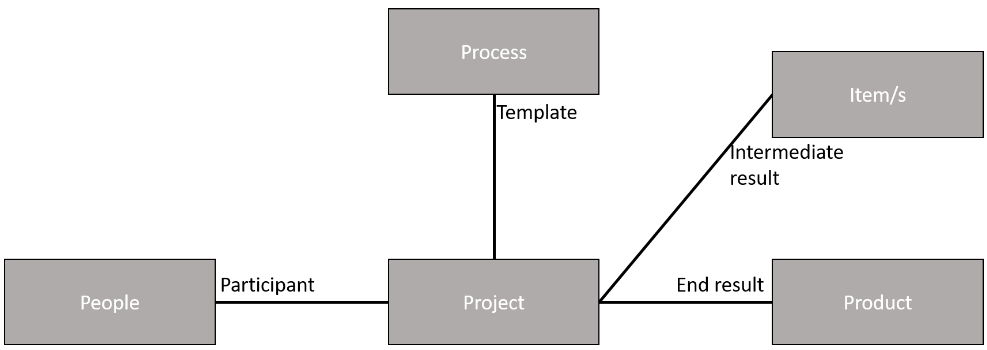


Figure 1.1: Relationship between 4Ps of NPD viz. project, process, product and people

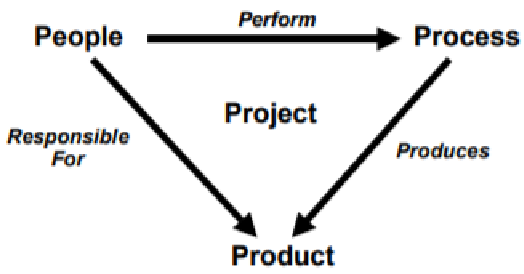


Figure 1.2: Another way to depict relationship between 4Ps of NPD viz. project, process, product and people [Source: Hawker [2002]]

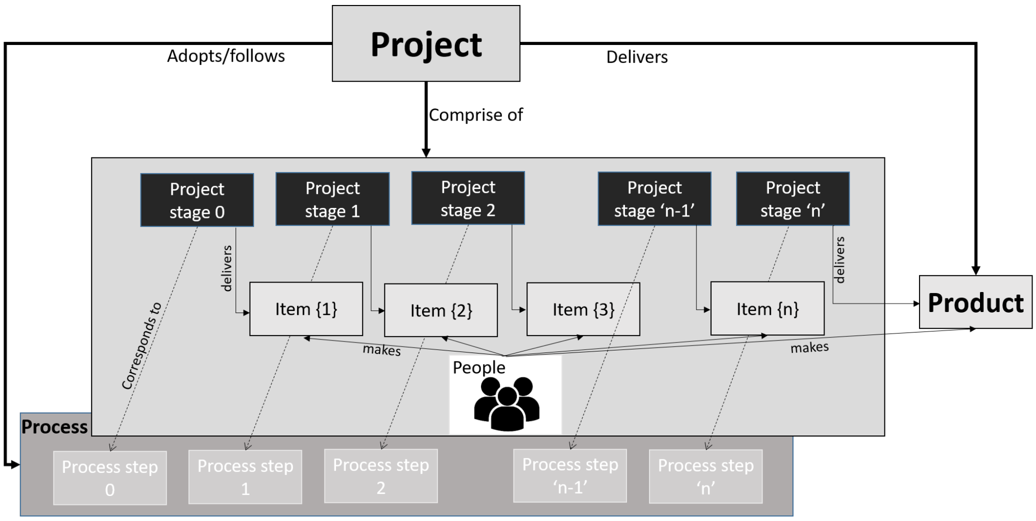


Figure 1.3: An NPD project with several project stages

process steps. Different stages in the NPD project are dictated by various process steps of the adopted NPD process model [1]. This is shown in figure 1.3. Once a customer's need for a product is identified, an NPD project can be formalised by a product company by setting its scope [Relich and Pawlewski, 2018]. The detailed description of various terms used in the scope of this work is given under.

The Project

The project delivers the product. In other words, an NPD project results in the release of a new product. Each stage of the NPD project is designed to gather specific information about the product. The information gathered in each stage is presented

[1] A project manager adopts the NPD process model used in the company for their project. Whether or not each process step is included in the project is entirely dependent on the project manager/leader. In other words, the adaptation of the NPD process model is dependent on the project manager, who later executes the project based on the process to make the product.

as the set of deliverables in the decision meetings (or stage-gate reviews, if the company decides to follow Cooper's NPD model), which helps the project move from one stage to the next one [Edgett, 2015]. Each stage in the NPD project is defined by various cross-functional activities conducted within it in order to understand more about the product. With the progression from one stage to the other, the aim is to reduce the uncertainty and risks associated with the project[2].

The project follows a process. In the context of NPD, a new product development project follows an NPD process model used in an organisation. Each phase of the NPD project corresponds to different steps in the NPD process. In other words, the project manager follows an NPD process model, such that different process steps of the model can dictate various stages of the NPD project.

The Process

The term process is used in various contexts such as business process, manufacturing process, development process, software process etc. In the context of this work, the term 'process' refers to an NPD process model[3] dictated by a standard new product development model, which a product-based company [4] decides to follow. The NPD model process within an organisation is selected by the leaders of the organisation. Once the NPD process model is established within a company, the project managers adopt or adapt to it in order to suit the requirements of their respective projects.

The most commonly used NPD model Cooper's Stage-gate model ([Cooper, 2019, 2010], refer appendix A for more details) comprises of six process steps including discovery, scope, design, develop, scale up and launch. A company that follows Cooper's Stage-gate model as shown in Figure 1.4 will typically have following stages in their projects (unless a project manager decides to omit/modify one or more

[2]There are two levels of project risks: 1) risks in the project, and 2) risk of the project [Rose, 2013]. The former risk refers to the individual project's risk, however the latter denotes the overall risk in the project. The individual project risk dictates "what are the risks in the project", whereas the overall project dictates "how risky the project is". An NPD individual project risk is defined as "an uncertain event or condition that, if it occurs, has a positive or negative effect on one or more project objectives" [Hillson, 2016b]. On the other hand, the overall project risk is "the effect of uncertainty on the project as a whole" [Hillson, 2016b]. Hillson [2016b] argues that the overall project risk, although a super-set of individual project risks, is more than the summation of the individual risks in the risk register. According to them, overall project risk encapsulates all sources of variations within the project such as uncertainties arising due to the project team's competencies, external environment etc. Besides, they highlight that the measurement of overall project risk can be done in concept stages of the project with the help of Monte Carlo simulations etc.

[3]There are various NPD process models in the academic and industry literature. Refer to A for more details. However in the scope of this work, the stage-gate NPD model from [Cooper et al., 2004] is adopted due to its relevance and popularity in the field of New Product Development.The NPD process in a company can be demonstrated by any standard NPD model in practice, or the company can decide to develop an NPD process of their own. The development of the NPD process model for organisations is outside the scope of this thesis.

[4]A product based company is a business that is involved in the development of a new product.

stages):

Stage 0 'Discover': This stage of the NPD project relates to the discovery stages, where the aim is to uncover various business opportunities for new product ideas.

Stage 1 'Scope': In this stage, a desk-based preliminary investigation involving quick and inexpensive research is undertaken to set the initial scope for the project.

Stage 2 'Design' or 'business plan': In this stage, a detailed investigation involving primary research around customers, markets and technology is undertaken. The output of this stage is a business case, which consists of project and product definitions, high-level project plan and project's justification. This should be noted that this stage refers to the project design rather than the product design, which happens in the next stage of the NPD project. Note that the term 'design' refers to the project design and should not be confused with the design of the product. The design of product happens in the next stage called "development" in Cooper's stage-gate process model.

Stage 3 'Develop': This is the stage of actual detail design and development of the product. Not only the design of the product is finalised in this stage but also the design of the associated manufacturing/production process. Therefore, the development stage of the NPD project has several sub-stages [5] including concept product design, detailed product design, development of manufacturing processes and testing of several prototypes pertaining to product's components and modules. Besides, the cost analysis is carried out and customer feedback is also undertaken in this stage.

Stage 4 'Scale up' or 'testing and validation': This stage involves verification and validation of the product in labs, plants or marketplaces. Besides, marketing plans are tested and total financial analysis is undertaken in this stage.

Stage 5 'Launch': This stage corresponds to the commercialization of the product via the implementation of the production/operation and market launch plans.

After the launch stage, the product is executed in the field (or market) by its customers.

In the scope of this work, the NPD projects following the Cooper's stage gate model have been discussed. For simplicity purposes, various stages of the NPD project following the Cooper's stage date NPD process can be broadly classified into three stages: 1) Premise, comprising of discovery, scope and business plan, 2) Product development, comprising of development and scale up stages, and 3) Launch, comprising of launch stages (refer to appendix A for more details).

[5] In fact each stage of an NPD project can have several sub-stages.

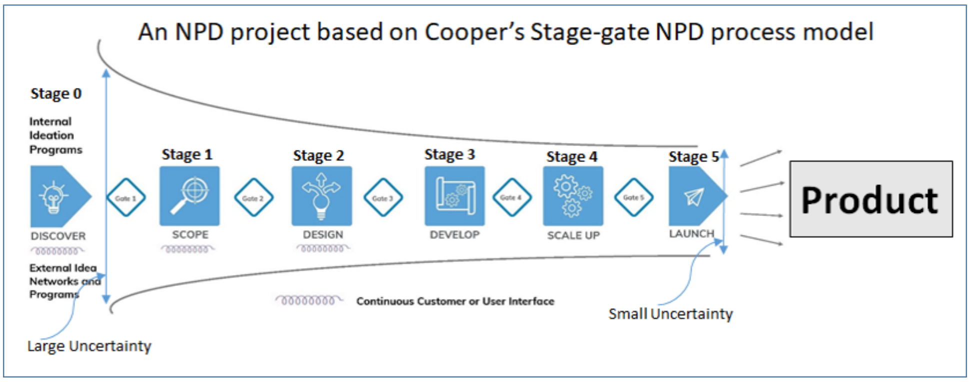


Figure 1.4: NPD project stages based on Cooper's stage-gate model

The Product

A product is an end result of an NPD project. A product is more than just an article or substance that is manufactured and marketed to fulfil customer's needs. The result of the intermediate stages of the NPD project is the production of several items. According to the Electropedia definition, an item [6] is "often comprised of elements that may each be individually considered. It may consist of hardware, software, people or any combination thereof" [InternationalElectrotechnicalCommission, 2015]. In other words, item is a general term for any kind of hardware, software or information produced, created, changed, or used by the people who develop the system.

In the scope of this work, the term product refers to the complete product-service system that is produced as a final result of the NPD project [Moser et al., 2015]. According to [Goedkoop et al., 1999], "a product-service system is a marketable set of products and services capable of jointly fulfilling a user's need". Mont [2002] defines a product-service system as "a system of products, services, supporting networks and infrastructure that is designed to be competitive, to satisfy customer needs and to have a lower environmental impact than traditional business models". In the scope of this work, the term product-service system is used in the context of the engineering domain. Therefore, when the term 'product' appears in this thesis, it means a set of engineered products that are tangible in nature yet augmented with intangible items such as its software, documentations, manuals etc.

[6]In software engineering, a generic term called artefact is used [Fernández et al., 2019]. However in the scope of this work, the term item is being suggested.

The People

People are involved throughout the entire life-cycle of the project [7]. In an NPD project, people not only budget, schedule and manage the project but also develop, test, use and benefit from the product. Therefore, the process that guides the new product development project must be people oriented, such that the adoption and adaption of the process to the project is as seamless as possible.

There are various roles of people in an NPD project. The project manager adopts (or adapts) and executes the project based on the NPD process model used in the company. Not only the project managers are required to identify, assess and mitigate the individual risks in their projects, but also account to project owners, sponsors and other stakeholders for managing overall risk of their respective projects.

There are various people involved in the premise stages of the NPD project (refer to Appendix A) such as product owner, project leader, project sponsor project manager, patent lawyers etc., marketing professionals, engineering managers, who sets out the requirements and scope for the project. Other people involved in the project include various R&D engineers (design, manufacturing, test etc.) and sales personnel. The engineers directly work on the tangible and intangible aspects of the product, whilst marketing and sales personnel work on strategies to position,launch and sell the product in the market, for example.

1.1.2 Challenges in the New Product Development projects

The development of a new product is a complex affair, where the complexity is exacerbated by various factors including globalisation, customer, competition, technology and regulations [Gertz and Haesar, 2015, Kherbash and Mocan, 2015, Steger, 2017]. Figure 1.5 presents some of the factors that contribute to product development complexity.

A brief discussion on various factors that contributes to the product development complexity is presented below.

Globalisation: With the advancements in transportation and communication technology, companies tend to operate globally to exploit the opportunities provided by globalisation in terms of sourcing, manufacturing and distribution [Steger, 2017]. A globally operable company have two or more franchise sites geographically distributed across the globe, each of which might only be involved in specific stages of an NPD project [Lanza et al., 2013]. This has been shown in Figure 1.6. Through a constructive co-operation between various sites, a successful delivery of the developed product to the market can be ensured [Gertz and Haesar, 2015].

[7] The life-cycle of the NPD project involves the process steps dictated by the NPD process model from start to finish plus the customer's execution of the product in the field.

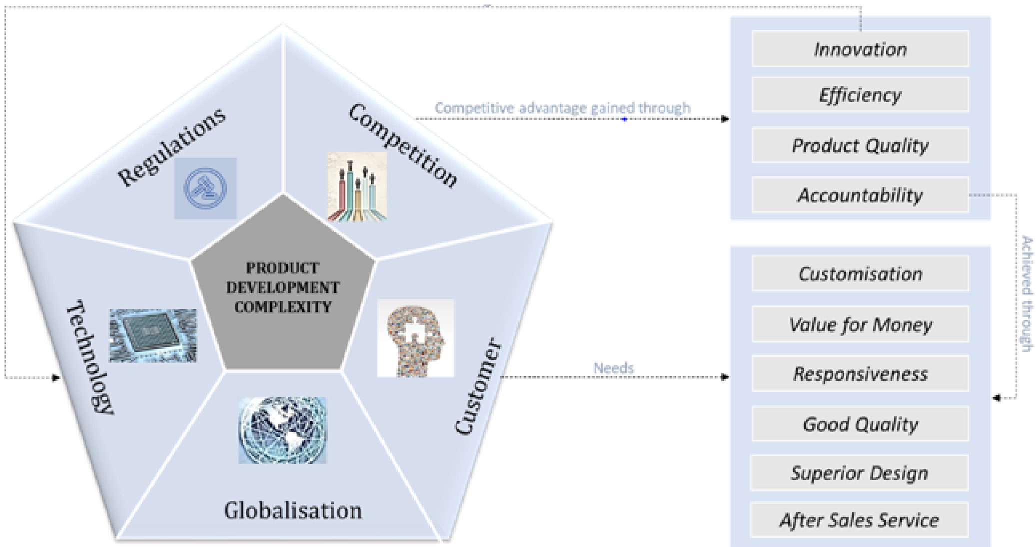


Figure 1.5: Product Development Complexity Diamond (Source: adapted from Gertz and Haesar [2015], Hosseini et al. [2018])

To ensure quality and a smooth delivery of a product, an effective integration of globally distributed multiple sites involving varied professions and trades is necessary [Whyte et al., 2016]. The integration of various sites needs to be facilitated by information exchange and digital collaboration, which comes with its own sets of challenges pertaining to language barriers, generational differences and internet security threats etc. [Swc, 2018]. These social and technological challenges imposed by digital collaboration in the era of globalisation plays a pivotal role in adding complexity to the new product development process of a project[Blanco et al., 2017].

Customer: Understanding customer needs and fulfilling them through product development process is the key to any company's success [Cui and Wu, 2017]. A company is more likely to fail if they jump straight to designing the product without fully understanding the customer needs and wants in the premise stages of the project. On the other hand, a company is more likely to succeed if they can develop a product in accordance with specific customers' needs that include, but not limited to, product's ability to: 1) demonstrate value for money, 2) be delivered quickly despite stochastic demands, 3) display good quality, 4) be distinguished from similar products available in the market and, 5) be effectively maintained by the manufacturer via their after-sales services [Grace and Iacono, 2015].

In order to make sure that a new product will rightly fit into the target market after launch, companies put enormous efforts in understanding customer needs and wants via qualitative and quantitative market research, for example interviews, surveys etc. [Mkrtchyan, 2018]. Conducting a market research to capture the voice

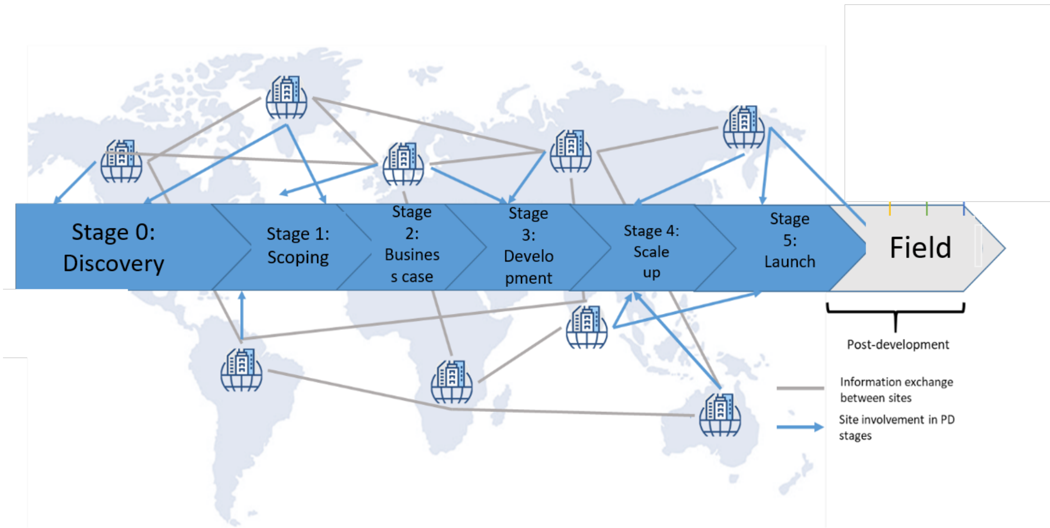


Figure 1.6: Globally distributed value creation network and product development process (Source: adapted from Cooper 2019; Rossetti et al. [2014])

of customer is very important, but it is not an easy to interpret customer's mind-set into specific product requirements in terms of big data analysis, complying with GDPR etc. [Puleston, 2018]. The difficulties faced by companies to understand and interpret customers needs are well recognised by researchers such as [Gertz and Haesar, 2015].

Competition: The complexity in the NPD projects is exacerbated by the competition in the market. In order to gain the competitive advantage, a company needs superiority in innovation, efficiency and product quality, and hold accountability to its customers [Hosseini et al., 2018]. Innovation is a crucial element of product development and can be achieved via the use of smart technologies [Song and Kang, 2016]. Efficiency may be gained through a low-cost structure, which can be achieved via decrease in production costs and increase in the employee productivity [Richards, 2017].

In an effort to decrease production costs, a product company need to make sure that they do not compromise the quality of its product and launch it to the customers before a competitor launches a similar product in the market [Dereli, 2015]. It is because the product companies hold accountability to its customers for ensuring the right quality and quickest delivery of their products [Hosseini et al., 2018].

A good quality product developed with lowest cost possible that needs to be delivered to the customers in the shortest time frames is not an easy task and requires a thorough project management during new product development [Gemünden, 2015].

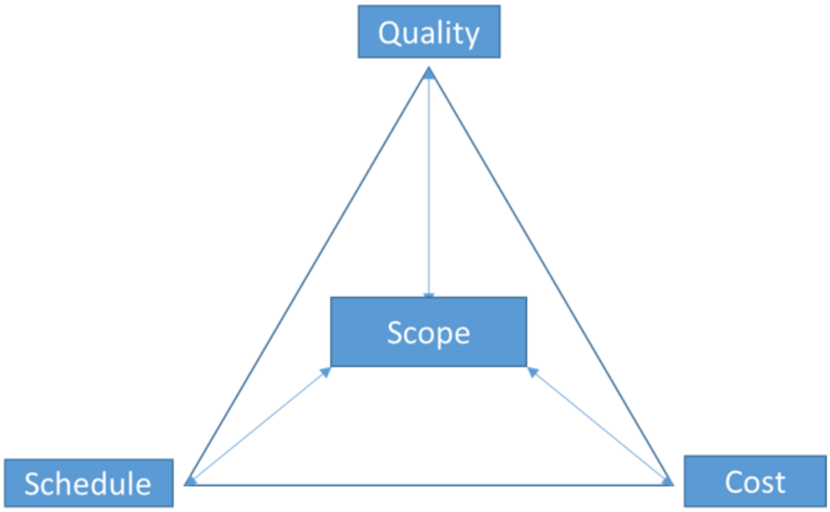


Figure 1.7: The project management triangle or iron triangle

In other words, achieving success on all three constraints of a project management triangle (or iron triangle), including cost, quality and time can be challenging (refer Figure 1.7). However, Gemünden (2015) argues that the success of a NPD project goes beyond the success of iron triangle and includes other aspects like stakeholder aspect, exploitation aspect and strategic aspect, which further add more complexity and challenges to the new product development projects.

Regulations: Regulations play an important role in the new product development projects [Gertz and Haesar, 2015]. Right from understanding the customer needs to deliver and operate the product in the field, companies need to fully comply with the regulatory standards, as the non-compliance can impose fines and/or legal action against the companies that can even damage their brand reputation [Shinder, 2018; TMF, 2018a]. Keeping up-to-date with changing regulatory standards of a region where a firm operates and familiarizing themselves with the legal content that exists in those standards is itself a big task [Shinder, 2018].

The complexity around the regulatory requirements is exacerbated by globalisation, where a single product may be developed and operated at multiple sites across the globe, whereby each site may have varying compliance standards [TMF; 2018b]. For instance, a company may face challenges if they develop an European Union (EU) compliant product but later decide to operate in North America without fully understanding the regulations in America. This clearly indicates that any NPD project is affected by region-specific regulations, the compliance of which should never be ignored throughout the NPD process [Hastrup and Rasmussen, 2014].

Technology: Technology is another aspect that adds complexity to the new

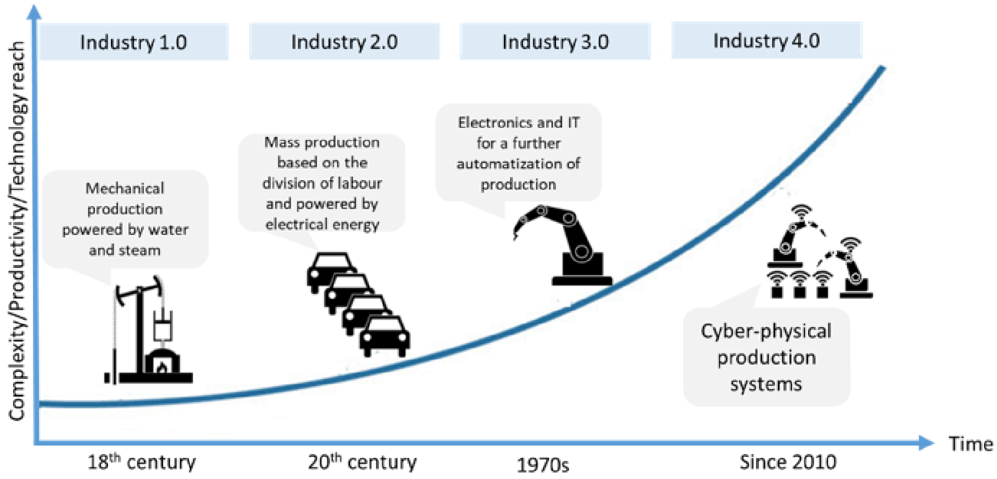


Figure 1.8: Evolution of manufacturing systems over time showing the convergence of software and IT with physical systems

product development projects. To cope with the latest technological advancements happening in the era of globalization and digitization, the technology-based companies continue to innovate and create new products that require multiple engineering disciplines to work collaboratively and effectively [Ottosson, 2018, Martin and Leurent, 2017].

An effective integration of multiple disciplines of engineering to create new products is a challenging task and requires manufacturers to come up with smarter ways of creating innovative and customized products for their customers [Campean et al., 2013a, Martin and Leurent, 2017]. It is because the products of today's era are themselves multidisciplinary in nature and may consist of various electromechanical components interfacing with many software and control features together citepchr13. Therefore now-a-days, manufacturers also put enormous efforts in building smart factories that allow them to integrate software and Information Technology with physical manufacturing systems (Holt, 2018).

Figure 1.8 demonstrates the evolution of manufacturing systems from the age of pure mechanization to the era of cyber-physical systems (Rojko, 2017). In order to survive in today's era of Industry 4.0, where the next generation of IoT based products are coming into play, companies need to remain proactive in adopting newer technologies within their factories that can help them make their products new and innovative [Golovatchev et al., 2017].

The new and smart technologies of today include, but are not limited to, sensors, intelligent robots, autonomous drones and additive manufacturing (Finance, 2015). These technologies can either form the basis for any new smart product to be launched into the market or be utilized within a manufacturing process or a factory that builds the product [Savastano et al., 2018, Golovatchev et al., 2017]). This clearly indicates that not only the products now-a-days are becoming increasingly complex but also the manufacturing processes that make them, indicating a further addition to the complexity in the NPD projects.

Another contributing factor that adds to the NPD project complexity is the people working for the project [8]. The people are complex and it is important to manage their expectations throughout the NPD project in order to maximize their efficiency and output [Hawker, 2002]. Factors that affect people involved in the projects include project's feasibility, team structure, risk management, schedule and project's understandability [Jacobson, Ivar, 2000]. An infeasible project can be terminated later, which may give rise to morale issues amongst people. Similarly, open risks in the project that have not been addressed during the life-cycle of the project may create uneasiness amongst people. Another issue may be a poor team structure that may compromise on effectiveness of people in the team. Besides, an unrealistic project schedules may also result in plummeting of people's morale and sense of accomplishment. In addition, lack of visibility of strategic vision for the project may result in poor understanding of project tasks, which people are working on.

From the discussion above, it can be inferred that the management of NPD projects is a challenging task that involves organisation and management of several aspects including NPD process, product and the people involved.

1.1.3 New Product failures: A result of the failures in the NPD project

The ultimate aim of an NPD project is deliver a new product to the market. An NPD project is defined by its objectives related to product's quality, project's budget and schedule. Failure to meet the objectives of an NPD project is considered as the failure of the product in the market [Ford, 2016b, Kim et al., 2016].

Due to the challenges in the new product development projects discussed earlier, the success of new products in the market remains a critical challenge for companies [Geise, 2017]. It has been reported in the literature that around 80-95% of new products launched every year fail to succeed in the market depending upon the industry [Geise, 2017, Wengel and Hall, 2014].

Nielsen's research conducted in year 2014 illustrates that out of 24,543 new products that were launched in that year, 27% of them were found to be failed, 16%

[8] This factor has not been covered in product development complexity diamond by Gertz and Haesar [2015], Hosseini et al. [2018]

of them disappointed the customers and 37% of them had to be cancelled [Wengel and Hall, 2014]. This totals to a failure rate of 80% in the market. According to recent researches, the product failure rate of 80% has remained consistent over the years [Malek and Melgrejo, 2018, Kocina, 2017].

Savoia [2014] envision that "most new products will fail in the market even if they are competently executed".They state this projection as "The Law of Market Failure". Thus, it is really important to explore several reasons for new product failures, such that companies can take appropriate actions to mitigate them. Studies suggest that the reasons for new product failures can be attributed to product's bad quality, inadequate performance, lack of adequate features in design, poor aesthetics, wrong time for launch, incorrect pricing and mistaken positioning etc. [Williams, 2015, Savoia, 2014].

Gourville (2005) argues that products fail due to the "curse of innovation", which implies that often developers of the product fail to understand the consumer behaviours and their hesitation in adopting the new product [Gourville, 2005]. Similarly, consumers fail to see the value of the product that developers had promised. This means, there exists a lack of alignment of thoughts between the developers, who develop and often overvalue their product, and the consumers, who often resist the change and undervalue the innovation compared to existing options [Gourville, 2005]

Davis [2013] suggests that the product failures observed in the field (or market) are the inevitable by-product of the new product development process. According to them, failures can be attributed to several reasons including inability to define appropriate product requirements, choosing complex designs, lack of understanding of operational environments, wrong testing assumptions when trying to validate the new design, shipping issues etc. As per Davis [2013], multiple things can go wrong at every step of an NPD process and the failure modes [9] can be introduced, which leads to the project failure that is deemed as product failure in the field.

Savoia [2014] in their FLOP analysis discusses three types of failures. These include Failure in Launch, Operations and Premise. The three types of failures from FLOP analysis are also in line with research conducted by Malek and Melgrejo [2018], where they discuss three common reasons of innovation failures as: 1) lack of sufficient marketing support, 2) failure to provide a satisfactory product experience and 3) failure to address a broad customer need, respectively.

Figure 1.9 depicts the categorisation of all potential failures of any product

[9] The term 'failure mode' in the context of NPD project can be broadly understood as deviation of project from its intended objectives expressed in terms of product's quality, cost and time. This should be noted that the business objectives are different than project objectives. The business objectives described the net effect of the end product such as its selling price, expected rate of demand etc.

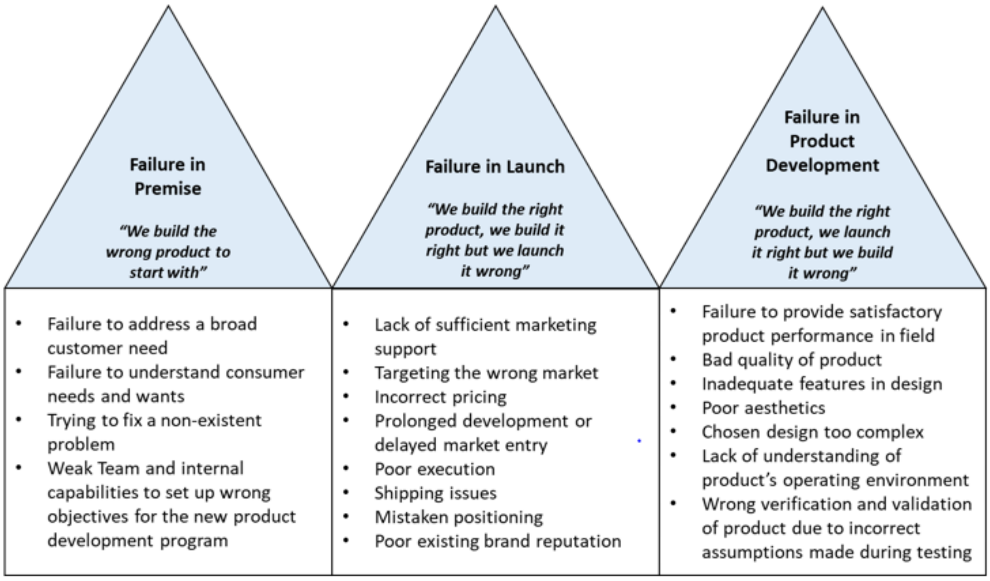


Figure 1.9: Three types of failures in the NPD process (Source: adapted from Savoia [2014], Davis [2013], Malek and Melgrejo [2018];)

into three failure categories presented by Savoia [2014][10].

In line with Davis [2013], it is suggested that the failures arising in premise, product development and/or launch stages of NPD project, if left untreated or unaddressed can lead to 'escaped failure modes [11]' in the field. In other words, the source of escaped failure modes are the missed opportunities to treat the failures arising during several stages of the NPD project. This is shown in Figure 1.10.

A hypothetical example of a new light bulb project is presented below to aid the understanding of the reader about possible failure modes related to the light bulb project. Suppose a bulb manufacturer decides to launch a new series of warm yellow light bulbs in a region where people have mostly used cool white light bulbs in the past. The main driver to do so is the market survey conducted by the manufacturer, which showed that the people in the region do not prefer cool white lights bulbs because of their overly bright nature.

The manufacturer expects the light bulb project to be a right-first-time project. A right-first-time project means a successful NPD project that achieves all its states objectives right-first-time without having to iterate back to the NPD process. Suppose for the light bulb project the following objectives have been set:

[10]For clarity purposes, the author will make use of the term "Failure in Product Development" instead of the term "Failure in Operations". This renaming has been proposed as the readers may confuse the term 'operations' with the 'field' or 'market'. Besides, in context of the work from Savoia [2014], the term failure in operations actually represents the issues in product development.

[11]In the context of this work, the term 'escaped failure mode' is also referred to as NPD project failure effect or simply as the NPD project failure

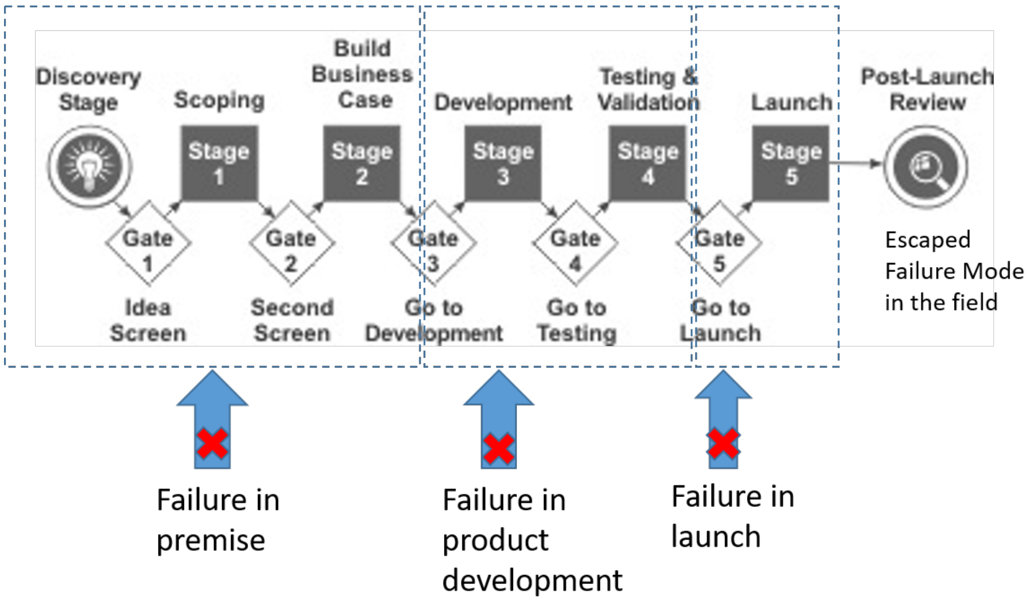


Figure 1.10: Failures introduced at various stages of the NPD project

1) The bulb should be able to achieve intended product quality such as achieving functional intent of emitting light at the rate of 120V/75W, 2) The bulb project should be able to complete in one year time frame in order to achieve a timed entry in the market, and 3) The BOM cost for the bulb should not be more than $10.

After the launch in the market, the new series bulb project is deemed as a failure because of its ability to achieve the intended objectives. There may have been various reasons behind the failure of new series of light bulbs, some of them are listed in Table 1.1. It is evident from the example above that the NPD project failure can directly be attributed to various stages pertaining to premise, product development and launch.

The underlying reasons (or causes) for NPD project failures in premise, product development and launch can be attributed to failures at different levels viz. product, process and people Davis [2013]. In addition to these, NPD project failures are a result of external environment where the project operate in Davis [2013]. The product-specific failures are related to any failure directly associated with the product itself [12]. The process-specific failure relates to incorrect adaptation of the company-wide NPD process model to the project as well as wrong execution of it. The people-specific failures relate to factors affecting people's performance such as poor team structures, poor understanding of the project, communication issues, lack of skills, poor support from the top management etc.

[12]For instance, in the light bulb example discussed earlier, the poor quality of filament is a product-specific failure.

Bulb project objectives	"Escaped" Failure Mode	Failure causes	Source of Failure
To emit light during operation (Functional intent)	Inability to emit light after only few hours of operational use	Poor quality of filament	Failure in Product Development
		Weakening of connections due to frequent shaking of light filament of in houses that experience excessive vibrations from nearby rail-tracks	
		Corrosion on the connector due to operations in the humid conditions	
The bulb project should be able to complete in one year time frame in order to achieve a timed entry in the market	Delayed entry to the market	Shipping took longer than expected	Failure in Launch
The BOM cost for the bulb should not be more than \$10.	The BOM cost of the bulb is more than $10	Unrealistic budget set by the project team	Failure in Premise

Table 1.1: Product failure example

It is now clear from the discussion above that the failure in the NPD project is deemed as a failure of the new product in the market. The escaped failure mode impairs the worth or utility of a product as it serves as the prime reason for customer dissatisfaction Cooper [2019].

1.2 Motivation

1.2.1 Failures are annoying: costly, painful and fatal

The escaped failure modes makes the product defective, faulty or not worthy in the field Davis [2013]. The escaped failure modes can be costly, painful and in certain cases fatal too Saxena et al. [2015]. They result in unwanted costs borne by the company, which comes in form of complaints, warranties, recalls, allowances, penalties, lost opportunities and lost brand reputation (refer Figure 1.11). The costs, which arise as result of a failed product being delivered to the customer, are often referred to as external cost of poor quality Chiarini [2015].

There have been major incidents in the past, where escaped failure modes have proven to be fatal, e.g. in case of Toyota, where in year 2010, the accelerator pedals were having issues with sticking down and not bouncing back to original position whilst moving. Eighty nine deaths and fifty seven injuries were suspected to be linked to faulty accelerator pedals and software issues [AP, 2010]. Toyota recalled

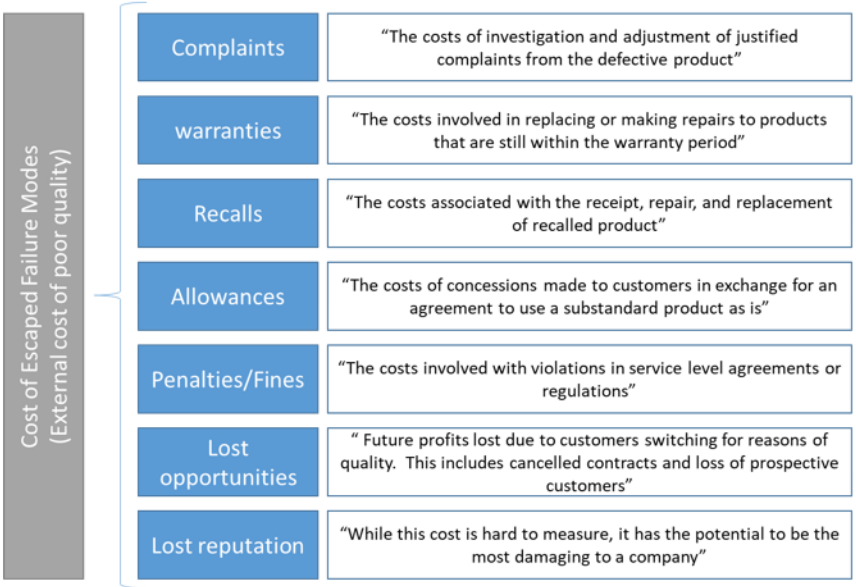


Figure 1.11: Costs borne by companies due to escaped failure modes (Source: adapted from Ross, 2017)

more than 8 million cars and incurred a loss of 5.5 billion US dollars in recalls [AP, 2010; Tran, 2016]. In addition, they were fined \$16.4 million for their slow response to recall of pedals [AP, 2010].

Another recent example from year 2019 is of Boeing 737 Max airplane, where the repeated engaging of anti-stall system had contributed to the fatal crashes [Reuters, 2019]. A total of three hundred and forty six people were killed in two different crashes of Lion air and Ethiopian airline respectively, which happened subsequently one after the other in less than five months [Leggett, 2019, Glanz, 2019]. As a consequence of these crashes, the 737 Max planes had been grounded [Josephs, 2019]. A report from Rushe and Davies [2019] suggested that this failure could potentially cost Boeing more than a billion dollars. Some other examples of various damages incurred by the companies as a result of escaped failure modes have been summarised in the Table 1.2.

It is now clear that the NPD project failures can be painful, expensive and fatal in some cases. Overall the cost associated with NPD project failures (or escaped failure mode) can be related to complaints, warranty claims, recalls, allowances, penalties/fines, lost opportunities and lost reputation etc. Therefore, companies need appropriate measures (or countermeasures) and strategies to mitigate the failure modes during the course of the NPD project. The cost associated within the project whilst developing countermeasures to treat the failure modes (or cost of countermeasures) can be measured against the following:

Year	Company	Event	Cost of escaped failure mode to the company
2006	Dell	Recalled 4 million laptops due to overheating batteries	$400 million
2007	Mattel	Recalled 19 million toys supplied from China due to potential safety issues with small and powerful magnets	$30 million
2010	Toyota	Recalled more than 8 million cars due to faulty accelerator pedals and software issues	$16.4 million fine 52 deaths 38 injuries
2014	Daimler Group	Guarantee claims (warranty and goodwill commitments) in automotive division (Mercedes Benz)	$1.8 billion
2014	Corona Beer	Needed to recall 1% of product due to potential remains of small pieces of glass in the bottles	~$37 million
2015	Alton Tower	Needed to pay compensation to the customers who suffered from the crash of the rollercoaster	~$50 million 16 injuries
2019	Boeing	Global grounding of 737 Max aeroplane following two fatal crashes (i.e. Lion Air and Ethiopian airline) occurred due to suspected fault related to anti-stall software	$1 billion+ (projected) 346 deaths

Table 1.2: Various damages to the companies due to escaped failure modes (Source: Tran [2016], Salo [2016], Riley [2016], Rushe and Davies [2019])

- Scrap: Every penny spent in labour and material for producing a defective product that needs to be scrapped.
- Rework: The costs involved to carry out a repair work after a defect (or failure mode) is observed.
- Re-testing: The costs involved in re-testing the products for conformance after a repair or revision has taken place.
- Downtime: The loss pertaining to the inability of keeping machines up and running due to quality problems.
- Failure Analysis: The time and costs involved in analysing a non-conforming product to find the root causes of failures.
- Changing processes: The cost of modifying the design or manufacturing process to address the deficiencies observed in the product.
- Downgrading: The loss incurred by a company to sell a non-conforming product "as is" at a reduced price.
- Back-orders: The loss of revenues due to inability of meeting customer demands and potentially loosing future orders.

The cost of countermeasures is highest when failure modes are detected (or observed) late in the NPD project and there is little time left to evaluate and tackle the issues. On the contrary, the lowest cost of countermeasures is observed when failure modes are identified and mitigated right in the early stages of the NPD project [Saxena et al., 2015]. This argument is in line with rule of ten, which emphasises on the fact that deploying countermeasures to treat failure modes in a particular stage of NPD process are around ten times cheaper than doing so in the next stage (Majuntke, 2015). The relationship between costs of countermeasures w.r.t various stages of NPD project is shown in Figure 1.12.

1.2.2 Managing failure modes within the NPD projects

Based on the discussion in last section, it can be concluded that the failure modes are detrimental to manufacturer's success. Thus, managing failure modes during the several stages of NPD project is crucial to company's growth. In the scope of this work, the term "managing failure modes" refers to the identification of all potential failure modes (or risks) during the course of the NPD project and mitigating them through countermeasures in order to minimize the risk associated with escaped failure modes.

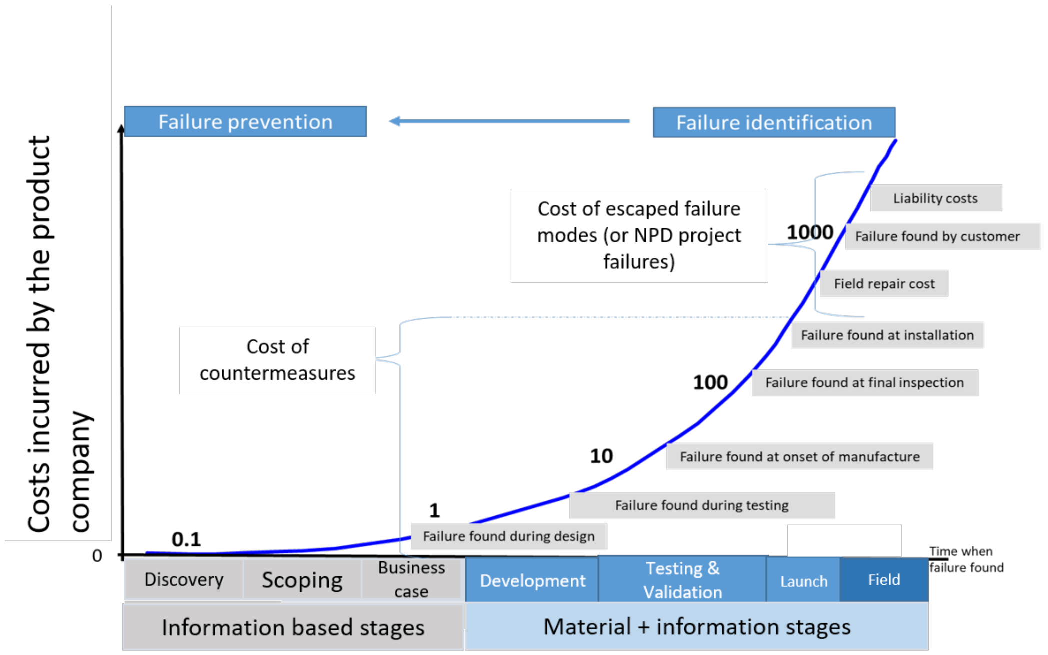


Figure 1.12: Rule of ten (Source: adapted from Majuntke [2015]; Panigrahi [2017])

Failure modes escape into the field because it may not be possible to identify and mitigate all possible failure modes occurred during various NPD project stages Hillson [2016a]. Projects which do not have appropriate risk management strategies in place often run into the problems for deploying numbers of countermeasures in the later stages of NPD projects.

The late detection of failure modes happens because it is easier to uncover failure modes in the material stages when a lots of hardware is available, as compared to the information stages (or premise stages) when the knowledge regarding the potential failure modes remains in developer's mind [Ford, 2016a, Saxena et al., 2015]. Furthermore, it is obvious from Figure 1.12 that cost of deploying countermeasures late in the NPD project is much higher than the cost of deploying countermeasures right early in the information based stages of NPD project. The projects that has appropriate risk management strategies in place focus on mitigating the potential failure modes (or risks [13]) right early in the information stages of NPD project.

The risk management strategies for projects include risk avoidance, risk transfer, risk mitigation and risk acceptance [Asadi, 2015].The risk avoidance strategy focuses on eliminating the project risk completely by preventing the failure causes

[13] In the scope of this work, the two terms 'potential failure modes' for projects and 'risks' are used interchangeably. Since risk is a generic term that can be used to describe a potential failure, its effect and the cause, the terms 'potential failure mode', 'failure cause' and 'failure effect' are preferred. Besides, only 'negative' risks are considered in the scope of this work.

from happening. The risk transfer strategy focuses on shifting the risk to a third party such a insurance companies or vendor, who then owns the risk thereafter. The risk mitigation strategy emphasizes on reducing the probability of the occurrence of risks. And, the risk acceptance strategy means accepting the risk either because its impact is low or when it is not possible to adopt other three strategies viz. avoid, transfer and mitigate.

1.3 Research aim and objectives

This work highlights the importance of risk avoidance or potential failure mode avoidance. In an ideal scenario, when the risk avoidance (or failure mode avoidance) strategy is adopted in order to treat all possible failure causes in the project, a right-first-time project can be obtained [Goodland, 2016]. In reality, it may not be possible to identify and eliminate all potential failure causes in the NPD project [Hillson, 2016]. Therefore, it is crucial for the project managers to assess the impact of individual project risks and measure them individually, such that suitable risk management strategy for every possible risk can be adopted and highest impacting risks can be avoided.

The Failure Mode Avoidance methodology refers to a pragmatic and disciplined approach of identifying potential failure modes early in the NPD process and eliminating them through countermeasures as soon as they are identified at any NPD project stage [Campean et al., 2013a]. Therefore in order to achieve a right-first-time project, a failure mode avoidance methodology can be adopted. So far the failure mode avoidance methodology has been applied only to the product development stages of the NPD process to develop a right-firs-time product rather than a right-first-time project [Campean et al., 2013a, Goodland et al., 2013b] (refer Chapter 2 for more details). This work emphasize on exploring the failure mode avoidance methodology at the holistic project level covering all stages of the NPD project.

The aim of this work is to examine the feasibility of achieving right-first-time NPD projects by applying a Failure Mode Avoidance methodology throughout the NPD process rather than just, as traditionally, in the product development stages.

To meet this aim, the following objectives have been set.

- To conduct a literature review on NPD project risk management strategies and Failure Mode Avoidance.
- To investigate the tools and methods that can enable failure mode avoidance in NPD projects.

- To identify the gaps in the literature in the field of failure mode avoidance when applied to NPD projects.
- To develop a research methodology that presents the pathway to apply failure mode avoidance methodology in NPD projects whilst addressing the identified gaps in the literature.
- To develop a framework that facilitates the use of a failure mode avoidance approach in NPD projects.
- To investigate the feasibility of applying a failure mode avoidance methodology to a real-life company-based NPD project.
- To identify the limitations of the proposed framework and identify future research that can be undertaken to improve this work.

Chapter 2

Literature Review

For managing risks or potential failures in the NPD projects, many NPD studies including Hawker [2002], Ahmed [2017], Galli [2017] use the term ‘risk’ and not the ’potential failure mode’. However, some studies such as Wehbe and Hamzeh [2013], Segismundo and Miguel [2008b], Dewi et al. [2015] use the term failure mode and risk interchangeably. This work prefers the use of the term ’potential failure mode’ instead of ’risks’ in the context of NPD, because the term ’failure mode’ has strong associations with other terms such as failure causes and failure effects, which can provide a clear distinction of risks at various levels in the NPD projects [Saxena et al., 2015].

In the context of NPD projects, studies such as Asadi [2015], Aven [2016] have focused their research on risk management, whereby avoidance has remained only one of the four risk response strategies viz. 1) mitigation/reduction, 2) transfer, 3) avoidance and 4) accept. Whilst studies such as Bauly and Foo [2000], Hwang and Choi [2017], Peterson [2010] highlights the importance of risk avoidance (or failure mode avoidance) in the NPD projects, they do not provide a systematic and analytical approach to obtain a right-first-time project. Although the terms ’risk avoidance’ and ’failure mode avoidance’ seems synonyms, by definition they are different. Risk avoidance in NPD projects is only a risk mitigation strategy within the project management, whilst failure mode avoidance provides a systematic and analytical approach to obtain right-first-time projects. The importance of failure mode avoidance in NPD projects is discussed in the next section.

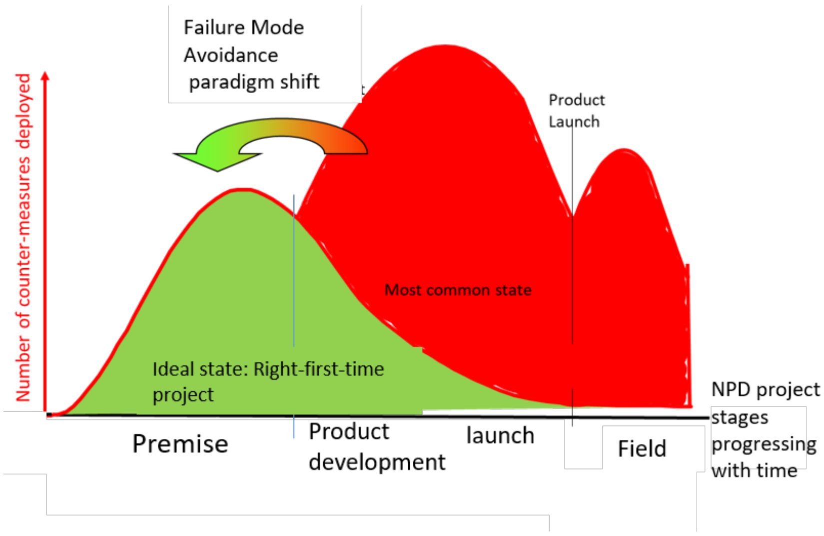


Figure 2.1: Failure Mode Avoidance: A paradigm shift from material stages to the information based stages (Source: adapted from Campean et al. [2013a]

2.1 Importance of Failure Mode Avoidance in NPD projects

The term 'failure mode avoidance' methodology refers to the avoidance[1] of potential systemic failure modes by identifying and detecting [2] them in the premise stages of New Product Development (NPD) projects [Saxena et al., 2015]. The Failure Mode Avoidance philosophy refers to an ideal state where it is presumed that *all* potential failure modes can be *identified and prevented* in the premise stages of an NPD project, where only the information exists and not the hardware of the product in making. The Figure 2.1 illustrates the paradigm shift from predominantly material based development and launch stages to information based premise stages.

It can be seen from the figure 2.1 that in the most common state, the

[1]Although the term failure mode avoidance highlights the usage of the avoidance strategy for managing failures, it does not exclude other managing strategies such as mitigation, transfer and acceptance of the risks. It is because failure mode avoidance is a *pragmatic* methodology, which regards the fact that the complete avoidance of failure is impossible. The reasons for complete elimination of failures are: 1) It may not be impossible to identify all failures [Hillson, 2016b], 2) It may not be cost effective to implement avoidance strategy for all failure modes. For more details, refer appendix B. Therefore, the failure mode avoidance methodology focuses on identifying and detecting the failure modes in the information based stages of the NPD project and thereafter implementing countermeasures for the failure modes after their prioritisation. The methodology focuses mainly on prevention of failure modes via the avoidance and reduction strategies undertaken in the response of high-priority failure modes using the countermeasures[Mode, 2011]. This aspect of identification as well as prioritisation will be covered in the later sections of this chapter.

[2]This work uses the two terms 'identification' and 'detection' of failure modes. The term 'identification' refers to the knowledge about the failure mode as soon as they are created in the NPD process, however the term 'detection' refers to confirming the presence of the failure mode after they are created.

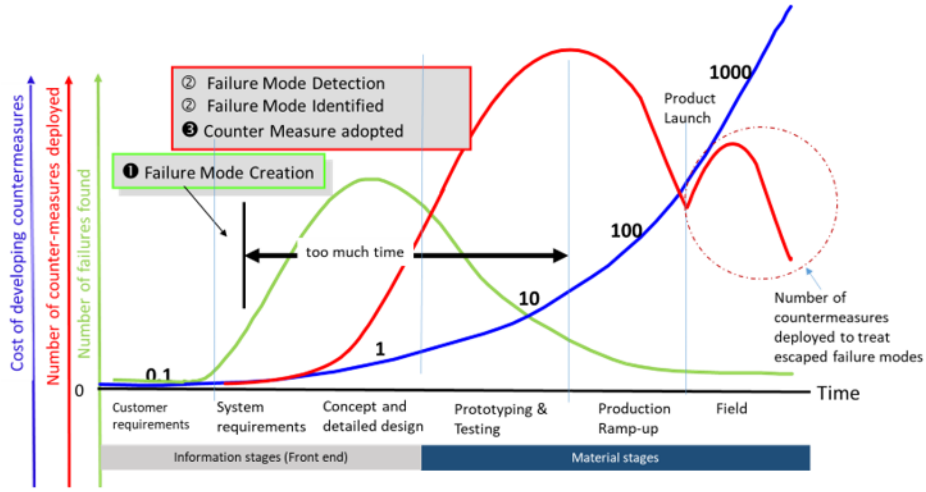


Figure 2.2: Detecting failure modes late (a) (Source: adapted from Saxena et al. [2015])

countermeasures are deployed too late. This countermeasure deployment takes place after the failure modes are naturally observed or detected during the verification stages of the NPD process, which are usually late in the NPD process [Campean et al., 2013a]. Besides, the number of countermeasures needed to prevent failure modes in the early NPD project stages are considerably less than than countermeasures deployed late in the NPD process. This reduction of countermeasures in the premise stages happens because of the structured thinking and approach taken by the project managers and engineers to prevent the failure modes as soon as they are identified, rather than letting them escape to the later stages of the NPD process where the treatment of failure mode is difficult and may require several countermeasures to be implemented [Campean et al., 2013a].

Not only late detection of failure modes results in increased cost, but also may result in unaddressed failure modes escaping into the field that needs countermeasures to be adopted in the field (refer to Figure 2.2).

The failure modes escape into the field because there exists reduced latitude for treating failure modes in the late stages of the NPD process as there is a lot of material involved and not much time left to fix all the failure modes before launch [Davis, 2006, Saxena et al., 2015]. On the contrary, there exists higher latitude to fix the identified failure modes in the front end (or premise) stages of NPD process, however the early identification and detection of all potential failure modes itself is a difficult task ([Saxena et al., 2015]. These examples presenting the two arguments about late versus early detection are presented in Figure 2.3 and Figure 2.4.

From the above discussion, it is now clear that early identification and detec-

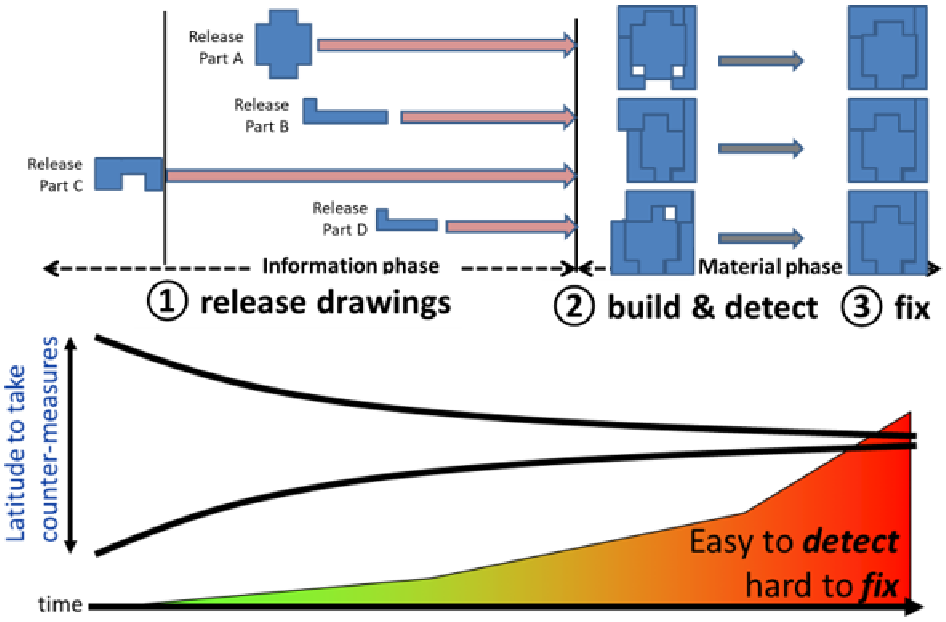


Figure 2.3: Detecting failure modes late (b) (Source: adapted from Saxena et al. [2015])

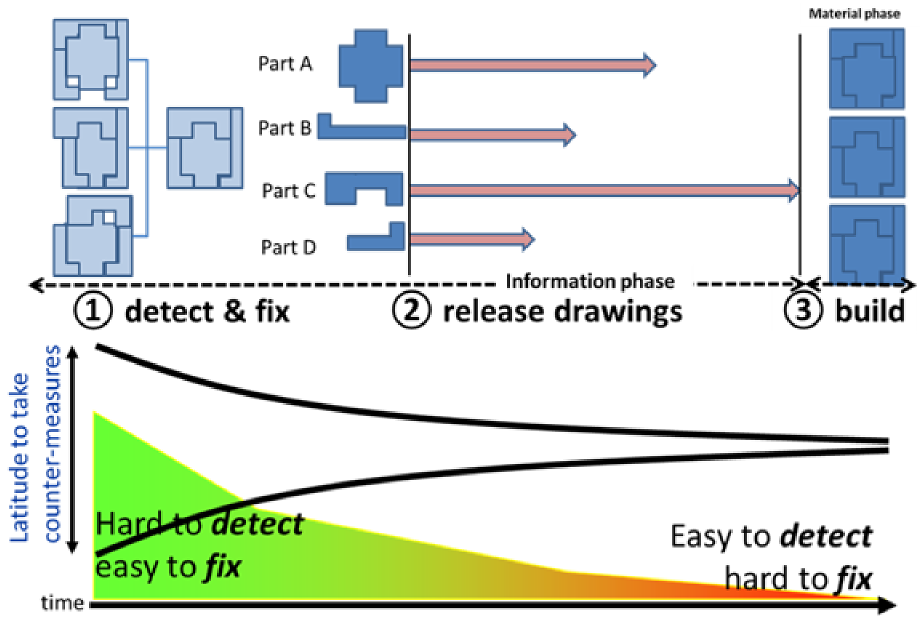


Figure 2.4: Detecting failure modes early (Source: adapted from Saxena et al. [2015])

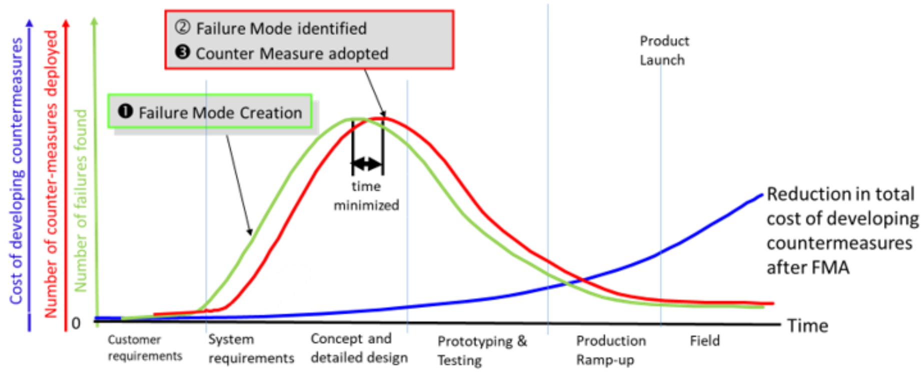


Figure 2.5: The concept of Failure Mode Avoidance methodology (Source: Saxena et al. [2015])

tion of failure modes is the key to implement the failure mode avoidance methodology [Saxena et al., 2015]. Besides, the methodology highlights the importance of preventing failure modes via the countermeasure development as soon as the failure modes are identified [Campean et al., 2013a]. Figure 2.5 illustrates the concept of Failure Mode Avoidance methodology, where it can be seen that the identification and mitigation of all failure modes takes place as soon as they are identified in early information based stages of NPD project. Furthermore, the identification and prevention of failure modes in the premise stages not only reduces the overall cost of deploying countermeasures in the NPD project but also prevents failure modes to escape into the field.

2.2 Failure Mode Avoidance in NPD projects

2.2.1 Existing studies on Failure Mode Avoidance

The last section signifies the importance of applying the failure mode avoidance in NPD projects. Applying failure mode avoidance avoidance in NPD projects mean the identification/detection of all potential failure modes relating to the project in the early information stages of NPD process. It is important to now review the studies on failure mode avoidance that already exists in industrial and academic literature.

In order to find relevant studies in the field of failure mode avoidance, a comprehensive, extensive and systematic literature review approach has been adopted (Onwuegbuzie and Freis, 2016). The literature search has been undertaken on the basis of the search strategy shown in figure 2.6.The term 'Failure Mode Avoidance' has been searched on four different databases including ASME, springerlink, google

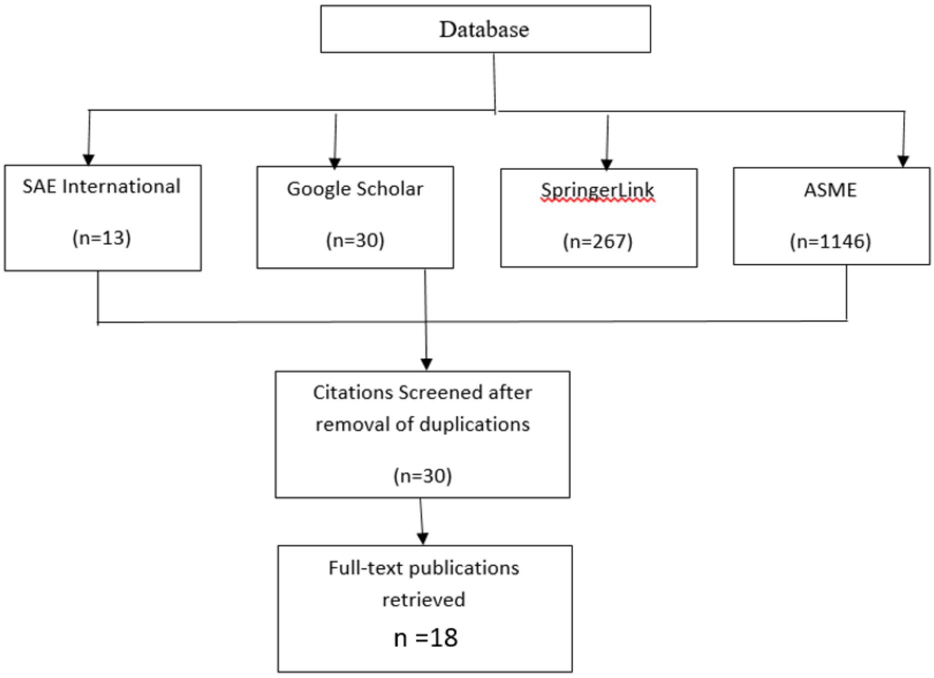


Figure 2.6: A search strategy for Failure Mode Avoidance

scholar and SAE international from year 2000 to 2021. Out of a total number of 1,456 articles that are returned, only 18 final articles are selected for full document review. The filtering to final 18 articles is based on title screen followed by the abstract screen that highlights failure mode avoidance as a keyword in their content. Besides, only peer reviewed articles published in English language has been considered.

Originally introduced by Don Clausing, the term Failure Mode Avoidance has been used by Clausing and Frey [2004], Brown [2004], Campean et al. [2010] in the context of reliability improvement for *products* [Campean et al., 2010]. Clausing and Frey [2004] and Clausing and Frey [2005b] focuses on improving the reliability of the products by robustness improvement and mistakes prevention. In fact Clausing and Frey [2005b] suggests that "reliability is Failure Mode Avoidance". They also present four concept design strategies to avoid the failure modes in the early design stages via expanding the operating window [3] in which the product functions. In other words, If the operating window is made larger, the number of failures in the product can significantly be reduced, hence improving the reliability. The study conducted by Clausing and Frey [2004] has been supported by two hardware based products, namely a paper handling equipment and a jet engine.

Along the similar lines to Clausing and Frey [2004], Brown [2004] also highlights the usage of failure mode avoidance methodology for the reliability improvement

[3]The operating window is the set of conditions under which the system operates without failures.

of products. They emphasize the use of methodology for the field returned units in order to distancing the failure mode from the product rather than using to probabilities to determine how often the product fails. They also presented the taxonomy for failure mechanisms as well as causes (noise factors [4]. The failure mechanisms taxonomy used by Brown [2004] include Yielding, ductile rupture, fatigue, wear, fretting, thermal relaxation, thermal shock, spalling, brinnelling, brittle fracture, corrosion, impact, creep, stress rupture, galling and seizure and radiation damage, as the underlying reasons for product failures. Various noise factors used in this study are: 1) piece to piece variation, 2) wear over time, 3) customer usage/duty cycle, 4) environment and 5) system interaction.

Unlike Clausing and Frey [2005b], Brown [2004] has not considered mistakes in the NPD as the other cause of failure in addition to noise factors. Moreover, Brown [2004] emphasize on the use of accelerated testing as the primary source of uncovering the failure modes for the field returned units. The purpose of accelerated testing is to subject the product to the noise factors it may face in the field, such that relevant failure mechanisms can be found and treated after the testing.

Zhou and Li [2006] highlight that failure mode avoidance is the ultimate goal of reliability engineering. They used the Design For Six Sigma (DFSS) coupled with transfer function analysis to avoid failures in the product design stages of the NPD process. They also used the example of a hardware product, (beam) to demonstrate the failure mode avoidance methodology.

Davis [2006] focus on "directing the actual failure modes themselves (the how and why of things failed), rather than the consequences of the failures after they have escaped into the field". Gremyr and Lönnqvist [2008] recognises failure mode avoidance as a proactive approach, where the focus is to shift the thinking from natural detection of failures to early identification and detection (refer figure 2.7). According to them, early identification means adoption of a 'genuine proactive' approach, where the failure modes are avoided before they are created. On the other hand, early detection means adoption of a proactive approach, where the potential failure modes are detected and treated before they actually become a sustained failure modes only to be occurred later on.

By using a series of well known engineering tools including Fault Tree Analysis (FTA), Parameter-Diagram (or p-diagram) and Design Verification Plan (DVP), Henshall and Campean [2009] present an approach to failure mode avoidance enabling right-first-time design. In their work, a four-step failure mode avoidance approach has been discussed using an automotive case study. They consider failure mode

[4] Brown [2004] does not include mistakes as one of the failure causes unlike Davis [2006], Saxena et al. [2015]

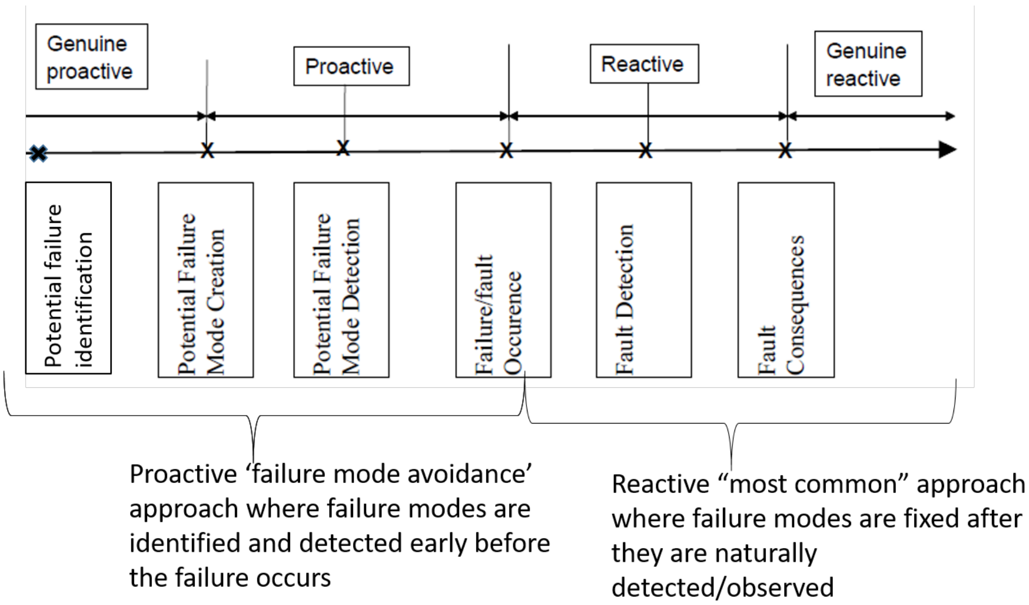


Figure 2.7: Proactive thinking enabling failure mode avoidance (Source: Adapted from Gremyr and Lönnqvist [2008]

avoidance as a process, which comprise of four steps namely: 1) understanding how the system functions (functional analysis); 2) identifying how the system fails to function and the effects of the failure (function failure analysis); 3) determining the cause of failure (robust design verification), and 4) developing and verifying countermeasures to failure (robust countermeasure development) [Campean et al., 2013a]. Each of these steps within is facilitated by a series of structured tools. These structured tools are integrated within each step of the process (See Figure 2.8), which ensure that there is clear flow of information, which in turn result in concise and manageable documentation [Campean et al., 2013a, Goodland, 2016] and enable the engineers to systematically apply the countermeasures. Interestingly, Failure Mode Effects and Analysis (FMEA) tool sits at the core of the failure mode avoidance process as depicted by [Henshall and Campean, 2009].

Henshall and Campean [2010] emphasize on the importance of design verification aspect in failure mode avoidance. Their approach illustrates the usage of component-level testing in the early design stages of the product development process [5]. Campean et al. [2013b] provides an integrated failure mode avoidance framework for multi-disciplinary systems engineering design of an after treatment system for a diesel exhaust system. In a separate work [Campean and Henshall, 2012], they provide a function decomposition analysis that helps identify functions and failure

[5] As mentioned in chapter 1, the product development process comprise of development and testing & validation stages of Cooper's NPD model

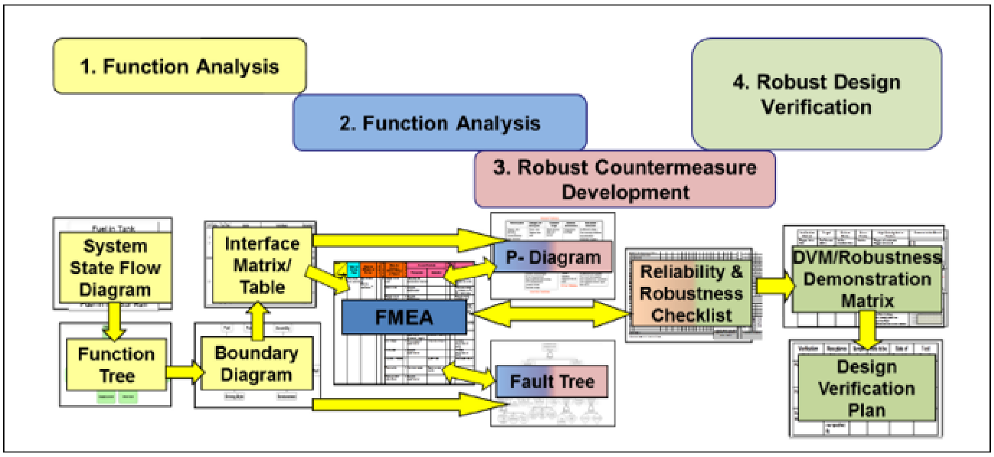


Figure 2.8: The Failure Mode Avoidance Process Outline (Source: Campean et al. [2013a])

modes in a systematic manner, which then helps avoid and mitigate the failure modes in the early design stages of product development process. The work done by Henshall and Campean [2010], Campean and Henshall [2012], Campean et al. [2013b] has been in the field of automotive sector, predominately in the hardware domain of products.

Unlike Campean et al. [2013a] that defines failure mode avoidance as a process, Saxena et al. [2015] defines this to be a method for "early identification of potential failure modes and development of robust countermeasures" via the use of the FMEA. They highlight the need for an analytical framework that can deal with the failure modes in the early design stages.

Goodland et al. [2013b,a], Goodland [2016] advocates the use of failure mode avoidance methodology in the field of manufacturing processes. They propose a manufacturing failure mode avoidance (MFailure Mode Avoidance) framework, which focus on identifying and mitigating the manufacturing process failure modes via the use of engineering tools such as process functional analysis, process flow matrix, process FMEA and six sigma tools. They illustrate that it is possible to avoid the manufacturing failure modes right early in the information stages of process design. Besides, they extend the use of the MFailure Mode Avoidance framework to the aerospace sector. Dobryden et al. [2017] validates the application of failure mode avoidance method proposed by Henshall and Campean [2009], Campean et al. [2010] for the hybrid electric Vehicle Systems.

From the above discussion, it can be concluded that the main essence of failure mode avoidance is the fact that it focuses mainly on identifying potential failure modes earlier in the information stages of any product development process because it is in the early stage of the NPD that the opportunity for change is greatest and the cost is lowest. [Campean et al., 2013a] and Goodland (2016) suggests the usage of Failure Mode Avoidance in the context of right-first-time development.

Qamar et al. [2017] suggests the use of model-based systems engineering approach to failure mode avoidance using a case study in the automotive sector. Murugesan et al. [2017] emphasise on using the failure mode avoidance for Solid Rocket Motor Pressure Monitoring Joint Seals via the use of FMEA tool to select a design that fails the least.

From the discussions above, it is evident that the Failure Mode Avoidance strategy can be applied for right-first-time development of new products. However, the usage of the Failure Mode Avoidance in the context of NPD projects is still an unexplored area.

2.2.2 Tools enabling Failure Mode Avoidance

Various structured tools are implemented in different steps of the Failure Mode Avoidance process. The Table 2.1 summarises the different tools that are used to implement the failure mode avoidance method ([Henshall and Campean, 2009, Campean et al., 2010, 2013b]). Each of these tools are key in discovering failure modes and development of countermeasures early in the product design process [Campean et al., 2013a, Dobryden et al., 2017]. For example, the System State Flow Diagram (SSFD) tool ensures that there exists high levels of system integration in the product development process, which helps in avoiding unnecessary iterations within the process and ensures that it flows smoothly.

The Interface Analysis Table (IAT) or Interface matrix is another tools that can be used whilst implementing failure mode avoidance. The IAT helps identify all the interfaces, for which it offers an information rich document that provides sound basis for functional requirements specification as well as offers information about the possible root causes of the functional failure modes. Thus, the use of IAT makes it easier to manage the failures that are likely to cause failure in a certain product development function (design or manufacturing) [Campean et al., 2013a,b, Goodland, 2016].

Another tool to facilitate failure mode avoidance is the Function Fault Tree (FFT), which helps in identification of root causes of failure modes. The FFT analysis is useful mainly in complex systems or those that involve combinations of root causes and events which when combined can lead to a significant failure mode [Campean and Henshall, 2012].

Another tool that supplements the failure mode avoidance is P-Diagram, which is a powerful tool in visualising the relationship between inputs, outputs,

FMA Process Step	Tools
Gain understanding of how the system functions	System Boundary Diagram Interface Matrix and List System State Flow Diagram Function Tree
Identify system failure modes and effects	FMEA
Analyse potential causes of system failure	Function Fault Tree P-Diagram
Develop countermeasures to failure, and methods of verification	Robustness Worksheet Design Verification Plan

Table 2.1: Failure Mode Avoidance Tools (Source: [Henshall and Campean, 2009, Campean et al., 2010])

functions, noise factors (or failure causes [6]) and failure modes of a system [Ford, 2016b, Campean et al., 2013b]. The p-diagrams provides a systematic approach to populate the FMEA, which has been considered as the core tool for implementing the failure mode avoidance [Liu, 2016, Dobryden et al., 2017, Goodland et al., 2013b, Campean et al., 2013b].

Whilst implementing Failure Mode Avoidance, two tools viz. robustness worksheet or robustness checklist and the design verification plan have been proposed by Campean et al. [2013a] for countermeasures development. Having a robustness checklist (RCL) tool in this regard, especially the one that is linked with P-Diagram and FFT proves to be useful when developing the countermeasures Campean et al. [2013a].

2.2.3 FMEA: The core tool for enabling Failure Mode Avoidance

From the discussions above, it should be noted that the core tool of Failure Mode Avoidance strategy is the FMEA, where the focus has shifted from failure modes and effects *analysis* to failure mode *avoidance*. Thus, the literature around FMEA is now expanded further below. Thus, one of the most widely used risk management tool in the NPD is the Failure Mode and Effects Analysis (FMEA) model.The failure mode and effects analysis (FMEA) has been most commonly used for conducting failure analysis in several engineering fields such as engineering product design, manufacturing, service reliability assessments, healthcare management, human resources, cyber-physical systems etc. [Gaur and Bhardwaj, 2014, Bhangu and Grover, 2019,

[6]There are two types of failure causes: 1) noise factors and 2) mistakes as discussed by Clausing and Frey [2004, 2005b]. Traditionally, only noise factors are considered in the p-diagram [Campean et al., 2010, Henshall and Campean, 2009, Campean et al., 2013b]. However this work aims to include both types of failure causes in the p-diagrams.

Sharma and Sharma, 2015].

A critical review of FMEA literature has been conducted. A quick search on the scopus database reveals 4308 documents in total over the span of 20 years. Although the research on the FMEA dates back to 70 years, only the documents from last 10 years have been included for this further review [Liu, 2016]. A quick analysis of the number of published papers shows that the 80% of the total documents have been published in last decade only. The FMEA literature can be found in articles, book chapters, company reports, patents, journal publication, company proceedings etc. However the focus is only on patents, internal journals and proceedings as they are peer reviewed and/or demonstrate scientific rigour.

Out of the 4,308 documents retrieved from the 'Scopus' database around the FMEA, 3080 articles have been covered in the last decade. In order to reveal the number of documents related to the FMEA limitations, keywords such as FMEA limitations and RPN limitations have been used. Only the articles published in the English language from journals, proceedings, books and patents have been considered. In total 60 articles are shown that highlights the issues with the FMEA.These 60 articles are reviewed manually via title screening following by the abstract screening. Out of these 60, 17 full-text publications have been reviewed.

In their article, Ambekar et al. [2013] defines FMEA as "a systematic process for identifying potential design and process failures before they occur, with the intent to eliminate them or minimise the risk associated with them" (EN IEC 60812, 2018). The FMEA had been first introduced by the United States Military Procedure MIL-P-1629 in the year 1949, and has also been used as a qualitative failure analysis by the space agency NASA to improve the safety and reliability of its long-lived communications satellites (Dobryden et al., 2017).

The FMEA aims to identify failure modes and actions that can be implemented to reduce or completely eliminate the potential failure from occurring [Carbone and Tippett, 2004]. In the FMEA, the NPD team evaluates failure modes for occurrence (O), severity (S) and detection (D) and allocates value leads to obtain a Risk Priority Number (RPN). The RPN is obtained by multiplication of the value leads for occurrence, severity and detection (RPN = O*S*D).

Over the years various versions of FMEA have come into picture. Many of these versions are used in both the engineering reliability as well as the NPD fields [Shin et al., 2018]. Some of the common types of FMEA include the concept FMEA (CFMEA), design FMEA (DFMEA), and process FMEA (PFMEA), and risk FMEA (RFMEA) Carbone and Tippett [2004], Ambekar et al. [2013]. In the year 2004, Carbone and Tippett [2004] extended the FMEA model and introduced a modified version of the FMEA to quantify and analyse project risks, known as risk FMEA or

Typical FMEA Columns	Failure ID	Failure Mode	Occurrence (O)	Severity (S)		Detection (D)	RPN
Typical RFMEA Columns	Risk ID	Risk Event	Likelihood	Impact	Risk Score	Detection	RPN

Figure 2.9: Simplified Standard FMEA and RFMEA Forms (Carbone & Tippett, 2004)

RFMEA. Figure 2.9 provides the differences between the simplified standard FMEA and RFMEA forms.

Studies Deng and Jiang [2017], Inmaculada Plaza et al. [2003] indicate that the FMEA is a useful tool to manage risks in the NPD because it helps in defining, identifying and eliminating potential risks and improves reliability of systems, designs, and products. It has been also regarded as a proactive engineering quality method for identifying and handling weak points, especially in the early phase of product development Inmaculada Plaza et al. [2003]. Considering its ability to assist companies in enhancing the quality/reliability of products, the FMEA has been used by companies operating in various sectors that range from aviation to medical industries. In fact, quality organisations such as the International Organisation for Standardization (ISO) have used the FMEA technique as a powerful analysis in their ISO-9000 series [Shin et al., 2018].

Due to FMEA's ability to help engineers identify the failures in the design and process whilst building a product, the application of FMEA has been extended in several industries to optimise the decision making process in NPD [Inmaculada Plaza et al., 2003, Segismundo and Miguel, 2008a, Zhang and Chu, 2011, Deng and Jiang, 2017, Shin et al., 2018]. Inmaculada Plaza et al. [2003] conclude that FMEA is a proactive tool that helps in identifying and handling weak points in the early phase of product development (Plaza et al., 2003). Proposing a systematization of technical risk management through the use of FMEA to optimise decision making process in NPD in the automotive sector, Segismundo and Miguel (2008) concluded that the use of FMEA in the sector greatly helped in reducing the number of project and test planning looping and reduced number of prototypes that were needed to approve product components.

Some researchers such as Shin et al. [2018], Zare and Dehghanbaghi [2013], have used the FMEA in the wider context of NPD projects. A replacement of FMEA with VMEA (Variation Mode and Effects analysis) has been suggested by Bergman et al. [2009] and Johannesson et al. [2013], where focus is to minimise the variations instead of the failures. Whilst establishing a link between the variations and the failures in design, Bergman et al. [2009] and Johannesson et al. [2013] demonstrate the best practices of Robust Design and Methodology in line with work conducted by Davis [2006] and Clausing [2004]. Nevertheless, it is evident that the literature examining the FMEA as a tool is divided into two streams. One stream of research examining FMEA as a tool to reduce risk has emerged in the wider reliability engineering literature whereas another stream investigates the use of FMEA as a risk management tool in the NPD projects.

Although FMEA have proven to be a very useful tool in the field of product's reliability engineering as well as NPD projects' risk management, it has been criticised due to its limitations [Spreafico et al., 2017]. Both qualitative as well as quantitative columns of the FMEA have been criticised in several studies[7], which have been discussed as follows:

Spreafico et al. [2017] highlights four problem classes related to the FMEA. These include: 1) applicability, 2) cause and effects, 3) risk analysis and 4) problem solving. The 'applicability' of the FMEA has been deemed to be a concern due to its subjectivity, time consuming nature and late application to name a few. The issues around the another problem class 'cause and effect' is mostly related with the qualitative columns of the FMEA as its often seen that academics and industrialists use the terms causes, modes and effects interchangeably [Saxena et al., 2015]. Besides, primary failure mode event is captured in the FMEA and secondary effects and combination of failure modes is often missed as that increases the complexity [Spreafico et al., 2017]. Moreover, the problem class pertaining to the 'risk analysis' highlights the issues with the subjectivity in scoring the RPNs and measuring the risks thereafter. Furthermore, the problem class around the 'problem solving' demonstrate the issues with the implementing the solutions after the FMEA study is complete.

The FMEA tool has attracted several criticism for its use in reliability engineering. For example, in their work, Ambekar et al. [2013] note that even though the use of the FMEA during the design or post-product launch has its own advantages, the tool does not provide the designer the information about the predominant failures that should receive attention when the product is designed. In their article, Tsai et al. [2018] state that the FMEA provides insufficient support for product design, especially at the early design stage. They note that the failure mechanism analysis, failure propagation and impact analysis in the FMEA is performed only after the completion of the detailed design, which does not help identify design defects and

[7] The columns of the FMEA can be divided into two categories: 1) qualitative and 2) quantitative [Saxena et al., 2015]. The qualitative columns include the columns related to functions, failure modes, failure causes, failure effects, existing controls, recommended actions. On the other hand, qualitative columns include the columns related to severity, occurrence, detection and RPN scores.

possible failures.

The critic of the FMEA for being insufficient in helping to detect failures, especially at the early stage of the product development led researchers to use the FMEA tool along with other risks management models to improve its applicability in risk management, especially at the fuzzy-end or the early stage of the product development. One such study has been conducted by [Shin et al., 2018]. Criticising the traditional FMEA tool as a model that fails to reflect influence of risks in a whole system, the authors use a combination of FMEA and Decision Making Trial and Evaluation Laboratory (DEMATEL) methodologies to investigate the impact of risks in the Research and Development (R&D) management. The authors conclude that using a combination of the FMEA and DEMATEL helps to systematically organise the list of failure modes and causes of failures, which according to the authors greatly contributes in enhancing the process of R&D risk management or at the early stage of the NPD.

Similar to the use of FMEA in reliability engineering, the FMEA is also not devoid of criticism for its use in the NPD projects. For example, the FMEA technique has been criticised by researchers in the context of NPD project for being too time consuming and for providing results that may differ and can be based on the levels of expertise of the analysers [Shin et al., 2018]. The FMEA tool has also been criticised for its inability to address the uncertainty in risk evaluation, thereby hampering its ability in accurately detecting risks in the NPD process [Deng and Jiang, 2017]. Saxena et al. [2015] highlights the issues with structure of the FMEA, where they present that FMEAs are highly structured from left to right but not from top to bottom.

Liu [2019], whilst conducting their research in the field of hospital management, focused mainly on the limitations of the quantitative columns of the FMEA. They were also able to produce a list of traditional as well as improved methods for scoring the columns in the FMEA. The traditional methods include RPN, hazard scoring matrix, simplified and portfolio matrix method to name a few. The improved methods include fuzzy interference method, fuzzy RPN method, probabilistic modification of FMEA, fuzzy VIKOR method to name a few. Many other researchers such as Emovon and Norman [2019], Liu et al. [2016a] have also highlighted the issues with the RPN.

Shaker et al. [2019], Yang et al. [2015], Guinot et al. [2017], Chang et al. [2015] showcases the following issues with the RPN scoring method.

- The three scores viz. severity, occurrence and detection scores are weighted equally ad their relative importance is not considered.

- The different combination of values of severity, occurrence and detection can reveal the same RPN, which makes it difficult to know the relative importance of failure modes over one another.
- The scoring can be subjective and it is difficult to precisely evaluate the scores.
- Any variation observed in the risk factors reflects strongly i the RPN values. This implies that the mathematical formula for the RPN is sensitive to the variations observed in the risk factors. This makes the formula debatable and questionable.
- There is a huge disparity in the RPN scoring as they can range from 1 to 1000. Besides, the RPN is non-continuous that leaves out many holes in the range.
- The application of RPN to measure the effectiveness of the corrective action is questionable.
- RPN does not consider indirect relationship between various components of the system and also ignores the inter-dependencies of the failure modes.
- The selection of the threshold value for the RPN, above which corrective actions should be taken, is considered dangerous. This is because this may result into the gaming ranking process, wherein stakeholders just focus on bringing the RPN below the threshold value rather than focusing on avoiding failures.

In order to overcome issues with the RPN, several research studies have been undertaken in the past decade. Research from Liu [2019] suggests that more than 75% of the articles they had reviewed used the RPN scoring method. However, newer ways of scoring have been proposed that address the issues with the RPN. Narayanagounder and Gurusami [2009] proposed a new method for prioritisation of failure modes that uses ANOVA technique for comparing the means of the RPN index. They mainly used the methodology to cover up two case studies 1) where two or more failure modes have got the same RPN values; 2) where teams disagreed on the scale of three risk factors (viz. severity, detection and occurrence). For the first case study, they used the risk priority code, to determine the critical failure mode; and for the second case study, they used RPN means and ranges. Thereafter, single way ANOVA has been used to compare the means.

Carmignani [2009] presented the criticisms around the RPN as they highlighted its inability to include the cost of corrective actions into the calculations. To resolve this concern, they proposed a PC-FMEA that is able to determine the profitability by considering the cost of corrective correction into account. In 2014, Shafiee and Dinmohammadi [2014] also used the FMEA for the onshore and offshore wind turbines. In their study, they extended the application of RPN to include the economic considerations.

Suganthi and Kumar [2010] used the SIPAC (Study, Identify, Perform, Analyse and Continue) model to increase the efficiency of the FMEA tool. Besides, they proposed a simplified formula for risk reduction over time, such that the true value of implementation of the corrective actions can be assessed.

Gargama and Chaturvedi [2011] developed a fuzzy RPN method by treating three risk factors as the fuzzy linguistic variables. Similarly, Tay et al. [2012] highlighted the use of FIS (Fuzzy Interference System) with the RPN to address some of the issues associated with the RPN technique. The study from Tay et al. [2012] is aimed at the following:

- It uses sufficient mathematical foundations attempts to preserve the monotonicity of the FIS-based RPN models
- It attempts to formulate the process of designing fuzzy membership functions in an automated manner
- It proposes a framework to minimise the number of fuzzy rules for FMEA users.

Jong et al. [2014] applied the concept of FIS with RPN to the field of edible bird nest processing. Then in year 2015, they extended their bird nest study to use three different approaches integrated with the FMEA. These include 1) Euclidean distance based similarity measure, which allows similar failure modes to be quantified; 2) fuzzy art that allows failure modes to be categorised into various groups and 3) risk interval measure that allows the prioritisation of the failure modes based on various groups.

Barends et al. [2012] also illustrates that the traditional RPN may be misleading because the failure mode with the highest RPN value might not actually be the one that pose highest risk. They focused on detection and occurrence being the main driver for failure mitigation and gave a probabilistic view to these risk factors. They also suggested that probability of occurrence of a non-detected failure mode P(uf) can be calculated by P(uf) = P(O) $*$ (1 minus P(D)), where P(O) denoted the probability of occurrence and P(D) denotes the probability of detection of a failure mode. As per the author, the value of P(uf) should be minimized.

Liu et al. [2012] uses the fuzzy sets and VIKOR (abbreviated for 'VlseKriterijumska Optimizacija I Kompromisno Resenje,' meaning multi-criteria optimization and compromise solution) method to overcome the deficiencies of the RPN method. In year 2014, Liu et al. [2014] used the intuitionistic fuzzy hybrid weighted Euclidean distance operator to rank and prioritise the failure modes. They claim that more the distance is from the reference series, more risky the failure mode is. They also claimed their proposed method to be more effective than fuzzy FMEA from Pillay and Wang [2003], OWA based FMEA from Wei and Chang [2011] and intuitionistic fuzzy FMEA from [Chang and Cheng, 2010].

Mohammadi and Tavakolan [2013] applied the fuzzy logic and AHP with the FMEAs in the field of project management. Seven membership functions were used for each risk factor and 343 fuzzy rules were considered for the analysis. Ilangkumaran et al. [2014] and Shi et al. [2016] also uses fuzzy AHP technique in the FMEA for the purposes of risk evaluation. Emovon et al. [2014b] extended the concept of traditional RPN to AVRPN (average RPN) that uses the averaging technique. Also they made use of TOPSIS (abbreviated for 'Technique of Order Preference Similarity to the Ideal Solution') method to weigh the risk factors and prioritise the failure modes in the field of marine machinery systems. Later, Emovon et al. [2015b] attempted to combine VIKOR and CP (compromise programming) for risk prioritisation in the FMEAs.

Chang et al. [2015] used the FMEA with the Monte Carlo simulation for the evaluation of RPN values and prioritising the failure modes accordingly. They presented a case study in aviation industry. Panchal and Kumar [2016] used the fuzzy decision support system for the analysis of thermal power plant's FMEA. In an another study from Liu et al. [2016b], ELECTRE (abbreviated for 'ELimination Et Choix Traduisant la REalité' or ELimination Et Choice Translating REality) method has been used in conjunction with the FMEAs. Liu et al. [2016b] used the FMEA with the TOPSIS theory for their study of wind turbine's fuzzy FMEA. In year 2015, Liu et al. [2015] also combined the FMEA with fuzzy DEMATEL technique.

Research kept going for fuzzy FMEAs such as in Khuankrue et al. [2017], Panchal et al. [2018], Renjith et al. [2018]. Lo and Liou [2018] developed a novel multi criteria decision making (MCDM) based FMEA model using the probability-based Grey relational analysis to evaluate the RPN. A similar study has been conducted by Li and Chen (2019), where they also used Grey relational projection method for establishing a quantitative metric instead of the traditional RPN.

In 2019, Josephs [2019] used the vague set based RPN method for quantitative analysis and pattern recognition for prioritising the actions for the failure modes. Another study that uses MCDM approach to prioritise failure modes is Gugaliya et al. [2019] that takes a hybrid approach by using AHP and ERVD together. More studies using fuzzy FMEA combined with one or more MCDM approaches include [Zandi et al., 2020, Das et al., 2020, Nguyen, 2020, Srivastava et al., 2020, Wang et al., 2020, Kaya, 2020].

Recently Emovon and Norman [2019] challenged the usage of MCDM methods and proposed a new method of combining Taguchi and FMEAs for analysis of risks. However their study is restricted to engineering systems. Based on the research conducted above in the field of Failure Mode Avoidance and FMEA, the state of the art is presented in section below, which is focused on highlighting the gaps in the reviewed studies.

2.3 Current state-of-the-art

Numerous risk management tools that can help companies to manage risks within the NPD process have been introduced over the years. Some of the most widely used risk management tools and methods include the Bayesian Network, bubble diagrams, Failure Mode Avoidance, FMEA etc [Chin et al., 2009, Abrahamsen and Aven, 2011, Hamza, 2009]. The Bayesian Network as used by Chin et al. [2009] constructs a relationship of critical risk factors in the NPD projects and has identified four major nodes of risks. These include: research and development (R&D) risk (RADR), supplier's risk (SUPR), production risk (PROR), and product reliability risk (PRRR). The Bayesian Network tool has been applied in analysis of NPD and is known as a tool for reasoning with probability which elicits experts' judgement, and in turn facilitates a quantitative and more accurate risk-based NPD project assessment. However, the model suffers from major shortcomings such as inability to inculcate large number of conditional risk probabilities evident in complex NPD processes and a lack of flexibility to accommodate different forms of input from experts [Chin et al., 2009].

Some more but relatively less popular RM tools such as the Bubble Diagrams introduced by Abrahamsen and Aven [2011] and Control Charts by Hamza [2009] have also been used in risk management in the NPD projects. Abrahamsen and Aven [2011] propose a bubble diagram that suggests managing safety related uncertainties. On the other hand, Hamza [2009] proposes the use of control charts and process sigma to control productivity of deliverable and maintain on-time delivery and cost effectiveness of products which help companies, especially construction companies to deliver products on time and within budget.

Some researchers such as Chauhan et al. [2017], Deng and Jiang [2017] have introduced integrated RM model to effectively deal with risks that may occur in the entire life-cycle of NPD projects. For example, in their work, Chauhan et al. [2017] have proposed a three-stage holistic RM method for overall management of NPD risks. On the other hand, Deng and Jiang [2017] introduced a fuzzy risk evaluation in FMEA. It is worth noting that the models introduced by Chauhan et al. [2017]

and Deng and Jiang [2017] aim to reduce the risk evaluation approach in FMEA to help experts in making appropriate decisions to tackle risks and ensure success of the NPD process and project.

It is worth noting that each of these tools and methods are used on an adhoc basis and lack a holistic approach that can be used to reduce or mitigate risks in the entire life-cycle of the NPD project [Chauhan et al., 2017]. Therefore, efforts towards introducing holistic risk management tools, which organisations can use as guidelines to assess NPD projects' risks are needed [Chauhan et al., 2017]. Moreover, none of these studies have been able to define and obtain the right-first-time projects.

Out of all risk management tools and framework reviewed in the scope of this work, although in product development domain, Failure Mode Avoidance is the only approach that enable right-first-time development in a systematic and analytical manner using mainly the FMEAs (refer table 2.2 and table 2.3). One of the major strengths of the Failure Mode Avoidance is the fact that it has been found Henshall et al. [2014], Campean et al. [2013a] to be very effective in industrial case studies and has been largely adopted in the automotive and aerospace industry as a way to enhance the effectiveness in product development stages of NPD process and produce right-first-time products. The Bradford Engineering Quality Improvement Centre (BEQIC) framework from Henshall et al. [2017] as well as Manufacturing Failure Mode Avoidance framework (MFailure Mode Avoidance) from Goodland (2016) treats the Failure Mode Avoidance approach as a process, contrary to a method.

It should be noted though that none of the existing studies related to failure mode avoidance covers premise and launch stages of NPD project. Moreover in order to obtain a right-first-time project, the failure mode avoidance principles should be implemented throughout the NPD process, which the current studies fail to define. Moreover, these current frameworks just focuses on robustness improvement aspect and fails to include mistake prevention as proposed by Clausing and Frey [2005a] and Davis [2006]. Furthermore, none of the Failure Mode Avoidance frameworks so far provides a quantitative measure to demonstrate the effectiveness of Failure Mode Avoidance method. Therefore, development of a generic Failure Mode Avoidance framework is needed that can be applied systematically in the scope of NPD projects to reveal advantageous findings.

As discussed earlier, the core tool to implement the failure mode avoidance methodology is the FMEA. Most of the research in the field of FMEA improvements in the last decade has been focused on overcoming the structural problems of the FMEA and the limitations of the RPN. The structural problems can be addressed by developing the taxonomies of failure modes, causes and effects [Pangione et al., 2020, Irshad et al., 2018]. For overcoming the limitations of the RPN, MCDM methods

Study by	Area of research	Focus on Right first time	Systematic risk identification	Analytical risk assessment	NPD project stage/sub-stage (or NPD process step) covered
Clausing and Frey (2004 & 2005)	Product reliability improvement via the robustness and mistake prevention	-	-	-	Early concept design stages of product development
Brown (2004)	Product reliability improvement via robustness of design	-	Taxonomy given for failure mechanisms and causes (noise factors)	-	"Re" product development of field returned units
Zhou & Li (2006)	Product reliability improvement via transfer functions and distance from failure modes	-	-	Computer Aided Reliability Design Method to evaluate transfer functions and distance from failure Modes	Product design and verification
Lönnqvist & Gremyr (2008)	Product reliability improvement via proactive thinking in early design stages	-	-	-	Early design stages of product development
Henshall and Campean (2009) Campean et al. (2012) Campean et al. (2013) Dobryden et al. (2017)	Reliable product design using engineering tools	Right-first-time product development through design	Systematic identification of failure modes using function decomposition analysis, p-diagram, design FMEA etc.	Assessment of risks via the FMEA scores pertaining to occurrence, detection and severity. Focus on prioritising the failure modes with traditional RPN methods.	Early design stages of product development

Table 2.2: Current State of the Art for Failure Mode Avoidance (a)

Study by	Area of research	Focus on Right first time development	Systematic risk identification	Analytical risk assessment	NPD project stage/sub-stage (or NPD process step) covered
Goodland et al. (2013) Goodland (2016)	Manufacturing process improvement	Right-first-time product development through process	Systematic identification of failure modes using process functional analysis, Process FMEA etc.	Assessment of risks via the FMEA scores. Focus on prioritising the failure modes with traditional RPN methods.	Early information based phases of manufacturing process within the product development process
Qamar (2017)	Improvement of product design	-	Systematic identification of failure modes using the concepts from Model based systems engineering embedded with requirements analysis, FMEAs and design verification.	-	Early design stages of product development
Murugesan (2017)	Selecting the best design concept	-	Systematic identification of failure modes using the FMEA.	The prioritisation of failure modes using the net RPN values.	Early design stages of product development
This work	Focus is to identify, assess and prevent the failure modes right early in the front end of NPD project, whilst also addressing the limitations of traditional FMEA.				

Table 2.3: Current State of the Art for Failure Mode Avoidance (b)

such as AHP, VIKOR, TOPSIS, DEMATEL etc. has been proposed. However, it is an added step that asks the team members to do more brainstorming and evaluation, which makes these approaches less practical for use. In other words, these MCDM approaches are computationally intensive and adds additional steps for the decision makers to determine weightings and ranking of individual failure modes, which is a tedious task [Emovon and Norman, 2019]. On the other hand, the conventional RPN is simple and easy to use [Ungureanu and Stan, 2016]. Therefore, a metric is needed that makes the best use of conventional RPN yet overcomes its limitations without adding additional manual steps for the users in the FMEA.

From the discussion above, it is clear that a new Failure Mode Avoidance framework is needed for the product-based companies that helps them obtain right-first-time projects. The new failure mode avoidance framework, which makes use of the FMEA as a core tool, should be able to systematically identify all possible failure modes in NPD projects, whilst also deal with them in a practical manner. Besides, the FMEA tool embedded in the new failure mode avoidance framework should overcome the limitations of the current FMEA practices. In the light of this need, the following research question has been set:

Is it possible to implement a Failure Mode Avoidance framework to achieve right-first-time NPD projects for product based companies?

The research methodology that provides the pathway to answer the aforesaid research question has been discussed in the next chapter.

Chapter 3

Research Design and Methodology

3.1 Research Design

The goal of this research is to investigate the possibility of applying the failure mode avoidance methodology to an NPD project in a real-life based company environment to obtain a right-first-time NPD project. Thus, the design of this research consists of the following steps:

- Preliminary research assessment: The first part of the study involves the preliminary literature search for understanding the risks in the New Product Development projects and to reflect the need for the failure mode avoidance methodology in the NPD projects.
- Formulation of aims and objectives: The insights gained from studying the preliminary literature are used to formulate the aims and objectives for this research.
- Intensive literature review and state of the art: A literature review have been conducted to investigate various studies in the field of failure mode avoidance. Gaps in the literature have been identified that highlights the need for implementing the failure mode avoidance methodology in NPD projects. The current studies in the field of failure mode avoidance present several frameworks that focuses only on obtaining right-first-time product designs or manufacturing. None of the examined studies have attempted to apply the failure mode avoidance methodology in the field of NPD projects.
- Formulation of the research question: Based on the literature review, a research question have been formulated. The primary problem that needs to be solved is

the implementation of the failure mode avoidance methodology in the holistic process of an NPD project.

- Research design and methodology: This illustrates the path through which this research work is carried out to answer the research question. The aim to present the research methodology that not only focuses on the overall research strategy but also on illustrating how the results from this work will be disseminated.

- Design and development of a theoretical framework enabling Failure Mode Avoidance in NPD projects: This study attempts to address the problem by developing a new analytical failure mode avoidance framework that uses tools such as FMEA and p-diagrams. To demonstrate the philosophy around an ideal state of obtaining right-first-time projects via the Failure Mode Avoidance methodology, a principle from the Mathematics and Science domains called 'symmetry' have been adopted in the context of New Product Development. Whilst developing the framework, the author also attempts to address the limitations of FMEA including the structural problems as well as some of the RPN limitations highlighted in chapter 2.

- Proposing the developed framework to a product-based company: The developed framework needs to be validated using a real-life based case study conducted for NPD projects. The developed framework is generic, such that it can be applied to the holistic process of an NPD project. The current frameworks have been applied mostly in the product domain in order to obtain right-first-time products via avoiding and mitigating the design and manufacturing process' failure modes. Therefore, the developed framework should first be applied to the product domain itself in order to validate its applicability in an already tested domain. Thereafter, the application of the framework should be extended to the project domain to seek benefits. The author intends to propose the developed framework to an unnamed company, such that it is possible to execute the framework using real-life case studies. The intention is to pitch the idea of applying the framework to the senior stakeholders (as referred to NPD experts in this work) of the selected company.

- Data collection: The qualitative and quantitative data needs to be collected in an attempt to apply the developed framework in the product as well as project domains. Therefore, two case studies from product and project domains respectively needs to be selected.

- Data analysis and synthesis of results: The collected data needs to be analysed using the mathematical formulations dictated by the framework. Thereafter, a

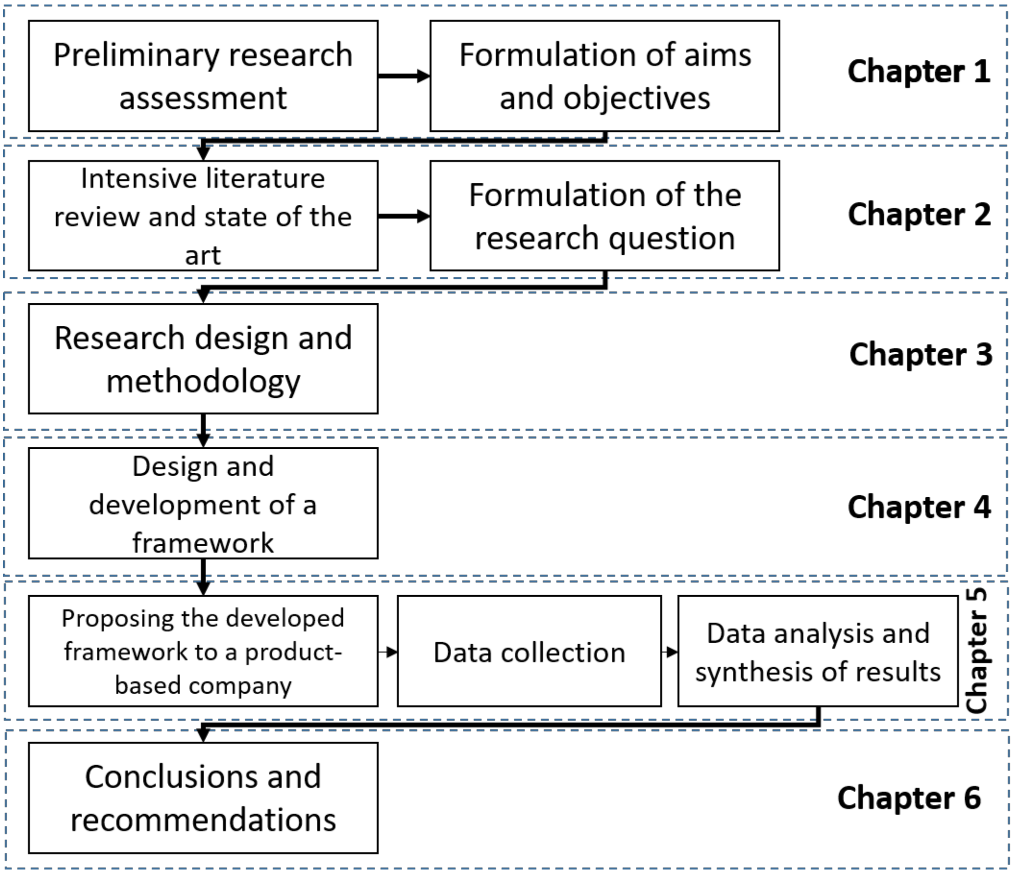


Figure 3.1: Research Methodology

qualitative analysis needs to be conducted using the stakeholder's reviews in order to understand the impact of implementing the framework on mitigating the product and project risks. The results then needs to be synthesized and presented to the stakeholders.

- Conclusions and recommendations: The advantages and limitations of the developed framework are presented in this thesis and recommendations are made for further improvement and application of the framework.

The design for the overall research of this study is depicted in figure 3.1.

3.2 Research Methodology

3.2.1 The Study area

The study area is the implementation of failure mode avoidance methodology in the complete NPD process to enable right-first-time development of NPD projects. The failure mode avoidance framework is developed using the principles from symmetry, p-diagrams and FMEA. Once the framework is constructed, it needs to be used in a product-based company for execution and validation.

This research study uses both qualitative as well as quantitative methods in combination with primary and secondary data sources.

3.2.2 The Secondary Data: Sources and collection

The population[1] of studies in the scope of this work refers to any study that has been conducted in the field of failure mode avoidance and the FMEA. A stratified sampling technique is used to divide the population of studies into two clusters. These clusters are: 1) the cluster of studies pertaining to Failure Mode Avoidance and 2) the cluster of studies pertaining to Failure Mode Effects and Analysis. A literature search has been conducted in both clusters to identify the gaps. These two clusters have been extensively reviewed in chapter 2. In order to maximise the extent of literature search, a systematic review of literature has been conducted for both Failure Mode Avoidance and the FMEA.

A narrative review of studies around other surrounding topics such as NPD risk management, risk avoidance, right-first-time development, symmetry and p-diagram has also been conducted to support the research. Furthermore, Cooper's stage-gate NPD model has been adopted after a meta-analysis is conducted to pull the relevant studies pertaining to several NPD models (refer appendix A), whereby the number of citations of a particular NPD model provides a direct measure of its popularity. The literature sources include journal articles, books, conference papers, standards and few other grey literature such as websites and blogs. The studies collected from these secondary data sources are collected using the desk-based reviews.

3.2.3 The Primary Data: Sources and collection

Once the theoretical framework is established using the principles from symmetry, p-diagrams and FMEA, it needs to be tested using the real-life data from a product-based company that specifically follow Cooper's NPD process model. There can be large number of product-based companies in the world, which adopts and follows Cooper's stage-gate model for their respective project portfolios. Therefore, a convenience sampling method is adopted in order to select a company that can help the author validate the framework.

An unnamed product-based company (referred to as company 'X' in the scope of this work) has been chosen because the author has several contacts within this

[1] "Population refers to the complete set of individuals (subjects or events) having common characteristics in which the researcher is interested" [Fraenkel and Warren, 2002; Sileyew, 2019].

company that enabled interaction and communications with the senior stakeholders of the company. These seniors stakeholders are considered as NPD experts, who based on their experience are able to direct the author to the relevant case studies that may benefit most out of the proposed framework. Therefore, the author intends to conduct one to one semi-structured interviews with NPD experts in order to propose the benefits of the framework and thereafter seek two case studies within the company pertaining to the product and project domains, which may benefit from the proposed failure mode avoidance framework.

The number of NPD experts are selected on the basis of a purposive sampling method because the focus is to obtain knowledge from the individuals that have a particular expertise in the field of New Product Development. As an initial estimate, a sample size of 10 experts is meant to be recruited for this qualitative interview study. This sample size has been determined based on the research from Guest et al. (2006), Saunders et al. (2012), Crouch & McKenzie (2006) and Clarke & Braun (2013). However, the author intends to stop the sampling until the point when saturation of knowledge is reached (Malterud et al., 2016). The sampling may continue in case the researcher continues to learn more with additional insights provided by the participants. Whilst doing this study, it was found that the point of saturation was reached at seven participant.

The inclusion criteria for selecting the participants, who are considered NPD subject matter experts for the study is given under:

- The participants should have worked or are currently working in any New Product Development organisation
- The participants should have at least 15 years of industry experience (Ericsson, 2006).
- The participants should have worked in two or more unique industrial sectors that produce engineered products or uses engineering to make products. These may include two or more of the following:
  - Automotive
  - Aerospace
  - Automation and robotics
  - Railways
  - Semiconductors and electronics
  - Software engineering and technology
  - Pharmaceutical

  - Food
  - Textile
  - Any other engineering industry

- The participants should be in leadership roles that may include managers leading a specific technical stream, head of the department (such as product development, quality and process), engineering directors or consultants.

- Should have served one or more of the following NPD roles:

  - Head of a company (Founder/CEO/Chairman etc.)
  - Board of Directors
  - Project sponsor (who makes all the budgeting decisions for the project)
  - Project leader (who leads the team to deliver a successful NPD project)
  - Project Manager (who co-ordinates day to day activities of the project to achieve stated project's objectives
  - NPD Process Leader (who leads the NPD processes within the organisation)
  - NPD Process Manager (who deals with the NPD processes within the organisation)
  - Product Development Leader (who leads the all Product Development activities on the allocated project)
  - Product Manager (who is responsible for leading the team to deliver the end product)
  - R&D Engineer (who is involved in design, manufacturing, build and/or test activities of the product)
  - Sales and marketing personnel (who is responsible for an effective launch of the product)
  - Finance personnel (who oversees all cost activities related to the product)

- Available and willing to participate in the study.

Based on the inclusion criteria set above, ten participants are identified by the researcher from the company 'X'. The data collection required an approval from Biomedical & Scientific Research Ethics Committee (BSREC) of University of Warwick. The approval is sought before the interviews began. Once the approval is granted, the certificate issuing the permission to conduct the interviews based on questionnaire study is received by the researcher (refer appendix C).

The participant information leaflet (PIL) as well as consent form are prepared as part of approval seeking (refer to appendix D and appendix E). The certificate and participant information leaflet are presented to the selected participants, such that they understand the participation terms before they volunteer to be interviewed. Thereafter, the participants are required to sign the consent form to provide their consent to use the primary information and data they provide.

An email invitation is sent to the selected participants giving them the overview of the interview process, a participant identity number, PIL and the certificate of approval. The participants are strongly suggested to read the terms of the PIL and provide their consent to be part of the study. This should be noted that the participants' identity is known to the researcher during the interviews. Therefore, any personal data (such as name, email address, associated organisation) need to be pseudonymised as quickly as possible after data collection is finished. This is to ensure confidentiality of company's data and any other information associated with the company. Besides, the key that links up the participant identity with the participant ID, which has been prepared by the researcher, is stored securely and confidentially in password protected servers of the University of Warwick. Thus, any personal data that identifies the participant will be initially pseudonymised during the analysis and then fully anonymised at the time of publishing the thesis. This means all direct and indirect identifiers will be removed from the research data and will be replaced with a participant number.

The documents and data collected as part of this study are also held securely in company's servers and any company sensitive information is not disclosed as part of this work. Thus, all company's data is kept confidential and anonymised completely, such that the identity of the company and its data is not revealed in any shape or form. All the identifiers (direct and indirect) are removed from the content of the thesis. These include any reports, names of engineering systems or assemblies, name of the project, pictures or any other company sensitive documentation. In order to present the meaningful data from the company that is deemed relevant for the purposes of this study, language has been changed in some places to reflect the anonymity. All the pictures used to present the engineering design has been redrawn and changed radically to move away from original representations of company-specific engineering drawings.

When participants meet the interviewer (author) face-to-face in the interview sessions, the terms of the PIL are again read to the participants by the author. If the participants still agree, a consent form needs to be signed by the participant as well as the author. The hand-written notes are taken during the interview sessions. Each interview is comprised of a qualitative session, which is based on retrieving the information from the participants about the following:

- Feedback on the proposed framework.
- Risks in the NPD projects they face or may have faced.
- Case studies in the Company 'X' that can benefit from proposed Failure Mode Avoidance framework.

From several case studies pointed by the participants, one case study is chosen in the product domain and the other one in project domain. The chosen case studies from several proposed case studies are a result of convenience sampling. The primary data is collected using primary sources such as NPD experts' opinions, stakeholders' opinions and judgement, discussions with employees, lesson learnt logs, requirement/specification documentations and architectural diagrams. The collection of primary data is made possible due to the opportunity given to the author to work with the employees of company 'X' towards an issue resolution using the proposed framework. The data collected and information gained from company 'X' is considered reliable as it provides confidence in decision-making based on a specific analysis undertaken by the author in order to address specific goals set in the scope of this thesis.

3.2.4 Data analysis: Methods and Validation

A framework analysis using a company's real data is undertaken based on the framework developed in the scope of this thesis. The framework analyses the failure data qualitatively using the concept of taxonomies and quantitatively using the mathematical measures including severity, criticality index and a newly proposed metric in the scope of this work called 'surprisal'. The developed framework is first applied to the chosen company's engineering product. Once it is established that the developed framework works for the product domain, the author looks at the possibility of extending it to the NPD project domain. The extension of the framework to the project domain is conditional to: 1) the validation of it in the product domain, 2) the information available at the time for the chosen project [2]. The qualitative and quantitative analyses are conducted using the framework to minimise the failures for a specific product and an NPD project selected for the purposes of this study. The analysis is undertaken based on following steps:

[2]For example, it may not be possible to apply the framework in case the project is in its late stages such as 'launch' because this is too late in the NPD process and it may be too expensive to treat the failure modes that occurred in the premise stages

- Constructing the problem statement: The author along with the core team members of the product's and project's task force (team of people who are supposed to work together for the issue resolution) respectively constructs the problem statements using the face-to-face meetings. For the application of the framework to the product domain, the core team members comprise of the author, system engineers, design engineers, manufacturing engineers and reliability engineers. The other team members of the task force include a project manager, who cascade the technical information to the rest of the stakeholders in the business, whilst engineers work on the technical issue resolution.

  For the application of framework to the NPD project domain, the second task force comprising of a project manager, a project sponsor, a logistics manager, a launch manager, a legal representative and a procurement lead have been formed by the author. After the task forces are formed, the implementation of framework in product and project domains consists of following steps [3]:

- Presenting symmetry concept to the stakeholders: This activity is led by the author to present the detailed aspects of the theory of symmetry and NPD Failure Mode Avoidance to the team members of the task forces.

- Developing p-diagrams: A workshop is organised by the author to produce p-diagrams for the product as well as project using the knowledge available within the task forces

- Developing the FMEA: This step is led by the author. Based on the understanding gained using the p-diagram, the author intends to sit individually with the design engineers and the project managers respectively to pre-populate some columns of the FMEA. After the one to one meetings, workshops with all the members of the task force are organised by the author. The purpose of the workshop is not only to review the pre-population but also to fill the rest of the columns that requires brainstorming with the members of the task force. Dictated by mathematical formulations of the framework, prioritisation of failure modes is carried out and mitigating actions are undertaken to treat the failure modes.

- Analysis and evaluation of the failures from the FMEA rows using the principles of the Failure Mode Avoidance framework: This analysis is undertaken by the author in conjunction with discussions with the members of the task forces.

[3] This should be noted that the application of framework is sequential, where the application to the product domain is followed by the project domain. The steps to execute the framework in both the domain remain the same.

Multiples iterations of workshops are carried out in order to bring the risk measures (or metrics) including Criticality Index (CI) and Surprisal values down to an acceptable level. The results from the analysis are discussed with the project managers from time to time, such that countermeasures can be implemented as soon as failure modes are created or detected.

3.2.5 Expected applications of the framework

The proposed framework is novel, so the intention is to test its applicability in an already tested domain for validation purposes. Therefore, the proposed framework will be first applied to the product design sub-stage [4] of the NPD project and then to the premise stages of the NPD project. Since the failure mode avoidance approach has already been applied several times in product design domain (refer chapter 2), it is considered as the most-suited domain for the developed framework. The author has high confidence that the framework will not only suit the product design sub-stage of the NPD project but also will yield additional benefits that can not be attained by applying traditional failure mode avoidance approaches.

Once the developed framework has been applied to and validated in the product design sub-stage, the intention is to look at the feasibility of applying the framework to the premise stages of the NPD project in order to avoid and mitigate the failure modes for the holistic NPD process. Again, the author has moderate confidence in applying the framework to the premise stages of the NPD project. The confidence is not high because it may require a cultural shift in applying the novel framework in the context of NPD projects, where the project managers are used to use traditional tools such as risk registers to record risks. Furthermore, to foresee the failure modes for the holistic NPD process early in the premise stages can be a challenging task.

The author envisage that the framework is generic and can be adapted to different applications in order to obtain NPD projects right-first-time. Due to time limitations to carry out this piece of research, it may not be possible to test the framework in every possible situation, which may include: 1) application of framework to a company that does not adopt the Cooper's stage gate model, 2) application to an NPD project that does not produce a non-engineered product such as food, petroleum etc., 3) application of the framework to a different organisation which is similar to Company 'X' in terms of NPD model, product portfolios and project portfolios, but varies significantly in terms of culture, tools, timelines for the projects etc., and 4) the application of the framework in a different industry sector such as finance. Therefore, the confidence on the statement that "the developed framework

[4] Product design sub-stage is the first step of Product development stages of the NPD project

is generic and can be applied to any other situation involving NPD projects" is low.

3.2.6 Dissemination of results

The results of applied Failure Mode Avoidance in engineering design and NPD project case studies have been presented to the members of two task forces from time to time. Besides, the results of the analysis are also presented to the senior stakeholders including the seven participants who the author interviewed before the study began [5].

The data analysis, results and interpretations are undertaken in detail in the scope of this work and will be published as a University of Warwick PhD thesis. The thesis will be available for public use via the University of Warwick Library. The intention is also to present the final findings using research publications such as journals, conference papers etc.

[5] During the interviews, the participants had been initially asked whether or not they will be interested in the research findings. To all those, who are willing to know the research are sent a slide pack demonstrating the impact of the developed framework in Company 'X's product and project.

Chapter 4

Failure Mode Avoidance framework for right-first-time New Product Development projects

Risk Management in NPD projects is an important area of research and there has been an increase in the number articles published in the recent years in the field [Poranaond and Thawesaengskulthai, 2014; Chauhan, 2018]. New Product Development (NPD) is considered as one of the most expensive as well as risky undertakings for the companies [Chin et al., 2009; Salavati et al., 2016; Chauhan et al., 2017]. As also discussed in Chapter 1, managing risks and avoiding failure modes during the NPD process is crucial for increasing the success rates of the product-based companies, such that escaped failure modes that comes as unpleasant surprises in the field can be avoided [Shin et al., 2018; Saxena et al., 2015].

It has been reported that reducing risks or potential failure modes in the NPD process may result in increase in customer value of the product [Browning et al., 2002]. Risks are generally understood as having the negative effects on project objectives due to an error or a failure that occurred during the NPD process [Browning et al., 2002]. However, this should be noted that risks are not always 'negative' and can also have positive effects on the project objectives [Shin et al., 2018; Teller et al., 2014; Ward & Chapman, 2003]. For example, inability to finish a project in an estimated budget and rather finishing it in a lower budget can be attributed to a planning error that occurred during the NPD process. In such a scenario, risk is considered positive, as it effects the project objectives in a positive way. Risk Management in NPD is therefore one of the success drivers for attaining enhancement in NPD performance

[Chauhan, 2018].

Whilst implementing the Failure Mode Avoidance methodology in the product design process, the analysis of failure modes is mainly carried out with the help of a DFMEA that helps to anticipate, identify and evaluate the design related failure modes for the product. This analysis of failure modes is done at the design phases of the NPD process in order to develop robust countermeasures that ensures avoidance and mitigation of failure modes against the noise factors and design mistakes that affects the product [Campean et al., 2013; Nuchpho et al., 2014]. The implementation of Failure Mode Avoidance in the product design process points towards achieving a right-first-time design. Similarly, the application of Failure Mode Avoidance in the manufacturing process points towards achieving a right-first-time manufacturing of the product [Goodland et al., 2013].

All Failure Mode Avoidance frameworks including BEQIC Failure Mode Avoidance framework and Manufacturing Failure Mode Avoidance (MFMA) framework are heavily focused on engineering design and manufacturing processes to achieve a right-first-time philosophy in design and manufacturing respectively in isolation, but lacks a holistic approach to achieve a right-first-time project as an output of the NPD process [Henshall et al., 2017; Goodland et al., 2013]. This chapter aims to address this gap via the development of a generic and analytical Failure Mode Avoidance framework that focuses on avoiding and mitigating the failure modes in the NPD process and achieve a right-first-time project as an output. The proposed framework for demonstrating the Failure Mode Avoidance *philosophy* uses the concepts from 'symmetry'[1], p-diagram and FMEA.

This chapter aims to illustrate the following:

- Understand how failure causes introduces 'asymmetry' in the NPD process to hamper the right-first-time development of new projects and act as fundamental quantity of information in the NPD process.

- Gather various risk factors in the NPD process and categorize them on the basis of risk sources or common root causes. This categorisation of risk factors helps produce a taxonomy for failure causes, which later supports the identification of failure modes in a systematic way.

- Develop a generic and analytical framework enabling the Failure Mode Avoidance approach in NPD projects.

[1]Symmetry is in-variance under transformation [Glattfelder, 2019].

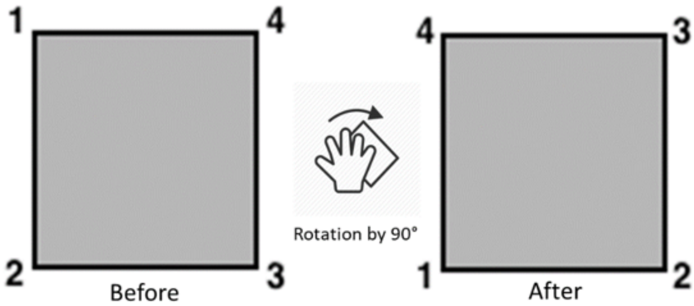


Figure 4.1: Symmetry for a rotation

4.1 Symmetry and asymmetry in the NPD process

4.1.1 The symmetry concept in NPD

According to the scientific definition of symmetry, “things look the same after a sequence of operations as they did before – the end result is the same as the starting point” [Weyl, 1928; Weyl, 2019]. Mathematically, a ’symmetry’ can be defined as “invariance under transformation”, which suggests that things look the same even after a change has been carried out with them [Glattfelder, 2019]. For example, if you rotate a square by 90 degrees, the end result is still the same – a square. In this case, a square has the symmetry in its shape, which means it’s geometry remains invariant even after a change, i.e. rotation by 90 degrees, has been performed (refer figure 4.1).

In the context of this work, the symmetry principle has been used as an analogy to demonstrate the ideal state of an NPD project. Hence, for achieving a right-first-time NPD project, the NPD functions [2] should remain invariant under the changes caused by the NPD process to the project. Therefore, in an ideal state the NPD project at the start of the NPD process should look exactly the same as the NPD project achieved at the end of the process. This symmetry concept in the context of an NPD project is shown in figure 4.2. If the symmetry in the NPD process is achieved first time the NPD process is executed, it is referred to as right-first-time project achievement in the scope of this work.

In order to attain a symmetry in the NPD process, the expected offerings of the NPD project should represent the actual offerings achieved by the end project (refer figure 4.3). In other words, the goal is to attain invariance of NPD functions under translation from ideation to launch. This argument suggests that the conservation law in the NPD process is related to conserving the NPD functions throughout the

[2]In the scope of this work, the NPD functions refer to the objectives of an NPD project or the business requirements set for the project in terms of cost, product’s quality and time. Thus, an NPD project is dictated by a project triangle comprising of cost, quality and time parameters.

Figure 4.2: Symmetry for an NPD project

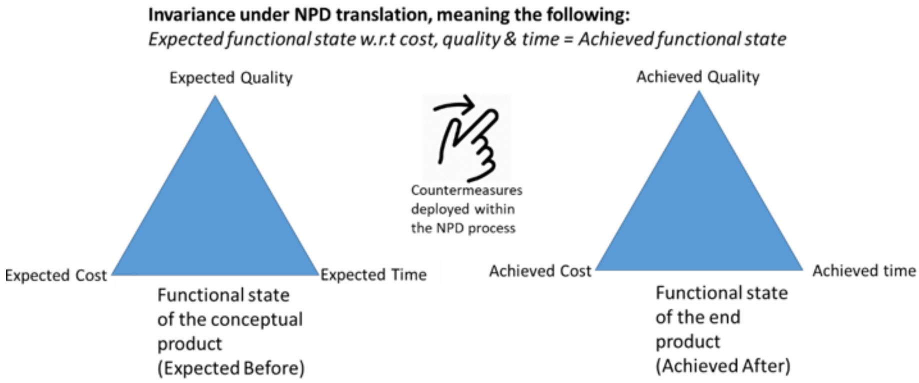


Figure 4.3: Proposed Symmetry for an NPD project

process. However in reality, the changes in the NPD process occur as a result of implementing the countermeasures that are used treat the failure modes[3] as and when they inevitably occur in the NPD process.

According to Noether [1971], the consequence of symmetry is a conservation law that defines a fundamental quantity. In other words, the symmetry principle is governed by a conservation law, meaning there should exist a fundamental quantity that remains conserved no matter what changes occur. For example, the symmetry principle relating to invariance w.r.t. time translation defines conservation of energy. Similarly, invariance w.r.t rotation defines conservation of angular momentum. In a chemical process, the fundamental quantity is the electrons as they remains conserved throughout a chemical process. These fundamental quantities such as energy, momentum and electrons in the sciences have been identified many years ago [Bluman et al., 2006, Pitts, 2019], however the fundamental quantity that remains conserved through out the NPD process is still unknown. Thus, the fundamental quantity in the NPD process needs to be explored. However, before exploring the

[3]Failure modes are various ways that deviates the project from its defined functions or functional state.

Figure 4.4: NPD pentagon

conservation law in the NPD process and identifying a fundamental quantity ensuring symmetry for the NPD projects, there is a need to develop a detailed understanding of the terms 'NPD functions' and 'NPD failure modes' used in the context of this work.

4.2 The NPD functions and NPD failure modes

The primary NPD function of an NPD project is to fulfill the set objectives of the NPD project triangle viz. cost, product's quality and time. Rose [2012] proposed five dimensions to NPD objectives instead of the three defined by the project triangle. Thus, they proposed an NPD pentagon, which can be understood as an extension of project's triangle, where 'quality' dimension has been replaced with 'features', time with 'schedule' and the cost dimension split into three costs, viz. 'development cost', 'product cost' and 'capital equipment cost' (refer figure 4.4 below). This should be noted that the 'feature' dimension as quoted by Eric P. Rose is just one of the many sub-dimensions of the bigger term 'quality' [Garvin, 1984; Zhu et al., 2018]. Therefore, an NPD pentagon needs some further extension to encapsulate all dimensions of 'quality' rather than just 'features'.

The term 'quality' exist in the literature from 1920s and has been applied in various sectors including engineering, education, healthcare, pharmaceuticals, fitness industry etc. over the years [Kemerling, 2015; Lewis, 2017; Nanda, 2016; Ah-Teck, 2011; Lim, 2018; Dailey, 2018; Parry, 2014; Talib et al., 2016; Polyakova; 2016]. Since the scope of this work is the right-first-time development of NPD projects that delivers engineered products, the term 'quality' is picked up from the vocabulary used in engineering and technology. According to Garvin [1984], the term 'quality'

Sub-dimension	Definition
Development cost	These are the cost incurred by the company to develop the product which includes labor costs, prototype parts cost, prototype manufacturing costs, testing costs etc.
Capital Equipment cost	These are the one-time fixed costs incurred by the company to setup the equipment for mass manufacturing of the product.
Product cost	These are the bill of material costs, as well as the operational costs required to keep the product running in the field.

Table 4.1: Three Sub-dimensions of cost. Source: adapted from Rose [2012]

is related to the product quality that has eight dimensions including performance, features, reliability, conformance, durability, serviceability, aesthetics and perceived quality. Zhu et al. [2018] extended the list of Garvin's eight distinct dimensions of quality to nine (refer table 4.2). The ninth quality dimension added by Zhu et al. [2018] is 'safety'.

Based on NPD pentagon, it can be observed that the cost dimension of project triangle has been split into 3 further sub-dimensions, i.e. development cost, capital equipment cost and product cost, each of which has been discussed in table 4.1.

Based on Garvin [1984] and Zhu et al. [2018], it can be noted that the quality dimension of the project triangle can be split into nine further sub-dimensions, i.e. performance, features, reliability, conformance, durability, serviceability, aesthetics, safety and perceived quality, each of which has been discussed in table 4.2.

Based on the above discussion, it should be noted that the cost dimension on the NPD project triangle can split further into 3 sub-dimensions discussed by Rose [2012] and the quality dimension can be split into 9 sub-dimensions dictated by Garvin [1984] and Zhu et al. [2018]. Thus, an extension to the NPD project triangle is proposed, which is referred to as 1:3:9 Time-Cost-Quality triangle and abbreviated as 139TCQ triangle in the scope of this work. The 139TCQ triangle has been shown in figure 4.5 below.

From an organizational perspective, the business requirements must be written at the start of the NPD project to describe the NPD functions. These requirements are usually related to one or more sub-dimensions of the 139TCQ triangle. Thus, the NPD functions denotes the ability of an NPD project to meet one or more stated dimensions of the 139TCQ triangle. On the contrary, product's inability to meet any dimension on the 139TCQ triangle is referred to as 'NPD failure mode' in the scope of this work. In other words, an NPD failure mode can be defined as any condition

	Dimension	Definition
1	Performance	A product's primary characteristics
2	Features	The "bells or whistles," a product's secondary characteristics that supplement its primary functioning
3	Reliability	The probability of a product malfunctioning or failing within a specified time period
4	Conformance	The degree to which a product's design and operating characteristics meet established standards
5	Durability	The life of a product or the amount of use a customer gets from a product before it deteriorates or must be replaced
6	Serviceability	The speed, courtesy, competence, and ease of repair
7	Aesthetics	How a product looks, feels, sounds, tastes, or smells
8	Perceived	The image, reputation, brand names, or other inferences of a product's attributes
9	*Safety*	*Freedom from unacceptable risk of injury or damage to health of users and damage to property or environment involved in the use of the product*

Table 4.2: Nine sub-dimensions of quality. Source: Zhu et al. [2018]

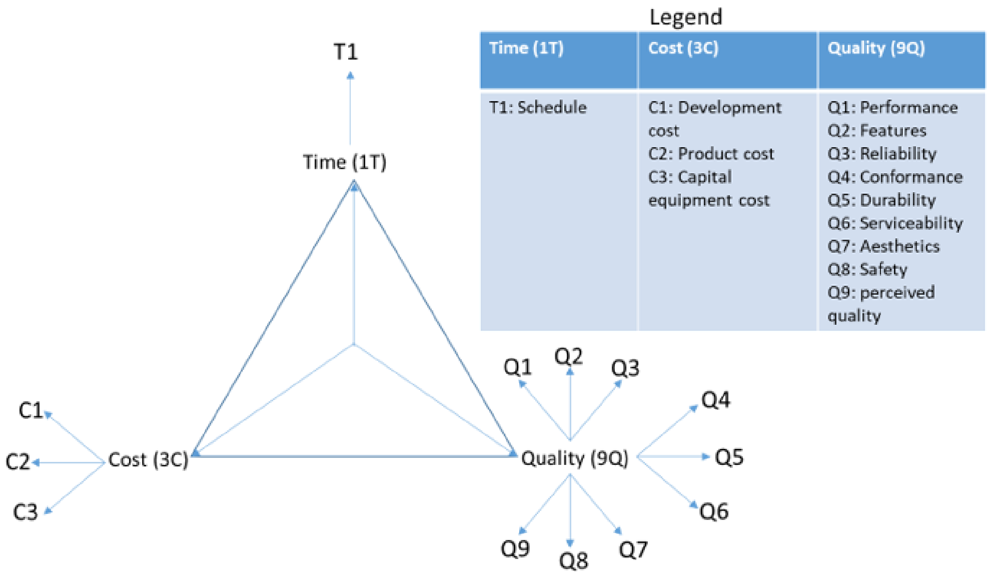


Figure 4.5: NPD project triangle or 139TCQ triangle. Source: Author

Business requirement (or NPD function)	Related dimension on 139TCQ triangle	Related sub-dimension on 139TCQ triangle	Failure Mode
The product AGV SHALL have a reliability of 95% at 1000 hours of operation.	Quality	Reliability	Failure in achieving desired features and functionalities of the product
The AGV SHALL be delivered to the customers in May 2020.	Time	Schedule	failure in finishing the NPD project on schedule
The AGV cost SHALL be no more than £15,550.	Cost	Product cost	Failure in completing the project in budgeted product cost etc.
The AGV SHALL maintain a cost of ownership of no more than £175 per month per unit.	Cost	Product cost	Failure in completing the project in budgeted product cost etc.

Table 4.3: Example illustrating failure modes derived from 139TCQ taxonomy

or state that affects the NPD functions or business requirements in a negative way. The NPD functions and associated failure mode for an exemplar Automated Guided Vehicle (AGV) project are shown in table 4.3 below.

Now that we understand the definitions of 'NPD function' and 'NPD failure mode', let us explore the conservation law and fundamental quantity when dealing with symmetry in the NPD process.

4.3 Fundamental quantity and conservation law

The possession of knowledge for all the possible failure modes at the start of the NPD process is critical to develop countermeasures, such that the failure modes can be either be avoided early before the failure modes are created or mitigated as soon as they are created in the process. The countermeasure deployment helps the project to maintain its functional state[4] and achieve symmetry in the NPD process. This should be noted though that a 100% deployment of countermeasures is only possible if the number of failure modes related to the product are fully known ideally at the beginning of the process, such that most failure modes can be avoided at the beginning of the process and rest mitigated via the controls built into the project.

Since the set of NPD functions should be finite, the set of failure modes should also be finite. This is due to Ford's taxonomy for failure modes that suggests that for each function, there are only maximum of five types of failure modes possible. These include: 1) no function, 2) partial function, 3) degraded function, 4) intermittent function, and 5) unintended function. The information about the

[4]Functional state of the product refers to the achieving all stated NPD functions.

finite set of failure modes, if available at the beginning of the NPD process helps developers/manufacturers plan out countermeasures that treat the failure modes and maintain functional state of the product as soon as measures are deployed. This suggests that the knowledge of failure modes helps maintain symmetry via the countermeasure implementation and keeping NPD functions invariant under changes caused by the countermeasures in the NPD project.

From the above discussion, it seems that the failure modes are the fundamental quantity of information in the NPD process. However, author believes that the failure causes are more fundamental than the failure modes. It is because, in reality, countermeasures can only be developed if causes of failure are known. Therefore, in order to develop countermeasures that eliminate the NPD failure modes completely, there is a need to identify failure causes that leads to failure modes and affects NPD functionality. The one to one relationship between failure causes and deployed countermeasures is shown in figure 4.6 below.

The figure 4.6[5] below also depicts that each function of the NPD project is associated with several failure modes, which results into the failure effects. Besides, each failure mode has one or many underlying causes, elimination of each of which using countermeasures means maintaining the functional state of the NPD project.

The failure causes are either the mistakes made in the NPD process at the project level or the external risk factors that leads to a failure. Either way, the failure causes leads to the failure modes, which further results in the failure effects (refer figure 4.7). Acquiring knowledge about failure causes (or root causes) is fundamental to develop countermeasures that treats the failure modes and maintains the symmetry in the NPD process. In an ideal state scenario, a complete elimination or avoidance of failure causes via the implementation of countermeasures maintains the full functional state of the NPD project, resulting into no deviation on the 139TCQ triangle and symmetry in the NPD process.

The conservation law states that some quantity (or the fundamental quantity) remains constant through a change or series of changes. Therefore, the fundamental quantity relating to symmetry in the NPD process should also remain constant throughout the process. Since we discussed that the fundamental quantity is the set of failure causes, the number of failure causes should remain constant throughout the NPD process, which means that a total of all independent failure causes relating to an NPD project are fixed. The fixed and the constant nature of the set of independent failure causes throughout the NPD process highlights the fact that although difficult, it should be ideally possible to identify all potential failure causes early at the premise

[5]The assumption is that all the failure causes are independent to each other. The compounded failure causes are not included for simplicity purposes. Besides, it is assumed that the countermeasure deployment does not result in any side-effect, which creates a new list of failure causes

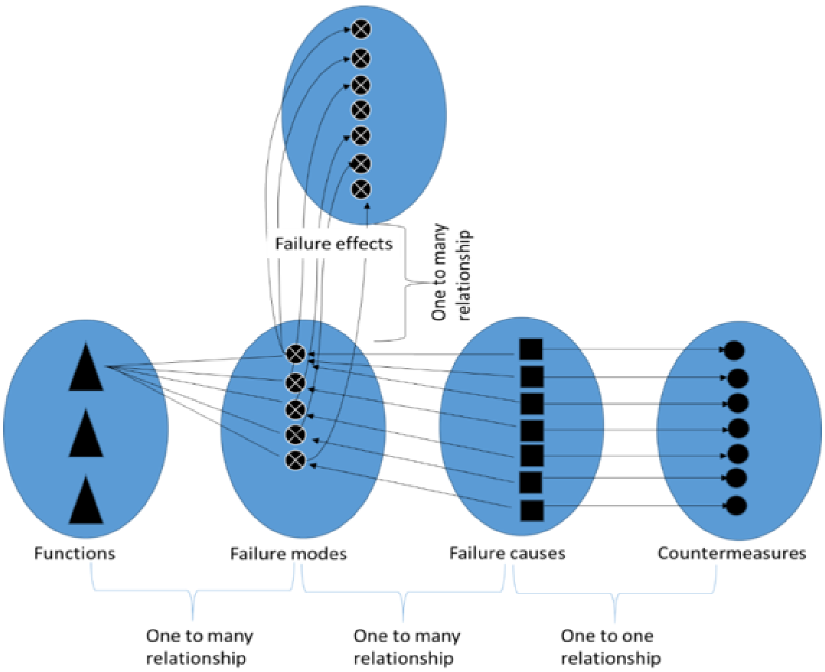


Figure 4.6: The relationship between causes, modes and effects (a)

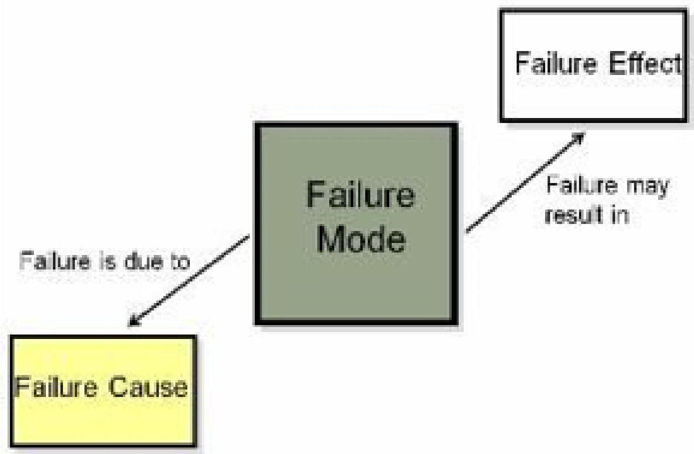


Figure 4.7: The relationship between Failure cause, mode and effects (b)

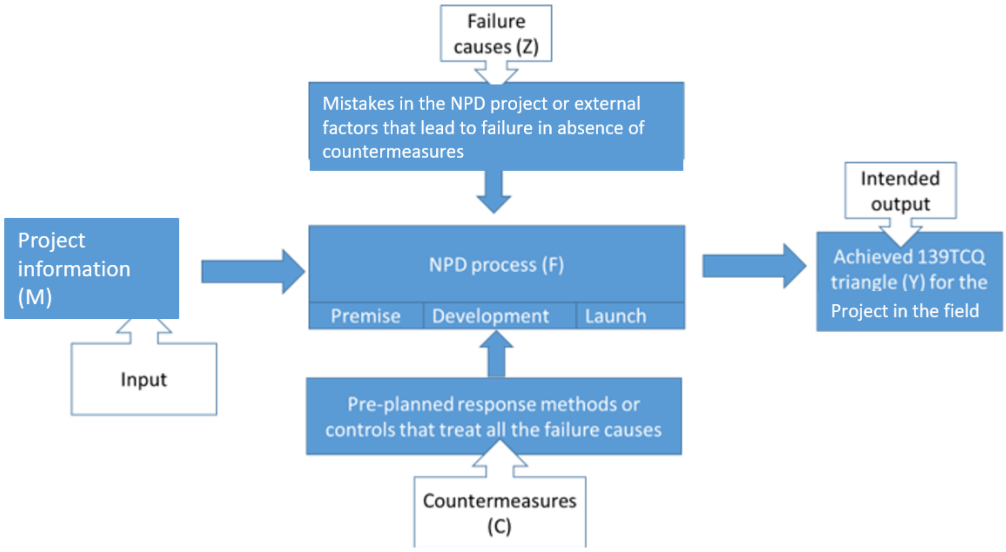


Figure 4.8: The p-diagram depicting symmetry in the NPD process

stages of the NPD project.

Identifying and attaining knowledge of all potential failure causes relating to an NPD project even before the failure modes are created at each NPD stage of the project can help the project managers make provisions and contingencies in the project, such that potential failure causes can either be avoided by changing the strategy at the very start (during premise phase) or mitigated with effective pre-planned countermeasures as soon as they are created in various stages of the project. In an ideal state, each failure cause has a corresponding response method or a control factor or a countermeasure, even before the development kicks off.

The figure 4.8 illustrates a p-diagram[6] to demonstrate the achievement of intended output 'Y' using an input 'M' and the transfer function 'F'. The input 'M' is related to any information available for the NPD project during the premise phase. These may include project charters, business requirements etc. The output 'Y' represents the achievement of 139TCQ triangle after the information about the project (M) is processed via the NPD process transfer function (F), where Y = F (M). However, the process function 'F' is affected by the interaction between the failure causes (Z) and countermeasures (C). Therefore 'F' is a function (f) of 'C' and 'Z'. Thus the following equation applies for an NPD process. $Y = f(M, C, Z)$

In an ideal state of symmetry in NPD process, when the failure causes are treated with pre-planned countermeasures, the difference 'Δ' between output 'Y' and input 'M' is zero [Enoch and Shuaib; 2015]. In order to observe delta 'Δ' equal to zero,

[6] The p-diagrams found so far in the existing studies has been used by researchers and practitioners in the context of product engineering and has not been adapted in the holistic context of NPD projects [Enoch et al., 2015; Haughey, 2019].

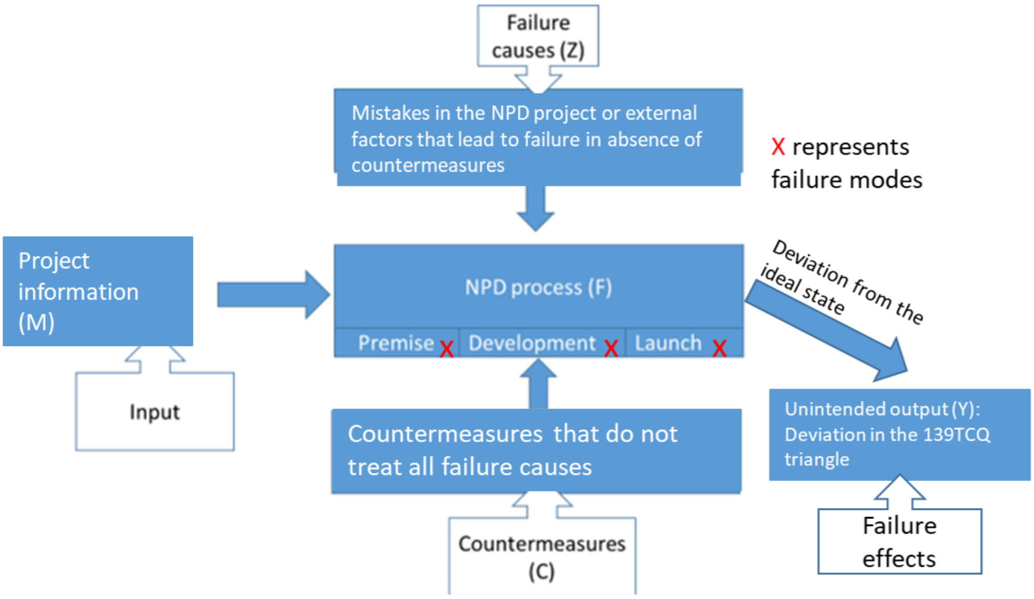


Figure 4.9: The asymmetry in the NPD process

the countermeasures should fully respond to the failure causes, such that no failure modes are observed in any stage of the NPD process. When the countermeasures can not treat the failure causes, the output 'Y' can not be achieved and failure states are observed. In other words, the inability to identify failure causes and treat them with fully effective countermeasures results in asymmetry in the NPD process. The asymmetry concept in the NPD process is discussed in detail below.

4.3.1 The asymmetry concept in NPD

In the scenario when the failure causes does not have a countermeasure associated with them and/or the countermeasure is not effective enough to treat them fully, they deviate the NPD project from their functional state and result in failure modes that causes the asymmetry in the NPD process. The asymmetry in the NPD process is shown in figure 4.9.

The asymmetry in the NPD process is a result of failure modes that goes untreated from one project stage to the other and then ultimately to the field. In case of asymmetry the delta 'Δ' is non-zero because of the imbalance that exists between two parameters viz. 'C' and 'Z', meaning that the available countermeasures are unable to treat all possible failure causes. In the worst case of asymmetry in the NPD process, none of the countermeasures can be planned proactively at the premise phases of the project and the output is affected due to one or more following reasons.

- The potential causes are not known at premise due to inability to foresee them in the information stages of the project. In this case, following two scenarios can happen.
  - The prevention controls are not implemented to treat the failure causes and failure modes go undetected through the NPD process only to be observed naturally in the field by the customers. This situation is deemed to be the mostly costly endeavor for the companies due to the rule-of-ten illustrated in figure 1.12 of chapter 1.
  - The non-identified failure causes are naturally detected later during the product development and launch stages of the NPD process. This situation leads to a decreased latitude of implementing countermeasures and none or ineffective countermeasures are undertaken at those stages. Both of these situations results in failures escaping into the field because the ineffective countermeasures does not fully treat the failure causes.
- The potential failure causes are known at premise but no or ineffective prevention control methods are implemented due to project team's inability to deal with them. In the scope of this work, this situation will be referred to as "mistakes".
- The potential failure causes are known but their existence is questioned as the project team is unsure whether or not the identified failure causes are really going to be happen. In such a situation, the countermeasures are not deployed until the failure causes are verified with the help of detection controls that are built into the process to excite and uncover the failure causes. The potential failure causes that needs to be verified using a detection control is referred to as "unverified risks" in the scope of this work. For unverified risks, following conditions arise.
  - The detection controls are applied too late, but are effective enough to excite the failure modes. This leads to a costly scenario of implementing countermeasures in the later stages of the project. In such a case, the countermeasure implementation is too expensive for the companies, thus latitude to implement all of them decreases, as a result failure modes may escape into the field.
  - The detection controls are applied as soon as failure modes are created but are not effective enough to excite and verify the failure mode, leading to "undetected" failure modes escaping into the field.

The escaped failure modes from the NPD process result in an unintended output observed in the field in the form of NPD failure modes. To establish a distinction between failure causes, modes and effects, following terminology has been proposed in the context of NPD project.

Failure causes: Refers to mistakes or external risk factors that leads to a failure mode.

Failure Modes: Refers to the loss of a function. A 'function' is defined as the intent or purpose of a specific project stage.

Failure Effects: Refers to the consequences of the failure modes on the intended output of the project expressed in terms of 139TCQ triangle. In the context of this work, the term 'failure effect' has been used interchangeably with the terms 'NPD failure mode' and 'unintended output'.

The flowchart illustrating the pathways to an unintended output is shown in figure 4.10. This flowchart presents an exhaustive list of pathways through which a potential failure cause of the NPD project may propagate to the end of the NPD process to create asymmetry. The result of this asymmetry is the unintended output that can be expressed in terms of observed deviation on the 139TCQ triangle from the originally envisaged targets that are usually set with the help of business requirements.

Based on the above discussion, it can be noted that the identification of the potential failure causes at the information stages (or premise) is the key to develop preventative countermeasures (or prevention controls). Therefore, there a need to develop a systematic method that helps NPD project managers to identify the potential failure causes early in the information stages of the NPD process and develop countermeasures for the same, such that a symmetry in the NPD process is achieved.

The methodology for systematically identifying and preventing the failure causes using the countermeasures early in the premise stages of the NPD project in order to minimize an effect on the intended output is termed as Failure Mode Avoidance. The framework for Failure Mode Avoidance for the NPD process is presented in the section below.

4.4 The basis for the NPD Failure Mode Avoidance framework

The holistic NPD Failure Mode Avoidance framework for preventing failure modes in the NPD process utilizes the best practices from the widely known FMEA tool, whilst also eliminating the structural problems of the FMEA as discussed in chapter

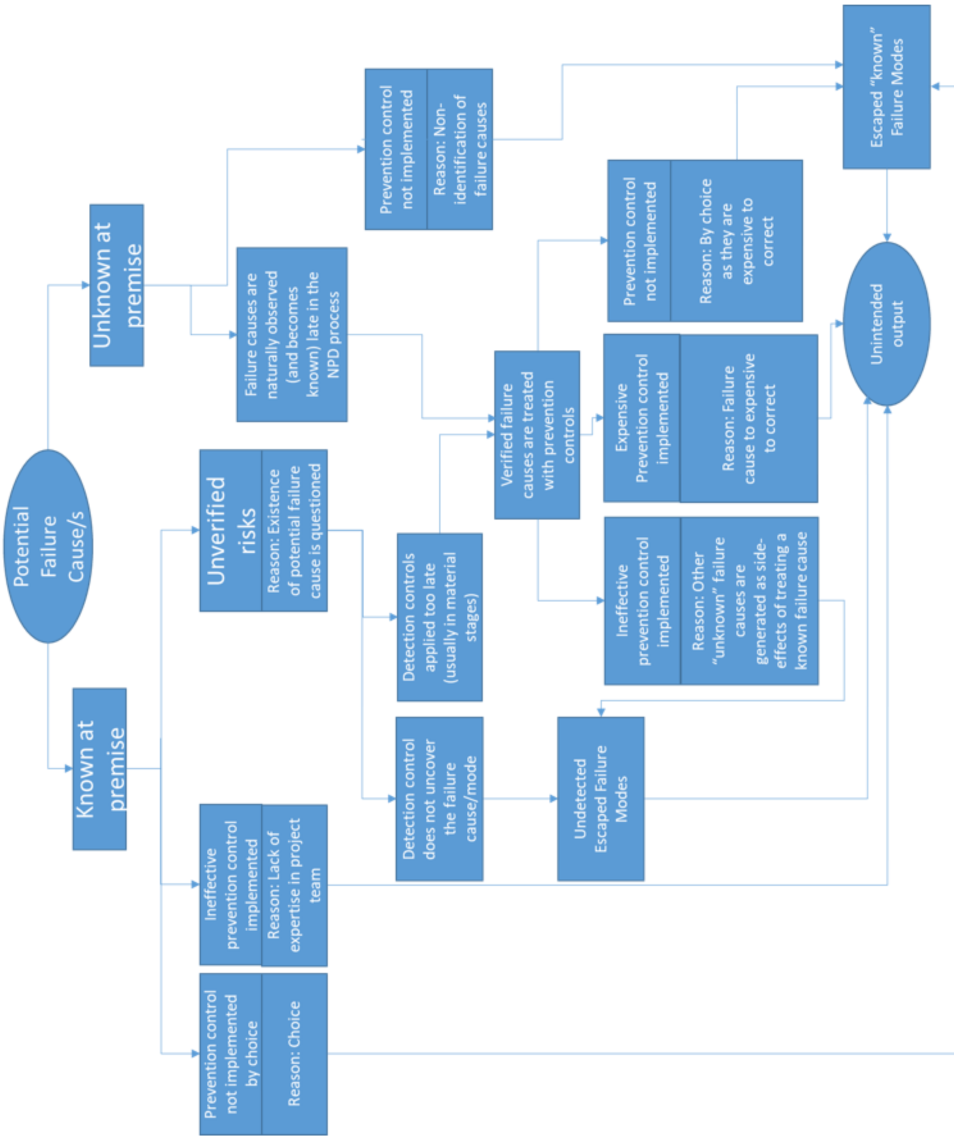


Figure 4.10: Pathways of failure causes

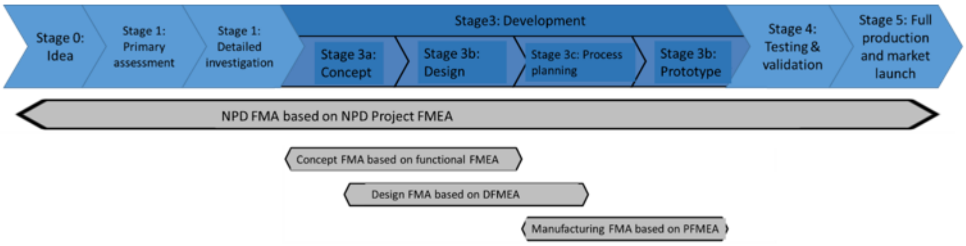


Figure 4.11: Failure Mode Avoidance can be applied at any level using the FMEA tool

2. The proposed framework is generic, systematic and analytical that can be used by the project managers during the premise stages of the project through to the launch, in order to achieve a minimal asymmetry in the NPD process. The proposed framework is considered generic as the principles can be applied to any stage or sub-stage of the NPD project. This generic application of the proposed framework is shown in Figure 4.11.

The figure 4.11 suggests that the proposed framework can be applied to any stage or sub-stage of the NPD project to yield benefits. Whilst the NPD Failure Mode Avoidance aims to deliver a right-first-time project, the 'design' Failure Mode Avoidance aims to produce a right-first-time design. The Failure Mode avoidance principles can also be applied to concept and manufacturing stages of product development to achieve a right-first-time concept and manufacturing respectively. Thus, whilst adopting the Failure Mode Avoidance approach, the context in which the framework is applied needs to be understood. For example, the context of this chapter is the NPD Failure Mode Avoidance in order to produce right-first-time NPD projects.

The NPD Failure Mode Avoidance is a pragmatic risk management approach that aims to prevent failure modes via the avoidance and mitigation strategies applied in the early information phases of the NPD process. These strategies aims to systematically treat most of the potential failure causes in the NPD process to an extent that a minimal level of deviation on the NPD project's output (i.e. on the 139TCQ triangle) is observed and until an acceptable level of risk is achieved.

A typical risk management framework comprise of four main stages: 1) identification, 2) analysis, 3) evaluation and 4) treatment [BS ISO 31000, 2018]. In the context of Failure Mode Avoidance, the risk 'treatment' stage should be thought as the failure 'prevention' stage, whereby the focus is to deploy prevention controls that eliminate or reduce the risk of potential failure modes. Therefore, the NPD Failure Mode Avoidance framework proposed in the scope of this work is based on following stages:

- *Failure Identification:* Focuses on identifying the failure modes, causes and effects using the concept of taxonomies. The taxonomies help the NPD project managers identify failure events (pertaining to causes, modes and effects) in a systematic manner. A failure event refers to the complete sequence where a failure cause initiates a 'mode' that further leads to an 'effect'.

- *Failure Analysis:* Focuses on analyzing each failure event quantitatively using the 'severity', 'occurrence' and 'detection' scores adopted from the traditional FMEAs [IEC 60812, 2018].

- *Failure Evaluation:* Focuses on evaluating each individual failure event using the 'criticality index' the 'surprisal' values (discussed later) and thereafter prioritising the most critical failure that require countermeasures.

- *Failure Cause Treatment:* Focuses on preventing the prioritised failure events using avoidance and mitigation strategies (referred to as prevention controls[7] in the scope of this work).

To summarise the above discussion, the proposed NPD Failure Mode Avoidance framework is analytical in nature that aims to systematically identify, evaluate and treat potential failure modes via the use of the following qualitative and quantitative techniques:

- Taxonomies for failure identification: The taxonomy for failure causes in NPD projects has been proposed in this chapter.

- The occurrence, detection and severity scores for failure analysis: These terminologies have been adopted from the traditional FMEAs, however a new scale for assessing the severity of a failure event in the context of NPD projects has been proposed.

- The usage of 'criticality index' and 'surprisal' values for failure evaluation: Unlike the usage of traditional RPN values in the FMEAs to prioritise the failure modes, a new method that uses the two indices viz. criticality and surprisal has been proposed.

- The use of prevention and early detection control methods for preventing the failure modes to progress in the next stages of NPD process: These are identified and implemented by the people involved in the project.

[7]The prevention controls are the countermeasures via which the failure causes are treated using the avoidance or mitigation strategies. The avoidance techniques involve eliminating the failure cause completely, whereas the mitigation techniques involve reducing the risk associated with failure by reducing the chances of failure cause from occurring.

This next section illustrates how the adoption of the NPD framework based on four stages viz. failure identification, analysis, evaluation and prevention.

4.4.1 Failure Identification

The steps for a complete failure identification include:

- Identify process steps within the NPD project.
- Identify the function of each process step using the objectives set by NPD practitioners (project managers and project sponsors) for each stage.
- Identify the failure modes associated with each function using the failure mode taxonomy.
- Identify the failure causes associated with each failure mode using the failure cause taxonomy.
- Identify the failure effect associated with each failure mode using the judgements of the project team to illustrate the impact of failure mode on the 139TCQ triangle.

The starting point for failure identification is to identify the function of the process step [Burge 2018]. Therefore, for any given NPD project, a clear list of objectives or functions for each stage should be defined, such that related failure modes, causes and effects can be identified. For example, an organization that adopts Cooper[1990] model may set the following objectives for each stage of NPD process.

Note that the function of each process step is different that the NPD functions as discussed in table 4.4. The NPD function is a high level function that is achieved via the fulfillment of process step functions. Based on the functions of each stage, the failure modes should be written based on the Ford's failure mode taxonomy discussed earlier. The taxonomy for the failure modes helps project managers think systematically to identify several potential failure modes in a systematic manner. The failure modes are specific to each NPD project based on process step functions, unlike the NPD functions that are usually generic for all NPD projects within an organization.

After the failure modes are derived using the taxonomy, they need to be associated with corresponding failure causes and effects. This should be noted that each failure mode can have multiple causes and multiple effects.

The effects of failures can be determined by asking questions to the project team such as – "what effect the failure mode will have on the project's 139TCQ triangle?" or "will the failure mode affect product quality? If yes, which dimension

Stage#	Process step	Objective/function
0	Idea	• To generate an idea for a product that potentially addresses a customer need • To align the product intent with overall corporate strategy
1	Primary assessment	• To assess the market • To write the business requirements • To assess the financials for the proposed product • To assess the technology that may be used for the development of the new product
2	Detailed investigation	• To assess the competitors • To define value proposition
3	Development	• To finalize a suitable design that gives appropriate levels of functions and reliability • To develop a prototype • To test the prototype
4	Testing and validation	• To test the product using customer field trials • To conduct market testing • To plan the launch
5	Full production & Market launch	• To mass-produce in order to meet the demands of the customers • To sell at a given price • To launch a finished product to the market • To provide post-launch support to the customers

Table 4.4: Failure Modes in the NPD process

will be affected?" By answering such question, a description of failure effect can be provided.

The identification of associated failure causes is crucial as they act as the fundamental quantity of information in the NPD process. In an ideal scenario, all potential failure causes should be identified and avoided in the early premise stages of the NPD process to achieve a symmetry in the NPD process. However, in a practical sense, it is difficult to identify all failure causes due to challenges presented in appendix B.

Despite the challenges in identifying potential failure causes, it may be possible to attain a list of most, if not all, potential failure causes that can be systematically identified at the start of the NPD process by the project managers working in conjunction with other members of the project team. Therefore, a taxonomy for NPD failure causes is needed to help the project team systematically identify the causes of failures affecting NPD project.

In order to produce a taxonomy for NPD failure causes, studies including Thauser [2017], Mansor [2016], Cooper [2003], Keizer & Vos [2003], Alrabghi et al. [2016], Coppendale [1995], Kim and Choi [2011] and Mansor et al. [2016] have been undertaken to establish a categorization of several NPD risk factors. It has been found that the risk factors identified based on these studies do not make a clear distinction between failure causes and failure modes, therefore the risk factors from these studies have been categorized into several categories shown below in table 4.5.

The table 4.5 classifies risk factors into two main categories viz. extrinsic and intrinsic. The intrinsic risks are the potential failure causes or modes that originate within an organization, whilst extrinsic risks are the ones that originate outside the NPD organization yet affects the NPD functions to induce asymmetry. The two types of risks has been further sub-categorized into groups based on the source of risk and reasons for risk. Both types of failure causes viz. extrinsic and intrinsic, affects the functions of the NPD process and gives rise to failure modes that further affects the output on 139TCQ triangle. Therefore, a relationship can be established between failure causes, failure modes and failure effects that has been presented in figure 4.12. It can be noted from table 4.5 that the three failure categories viz. failure in premise, failure in development and failure in launch (discussed in chapter 1) will inherently be covered when project managers attempts to prepare a list of failure modes and causes as per the figure shown in figure 4.12.

The presented taxonomy of failure causes can help the project manager identify potential failure causes in a systematic way. The usage of the taxonomies will be illustrated with the help of a real-life case study in the chapter 5. The identified list of failure events can be documented in a table format such as the one

Type	Group	Associated failure causes
Extrinsic risk	External factors	• Intellectual property or legal risk • Economic risk • Natural risk • Social risk • Technology risk • Competition risk • Financial unpredictability • Political risk • Changing customer needs
Intrinsic risk	Mistake in Strategic management	• No/poor product/s strategy • Leadership and cultural risk • Resource planning risk (recruiting right people, choosing right people for the team) • People development risk • Providing insufficient support to projects • Inability to cope up with environmental risks • Finance risk
Intrinsic risk	Mistake in Project Management	• Schedule risk • Resource planning risk • Communication risk • Process implementation risk • Budget risk • Control risk • Project structure risk
Intrinsic risk	Mistake by Project Team	• Lack of understanding of requirements
Intrinsic risk	Failure in Launch	• Logistic/ • transportation risk • Marketing risk
Intrinsic risk	Failure in development	• Systems engineering risk • Design risk • Manufacturing/build risk • Procurement risk • Testing risk • Compliance risk
Intrinsic risk	Failure in premise	• Misunderstanding customer requirements

Table 4.5: Categorization of risk factors into various failure categories

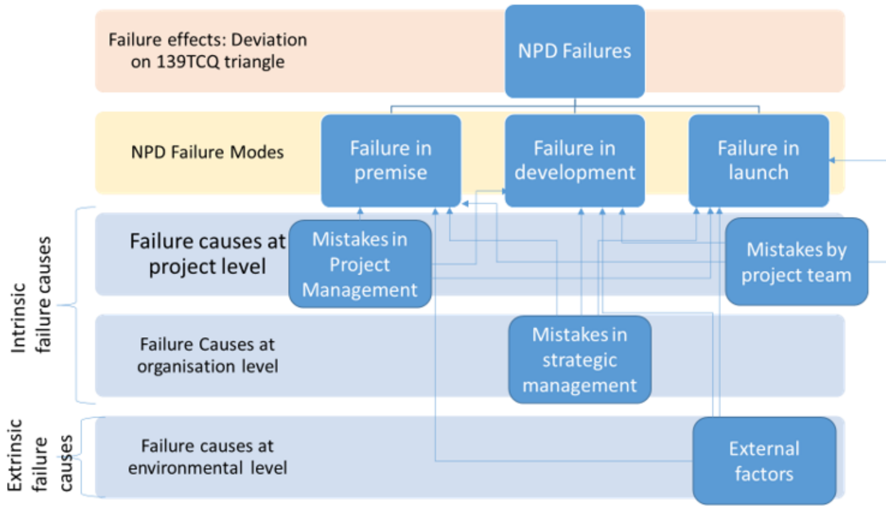


Figure 4.12: Taxonomy of failure proposed by author

shown in figure 4.13. Note that the maximum number of rows in the table are equal to the total number of failure causes identified for the set of failure modes. For the purposes of documenting the identified potential failures, the tabular format from the FMEA tool are proven to be useful. However, a "new" FMEA template has been proposed in the scope of this chapter.

The relevant team members of the project team should be called by the project manager in several workshops or meetings to identify and document potential failure events in the NPD project. The facilitation should be done by the project manager such that they can ensure that the proposed taxonomies are adopted during the identification process. The following spreadsheet[8] shown in figure 4.14 can be used by the project managers to systematically document all potential failure modes in a FMEA table format. To enable the project team to think of all potential failures in a systematic manner, a simple drop-down choice can be embedded into the spreadsheet such as the ones shown in figure 4.14.

A pictorial representation of identified failure events using the concept of taxonomies is given in figure 4.15, which also illustrates the relationship between functions, failure modes, causes and effects. For example, in figure 4.15, a function F1 for stage1 of an NPD process has 3 types of failure modes viz. FM1, FM2 and FM3. The failure mode FM1 has three associated failure causes FC1, FC2 and FC3, pertaining to two types of failure causes viz. external factors and mistakes in strategic management. Besides, FM1 has two separate failure effects FE1 and FE2,

[8]In the template, the taxonomies for failures have been embedded within the drop down menus. The proposed taxonomies used in the scope of this work have been shown, however project manager can choose to use a different taxonomy, in which case, the template should be adapted.

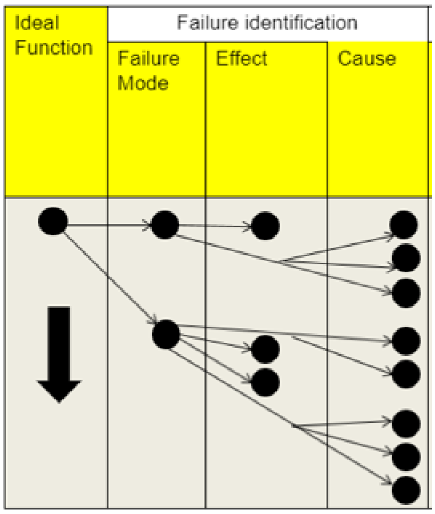


Figure 4.13: Failures represented in a table like format that later becomes the FMEA

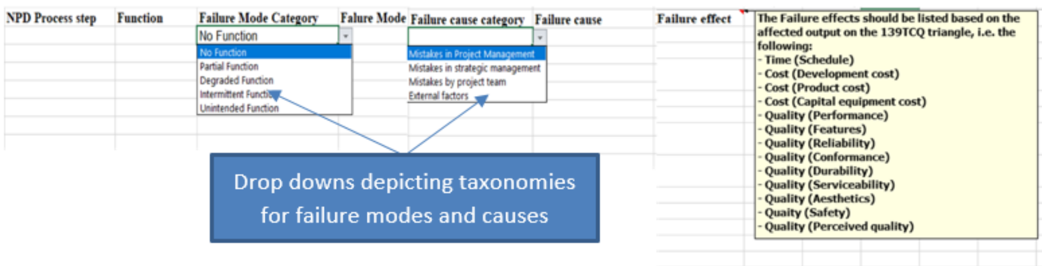
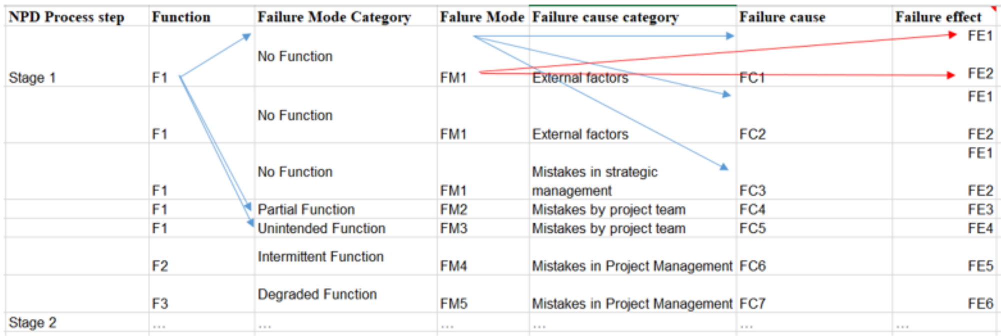


Figure 4.14: NPD FMEA development using drop-down



NPD Process step	Function	Failure Mode Category	Falure Mode	Failure cause category	Failure cause	Failure effect
Stage 1	F1	No Function	FM1	External factors	FC1	FE1 FE2
	F1	No Function	FM1	External factors	FC2	FE1 FE2
	F1	No Function	FM1	Mistakes in strategic management	FC3	FE1 FE2
	F1	Partial Function	FM2	Mistakes by project team	FC4	FE3
	F1	Unintended Function	FM3	Mistakes by project team	FC5	FE4
	F2	Intermittent Function	FM4	Mistakes in Project Management	FC6	FE5
	F3	Degraded Function	FM5	Mistakes in Project Management	FC7	FE6
Stage 2	...	...	...	...	...	...

Figure 4.15: NPD FMEA development

which are documented in the single cell. This is because the number of rows in the illustrated table should be driven by the number of failure causes as discussed earlier.

After the identification of failure events is complete, the columns related to the categories can be hidden to reveal a relatively simple figure such as the one shown in figure 4.16. Thereafter, each row should then be further analyzed as per the method discussed later.

4.4.2 Failure analysis

After the list of failures (i.e. failure modes, causes and effects) is created in a FMEA table format, each row needs to be analyzed further for the following:

- To identify if there are any planned prevention controls in the project that eliminate or reduce the occurrence of the potential failure causes.
- To understand if there are any planned detection controls that are able to excite the potential failure cause (and uncover failure modes) as soon as they are created. Ideally, the detection controls should be able to detect the existence of the failure cause in the same stage as they were created, such that prevention controls can be applied immediately to eliminate or reduce the occurrence of failure causes.
- To score each failure event using detection of failure cause ('D'), occurrence of failure cause ('O') and severity of the failure effect ('S'). Note that S, O and D are determined via severity, occurrence and detection scales ranging from 0 to 10.

To analyse the failure events in the project FMEA table, the additional columns including prevention control, detection control, detection score, occurrence score and severity scores should be added to the table. The prevention controls are

NPD Process step	**Function**	**Falure Mode**	**Failure cause**	**Failure effect**
Stage 1	F1	FM1	FC1	FE1 FE2
	F1	FM1	FC2	FE1 FE2
	F1	FM1	FC3	FE1 FE2
	F1	FM2	FC4	FE3
	F1	FM3	FC5	FE4
	F2	FM4	FC6	FE5
	F3	FM5	FC7	FE6
Stage 2	...	...	...	...

Figure 4.16: NPD FMEA development continued

the countermeasures that either stops failure causes from resulting into failure modes or reduce the likelihood of their occurrence. Therefore, the occurrence value (O), which is a measure of probability of a failure cause happening is affected in presence of a prevention control. Note that the occurrence score 'O' should be scored for a specific failure cause that results into a failure mode and then into a failure effect. In other words, the occurrence of the complete chain of event should be scored rather than the probability of only failure cause happening. The scoring can be undertaken using an occurrence scale such as the one shown in Figure 4.17.

The detection controls are planned control measures that can uncover the failure cause and the failure mode. An effective detection control has high chances of uncovering the failure causes and the respective modes. Thus, a most-effective detection control verifies the existence of a failure cause, such that it could be treated before it progresses into the further stages of the NPD process. Note that there can be several detection controls for each failure cause depending upon several techniques available to the project team to potentially excite a failure cause. The measurement of effectiveness of a detection control is measured by the detection scores. The detection score for a specific failure cause can be scored by the project team on the basis of a detection scale, such as the one shown in figure 4.18. This should be noted that the detection scale MUST be time-dependent, such that the one shown in figure 4.18, because the focus of this work is on the early detection of the failures.

Occurrence description	Score
Impossible, very unlikely	1
Unlikely event	2
Event with little chance	3
Low number of events	4
Occasionally occurs	5
Usually occurs	6
Often occurs	7
Mostly occurs	8
Very mostly occurs	9
Certainly occurs	10

Figure 4.17: Occurrence scale

The detection control implemented early should be given a lower score, whilst a detection control applied late should be given a higher number as per the chosen detection scale. Note that if a failure cause has more than one detection control, only the one with the lowest detection score should be selected for further evaluation purposes. This is because the intention is to select the best detection method available to uncover the failure cause.

After the detection and occurrence values are scored, severity of failure effects should be assessed. Note that each failure mode may have multiple failure effects. Therefore, each failure effect should be scored, however for further evaluation purposes, only the one with the highest value should be selected. This is because in a practical sense the intention is to evaluate the worst case scenario, such as actions could be taken to safeguard the project against worst possible risks. The severity score for a specific failure effect can be scored by the project team on the basis of a severity scale, such as the one shown in figure 4.19.

Note that the scales shown for detection, occurrence and severity are for reference purposes only and should be adapted by the project managers to suit the requirements of individual projects.

To demonstrate the method of analysis discussed in this section, the project FMEA table has been extended and shown in figure 4.20[9]. The extension is done

[9]Note that the text in capital case denotes the linguistic terms and the text in the small case

Opportunity for Detection	Rank	Likelihood of Detection
No detection opportunity	10	Absolute Uncertainty
Not likely to detect at any stage	9	Very Remote
Post Design Freeze and prior to launch	8	Remote
	7	Very Low
	6	Low
Prior to Design Freeze	5	Moderately
	4	Moderately High
	3	High
Virtual Analysis - Correlated	2	Very High
Detection Not Applicable; Failure Prevention	1	Amost Certain

Detection controls have strong detection capability. Virtual analysis using the information available (such as expert reviews, design reviews, FEA etc.) is highly correlated with actual and/or expected operating conditions prior to design

Figure 4.18: Detection scale adopted from Chrysler [2008]

Effect	Criteria	Ranking
Hazardous-without warning	· The deviation on the 139TCQ triangle leads to a failure that affects the safe product operation and/or involves non-compliance with government regulation. The failure occurs without any warning.	10
Hazardous-with warning	· The deviation on the 139TCQ triangle leads to a failure that affects the safe product operation and/or involves non-compliance with government regulation. The potential failure is observed with some form of warning.	9
Very High	· The deviation on the 139TCQ triangle leads to the Product / item inoperable, with loss of core functionality of the product	8
High	· The deviation on the 139TCQ triangle leads to the product / item being operable at significantly reduced levels of quality, and/or · High costs are involved to fix potential failure/s, and/or · Product launch date is affected to unacceptable limit, and/or · Loss of brand reputation as Customer is highly dissatisfied.	7
Moderate	· The deviation on the 139TCQ triangle leads to the product / item being operable but at a reduced levels of quality, and/or · Moderate amount of costs are involed to fix potential failure/s, and/or · Product launch date is affected to an unacceptable limit, and/or · Customer is dissatisfied.	6
Low	· The deviation on the 139TCQ triangle leads to the product / item being operable but the quality is reduced to an acceptable level, and/or · Low costs are involed to fix potential failure/s, and/or · Product launch date is affected to an acceptable, and/or · Customer is somewhat dissatisfied.	5
Very Low	· Quality is unaffected · Very low costs are involed to fix potential failure/s, and/or · Product launch date is not affected, and/or	4
Minor	· Quality is unaffected · Minor costs are involed to fix potential failure/s, and/or · Product launch date is not affected, and/or	3
Very Minor	· Quality is unaffected · Very little costs are involed to fix potential failure/s, and/or · Product launch date is not affected, and/or	2
None	· No effect on the 139 TCQ triangle	1

Figure 4.19: Severity scale developed by the author

NPD Process step	Function	Falure Mode	Failure cause	Failure effect	Prevention Control	Detection Control	Detection scores	Selected Detection scores	Ocurence score	Severity scores	Selected Severity score
Stage 1	F1	FM1	FC1	FE1 FE2	PC1	DC1	d1	d1	p1	**s11** s12	s11
	F1	FM1	FC2	FE1 FE2	None	DC21 DC22 DC23	d21 **d22** d23	d22	p2	s11 s12	s11
	F1	FM1	FC3	FE1 FE2	PC3	None	d3	d3	p3	s11 s12	s11
	F1	FM2	FC4	FE3	PC4	DC3	d4	d4	p4	s3	s3
	F1	FM3	FC5	FE4	None	None	d5	d5	p5	s4	s4
	F2	FM4	FC6	FE5	PC5	DC4	d6	d6	p6	s5	s5
	F3	FM5	FC7	FE6	PC6	DC5	d7	d7	p7	s6	s6
Stage 2	...	...	...	...							

Figure 4.20: NPD Project FMEA development

by adding relevant information in additional columns including prevention control, detection control, detection scores, selected detection scores, occurrence score, severity score and selected severity score for each recorded failure event.

As can be seen from figure 4.20, failure cause in presence of prevention controls drives the scoring in the occurrence score column [10], detection control drives the detection scoring and the failure effect drives the severity scoring. However, as discussed before, the best detection control and worst severity score should be selected for further evaluation. Thus, between FE1 and FE2, the severity score for FE1, i.e. s11 is selected because s11 is greater than s12. Similarly, between DC21, DC22, DC23, the detection score of d22 is selected as d22 is less than d21 and d23.

4.4.3 Evaluation

In real life scenarios, it may not be possible to develop countermeasures for all identified failure causes because it might be a laborious and a costly affair. Thus, the treatment of all possible failure causes is difficult, therefore fewer failure rows need to be selected from the FMEA table. This prioritisation of failure modes is done on the basis of severity scores being higher than a certain value chosen by the project manager of the project.

Let us assume that out of 'N' number of total failure events(or rows in the table), 'n' failure rows have a severity score higher than a certain value. Unlike the RPN that encapsulate the severity, detection and occurrence scores together, a special focus has been given to detection, as it is argued that the early detection is the key to prevention. For the 'n' number of selected failures, the analysis of failures

denotes numbers.

[10]See the link between FC4, PC4 and p4 for reference.

is based on following method:

- For ‘n’ number of selected failure modes, calculate the criticality index (’CIi’) for each ’i’th failure event by multiplying the severity and occurrence score values.

- Highlight each failure event on the basis of criticality bands (such as red, orange, yellow and green) dictated by a matrix such as the one shown in figure 4.21. The banding can be adapted based on individual project needs. Note that there are some failures in red region for which even if the criticality index is as low as 10, they are still considered as most critical. This is because these failure may be critical to safety legislation; therefore regardless of the occurrence scores, these types of failures need special attention when treatment methods are applied.

- Add surprisal column to the FMEA table and calculate the ‘surprisal ’ (in bits or shannons) for each ’i’th failure event using the formula below.

  $Su_i = -\sum_{i=1}^{n} log_2 d_i - \sum_{i=1}^{n} log_2 p_i$

  Where ’di’ denotes the probability of detection and ’pi’ denotes the probability of prevention. These probabilistic estimates are determined on the basis of detection and prevention scores. For example, the probabilities of detection and prevention are 0.999 and 0.999 respectively for the corresponding detection and occurrence scores of 1 and 1 respectively. Similarly, the probabilities of detection and prevention are 0.001 and 0.001 for the detection and occurrence scores of 1 and 1 respectively. Applying the surprisal formula given in this chapter, a higher probability of detection and prevention would mean a lower surprise in the field due to failures, thus a lower surprisal value and vice-versa.

- Assign a weight (’wi’) to the ’i’th failure. The weights are assigned on the basis of the banding given to the failure. For example, a project manager may decide to use a weight of ‘3’ for red or orange band (which they may refer to as ‘critical’ failure), ‘2’ for yellow (which they may refer to as ‘major’ failure) and ‘1’ for green (which they may refer to as ‘ordinary’ failure). Prioritise the failure events based on the given banding.

- Calculate the average criticality index (CI) and Surprisal (Su) for the project based on the following two proposed formulas:

  $CI = (\frac{1}{n}) * \sum_{i=1}^{n} CI_i$

  AND

  $S_u = \frac{\sum_{i=1}^{n} W_i * Su_i}{\sum_{i=1}^{n} W_i}$

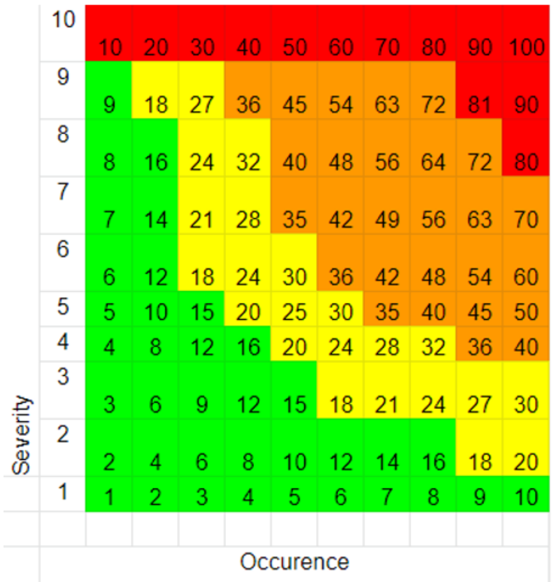


Figure 4.21: CI matrix (each cell is a multiplication of S*O) used for colour banding

4.4.4 Treatment

After each failure is analyzed using the method discussed in last section and given a CI, Su and wi values, efforts should be made to bring the CI and surprisal values down by developing further detection and prevention controls for each selected failure event, which improves the detection and occurrence scores. The weights wi should be revised based on new CI values. Thereafter, new average CI and Su values of the project should be determined. The new CI and Su values for the project should come down w.r.t to the previous iteration.

The minimization of CI and Su values for the failures in the project justifies the implementation of countermeasures that bring the overall average CI and Su values for the project down. The process of bringing the CI and Su values down should continue until a Surprisal value close to zero is reached or the analysis is aborted with satisfactory CI and Su values by the project manager.

4.5 The proposed framework

The earlier section has demonstrated the steps for the NPD Failure Mode Avoidance framework, which can now be summarized using the flowchart below (refer fig 4.22). The application and validation for the proposed framework in an industrial scenario can be found in chapter 5.

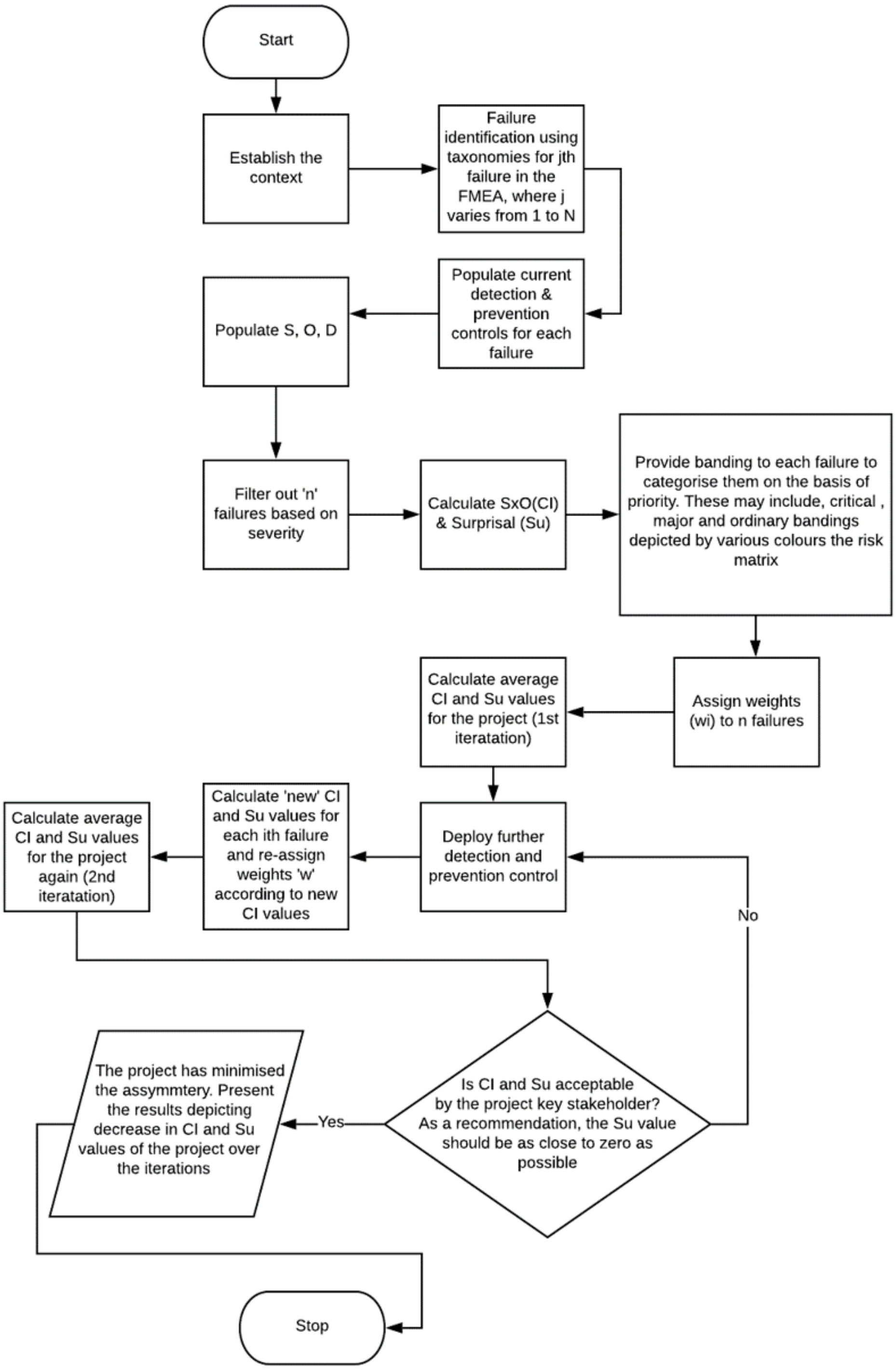


Figure 4.22: Summary of NPD framework produced

Chapter 5

Application of NPD Failure Mode Avoidance framework

This Chapter discusses the application for the NPD Failure Mode Avoidance framework in two different real-life case studies:

- To validate the application of developed framework in the product design: The developed framework is first tested at the product design sub-stage of the NPD project. This is done to ensure that the developed framework is still applicable in an already tested domain, i.e. product design. Interestingly, most existing frameworks have been applied in the product design sub-stage of product development (refer chapter 2, so the intention is to validate the applicability of the developed framework in an already tested domain.
- To extend the application of the framework to an NPD project: Once the benefits of framework has been established in the product design domain, the intention is to test the framework to the NPD project domain. The application of the framework to an NPD project of the chosen organisation largely depends on the decisions made by the project stakeholders including the project manager and the sponsor.

5.1 Validating the framework in Product Design

The first application of the developed Failure Mode Avoidance framework is based on a real-life case study in Company X. After discussing with stakeholders of the company, the author understood that the requirement was to develop a robust and mistake-free design of assembly 'T' within a system 'S', as there had been several complaints from the site (or field) about several component failures on the previous designs. The failures on the components were related to mechanical as well as electrical failures, all of which resulted in loss of primary function of assembly 'T' impacting the bigger system 'S'. The main function of assembly 'T' is to engage with the storage pallets, which needs to be transported from one place to the other via the other assemblies in System 'S'.

The NPD practitioners of the company were keen on adopting best practices from engineering design and reliability, such that failures can be avoided on assembly 'T' and overall improvement in system's yield can be observed. Therefore, the NPD stakeholders agreed to apply the proposed Failure Mode Avoidance framework on assembly 'T' because they believed that the framework may enhance the applicability and effectiveness of the traditional FMEA tool that had already been used by their engineers in product design.

5.1.1 Understanding the system

The efficiency of the system 'S' is predominantly determined by the number of successful pick ups and drop offs of the storage pallets made by assembly 'T'. The assembly 'T' mainly consists of a rectangular frame, which goes up and down on a guided channel, ultimately to engage/disengage with the storage pallet using the four grabbers available on each corner of the frame. Each grabber consists of a primary finger and a secondary finger.

The grabber should work in pair, meaning that the secondary finger should immediately follow the primary finger in order to reach the set positions on either side of the grabber. The primary finger is driven by a motor, which then drives the secondary finger. When the grabbers extend the fingers away from each other to reach the set positions, they are considered to be in the 'open' position. On the other hand, when the fingers are in proximity (close to each other), they are considered in the 'closed' position. The figure 5.1 below shows the open position of the old grabber module that needed further improvement.

In order to get more information about the failures, several failure reports from a centralised database were collected by the task force that included several engineers, project manager and author to establish the failure rates. Besides, the operations and maintenance personnel were contacted to understand the situation. It was observed that most failures on assembly 'T' that resulted in decrease in the efficiency of system 'S' were due to the failure of the grabber module. The assembly 'T' had several reported failures from the field attributed to the grabber module. These are discussed below:

- It was reported that the grabber often fails to engage or disengage with the

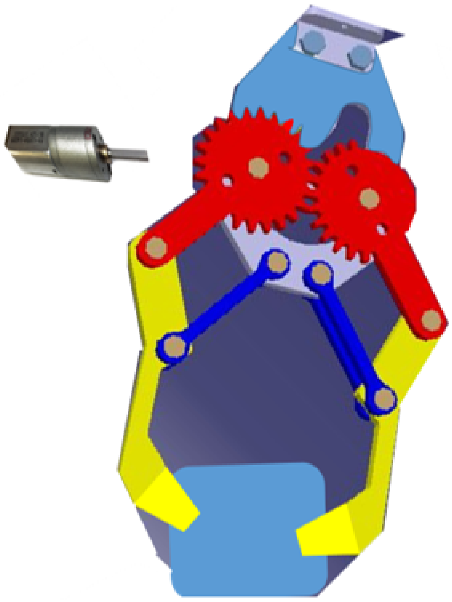


Figure 5.1: 'Open' position on the old grabber module (designed for reference purposes only)

pallet due to several catastrophic and degradation failures associated with the module. The grabber failed to engage or disengage with the pallet due to the following.

- Interface failures between the motor shaft and the primary finger. It was found that in some cases, the primary finger failed to move, even if the motor shaft was found to be moving. The exact underlying cause for this type of failure was not thoroughly investigated.
- Interface failures between the primary finger and the secondary finger. The gear interface between the primary and the secondary fingers experience wear issues leading to intermittent/no contact between the two fingers (refer figure 5.2).
- Interface failures between the grabbers and the pallet. It was noted that changes in the geometry of the fingers (such as lateral deformation) may cause misalignment issues with the slot inn the pallet, resulting in an unintended disengagement with the pallet. In some cases, the fingers were found to be broken.
- The grabber fingers took more time to open or close than expected. These were mainly attributed to the resistance in motion due to stiffer bearing surface.

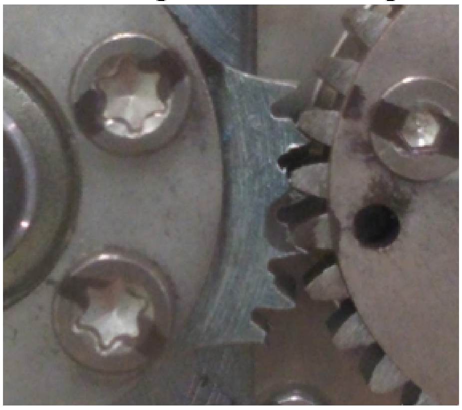


Figure 5.2: Wear issues on geared interface

- Components of assembly T (such as screws, external circlips or even the secondary gripper finger) kept falling inside the pallet, resulting in contamination of its contents.

Due to the reported failures on grabber module and decrease in efficiency of system 'S' as a result, a business need arose to develop another assembly 'T' with a new design of grabber module. The business requirement for the grabber module was to observe a failure-free operating period of 3 years. The mean life of old design was reported to be 0.08 years. The following problem statement was formulated by the task force.

"The current assembly 'T' has a mean life of 0.08 years as opposed to the business requirement of 3 years. The decreased mean life of the assembly 'T' is mainly due to failures in the grabber module, which results in 30% decrease in the up time of system 'S'. Thus, there exists a business need to improve the reliability of the grabber module by designing a new assembly 'T' that can achieve a failure-free operating period of 3 years when operated on site[1]."

In order to solve the issues around the assembly 'T', the author proposed to apply the principles the developed Failure Mode Avoidance framework in the context of engineering product development, such that a right-first-time design can be obtained. This chapter illustrates the use of Failure Mode Avoidance methodology to eliminate and mitigate the failures on assembly 'T'. In order to apply the framework for assembly 'T', following steps were proposed to the task force by the author, who were working in collaboration towards the issue resolution:

- To conduct a preliminary workshop with the team members: Author proposed to run a workshop, where the intention was to summarise the fundamentals of

[1]The term 'Site' here represents the 'field'

the framework to the task force. The following agenda was set:

  - To demonstrate symmetry/asymmetry principle in the context of assembly 'T' using the p-diagram.
  - To complete the p-diagram by brainstorming failure modes, effects and causes in the context of assembly 'T'. The information gathered in the p-diagram helps pre-populate the Design Failure Modes Effects and Analysis (DFMEA) in an efficient manner. The surrounding theory around this argument is also presented.

- Complete the DFMEA using the principles of Failure Mode Avoidance framework for the "new" assembly T after its design is 60-70% complete. This percentage had been proposed keeping in mind that the amount of information needed to execute the framework would be sufficient when the design is 60-70% complete.

- Procure the parts for the assembly and test the new design (using the Design Verification Plan and Report, abbreviated as DVP&R, which is an output of the DFMEAs) to validate the effectiveness of failure mode avoidance method in producing the desired output right-first time.

5.1.2 Symmetry/Asymmetry view on assembly 'T'

The problem statement highlighted that the reduced mean life of assembly 'T' is mainly due to the failures observed on the grabber module. Therefore, for the new design of assembly 'T' only grabber module was planned to be re-designed whilst keeping the other parts such as frame, PCBs and wiring unchanged. Therefore, the focus shifted from the complete assembly 'T' to the grabber module only, whilst not loosing sight of other components that link up the module with the rest of the assembly.

The proposed new design of the grabber module consisted of a link mechanism between the two fingers instead of gear interface that existed in the previous version. Besides, the interface of the shaft and the primary finger was changed too. The shaft of the motor and the grabber finger was "keyed" in previous version, whereas in new version a spline on the shaft had been press fitted. Thus, it was deemed that the grabbers' geometry in the new design had changed radically and the need to conduct the DFMEA was recognised. A conceptual design of the new grabber module is shown in figure 5.3 below.

In order to demonstrate the symmetry view on the grabber module, following p-diagrams as shown in figure 5.4 was formulated by the author in a workshop. The

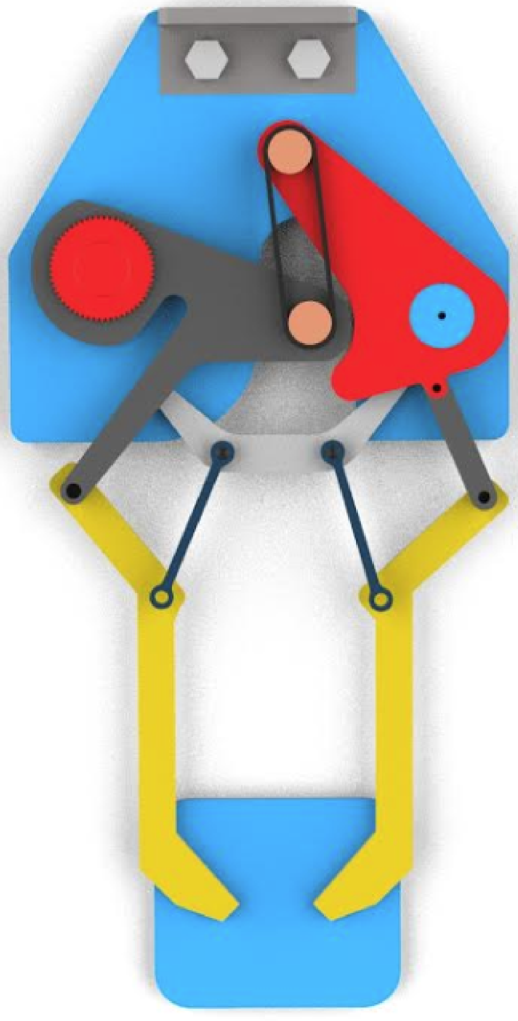


Figure 5.3: New grabber module design

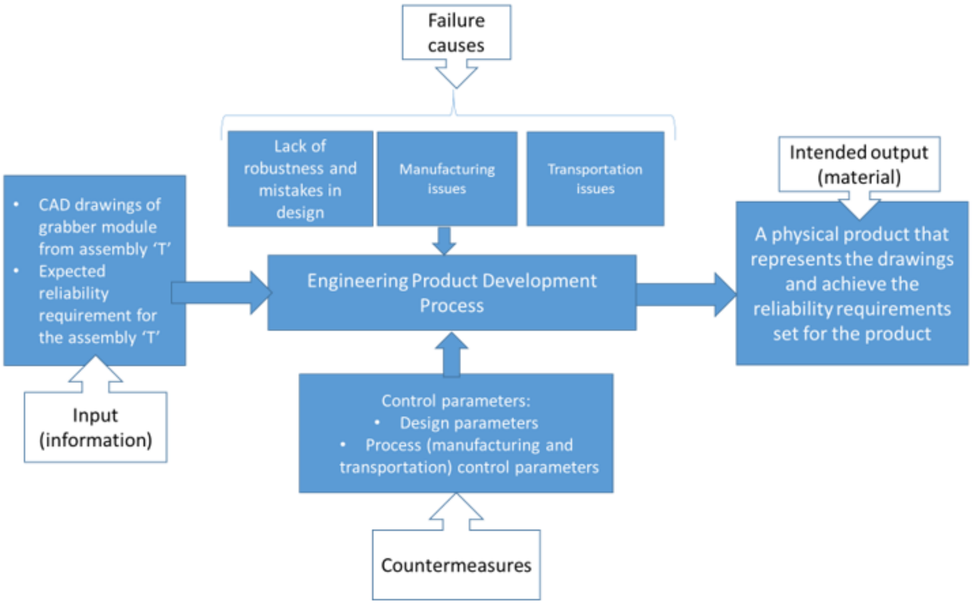


Figure 5.4: P-diagram with symmetry in the NPD process

workshop was conducted when the product design was in its concept stages. It can be seen from the p-diagram that the symmetry can be achieved via the transformation in the engineering 'product development' process. The transformation in the engineering product development process is the translation from information on the drawing (or a Computer Aided Design) to a material-based product, i.e. the finished grabber module in this case.

In an ideal case when symmetry in the engineering product development process is achieved, the finished product looks exactly the same as the released drawing even though a series of operations has been carried out including tooling, process design, supplier selection, manufacturing, transportation etc. Therefore, the knowledge of the product (in the form of drawings and requirements) at the beginning of the product development process is exactly the same as the knowledge gained for the finished product after the product development process is complete. In case of the grabber module, the intention is to achieve a finished physical product that exactly represents the drawing and fulfils the reliability requirement set for the module.

The p-diagram in figure 5.4 illustrates various types of failure causes getting inevitably introduced at various phases of development, which needs to be treated using the countermeasure as and soon as they are identified or created. Since there are several associated failure causes to grabber module, the workshop attendees were asked to define the main sources of failure causes. The attendees emphasized that the focus needs to be mainly on the design failure modes and associated causes. The aim

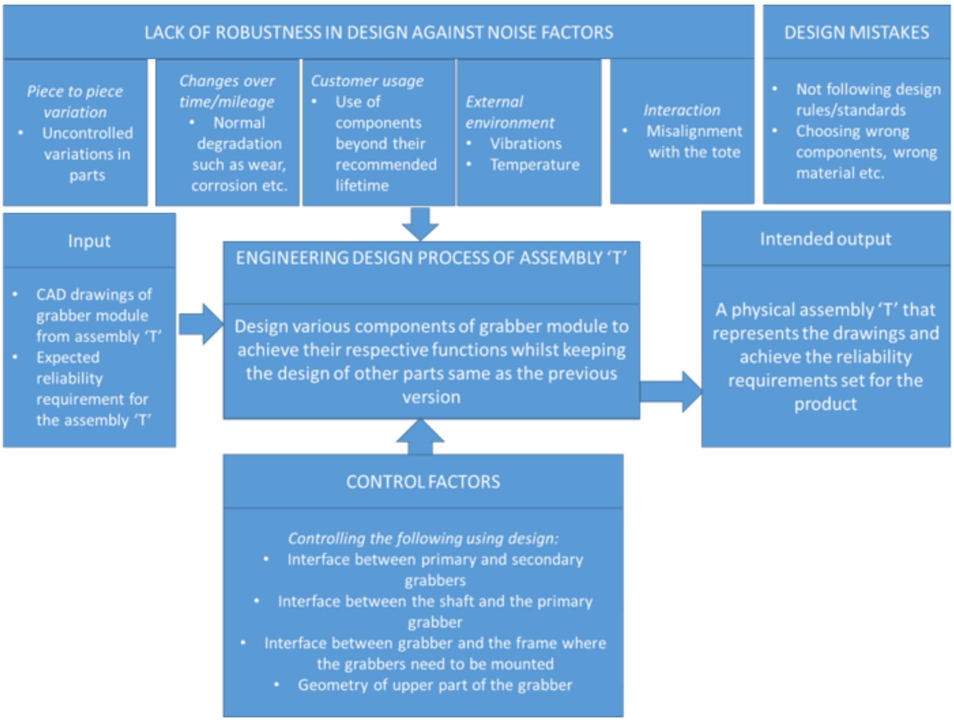


Figure 5.5: Detailed p-diagram with symmetry in the NPD process

was to achieve a right-first-time design, assuming manufacturing and transportation do not cause any issues. Having said that, it was emphasized by the author that any manufacturing, transportation and operations related failures that could be mitigated through design should be considered in the design process. Therefore, the intention is to identify all potential design related failure modes in early design phases of engineering product development process, such that a right-first-time design can be developed.

Since the focus had been on the design process, a detailed p-diagram to illustrate the concept of symmetry in design process has been shown in figure 5.5. A special focus has been given on expanding the failure causes as they act as the fundamental quantity in the product development process. In order to understand the failure causes in engineering context, a taxonomy of failure causes based on the work done by Davis (2006) has been adopted. As can be seen from the figure 5.5 that there are two types of failure causes in the design process: 1) lack of robustness of design against noise factors, 2) mistakes in design. The use of this taxonomy is important as it helps the engineers identify the product-related failure causes in a systematic manner.

After the p-diagram depicting a symmetry in the design process was constructed, the attendees were asked to create another p-diagram that illustrates the

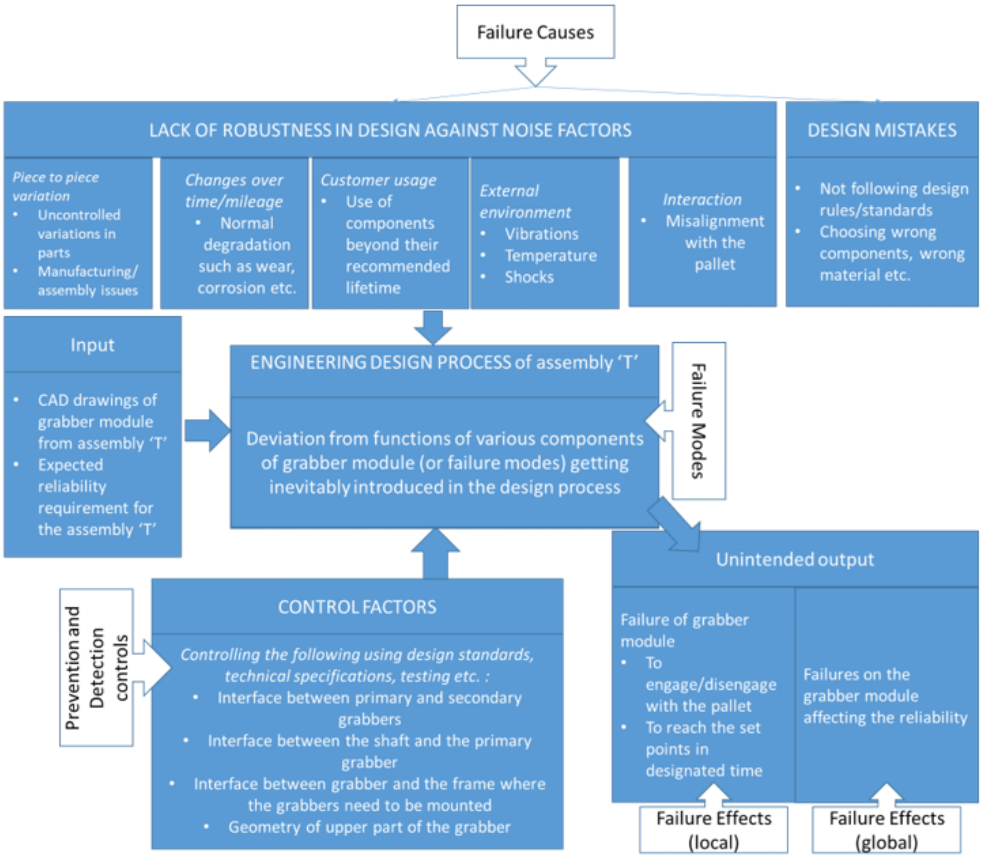


Figure 5.6: P-diagram with asymmetry in the NPD process

asymmetry in the product development process and create dysfunctional output because of the following reasons:

- It may not be possible to identify an exhaustive list of failure causes due to limitations in attaining knowledge of failure causes in early design phases and/or,
- Treatment of all potential identified failure causes with countermeasure deployment is a costly affair.

The introduction of failure causes deviates the components from achieving their respective functions, resulting in deviation on the output. The p-diagram to illustrate asymmetry is shown in figure 5.6.

The p-diagram not only helped the engineers to understand the system but also provided them with a logical structure to think about the failure causes in the design process. Besides, the p-diagram provided a systematic way to differentiate between the failure causes, failure modes, failure effects, prevention and detection controls as this is an important distinction to make whilst conducting the DFMEAs at a later stage.

As seen from the p-diagram shown in figure 5.6 illustrating the asymmetry in the design process, the failure modes cause deviation from the intended functions of the components of grabber module. For example, the function of the motor within the grabber module is to provide required torque to the primary finger, thus the possible failure modes relating to the motor based on the Ford's taxonomy have been discussed below:

- No Function: Unable to provide the required torque and RPM[2] to the primary finger.
- Partial Function (under or over function): Providing too much RPM than required or providing too little RPM than required.
- Intermittent Function: Providing torques at irregular intervals.
- Degraded Function: Providing less torque than required over time.
- Unintended Function: To provide the required torque to move the finger when not commanded to.

There are two levels of failure effects suggested for the grabber module viz. local and global. The p-diagram can be adapted to demonstrate as many as levels of failure effects as the team wants, which can then help them gain the understanding of effects of failure modes at local and global levels. However, this should be noted that the highest level of failure effect (global level failure effect) should correspond to the negation of the intended output (or in other words, one or more dimensions of the 139TCQ triangle). For example, in case of grabber module, the intended output is to achieve the required reliability requirement for the module, whereby reliability is one of the sub-dimensions of the quality dimension on 139TCQ triangle. The unintended output is not achieving the stated reliability requirement.

The failure causes are various noise factors and mistakes that initiates the failure modes. In the engineering design context, the failure mechanisms comes in play together with failure causes. The failure mechanisms are the underlying physical and chemical process that leads to the failures in the product [EN IEC 60812, 2018]. They are more fundamental than the failure causes because the prevention controls in product design are deployed in response to the failure mechanisms. This means that the countermeasures are taken against the failure mechanisms in order to improve the design. Thus in engineering context, the failure causes initiates the

[2] RPM abbreviated for revolutions per minute

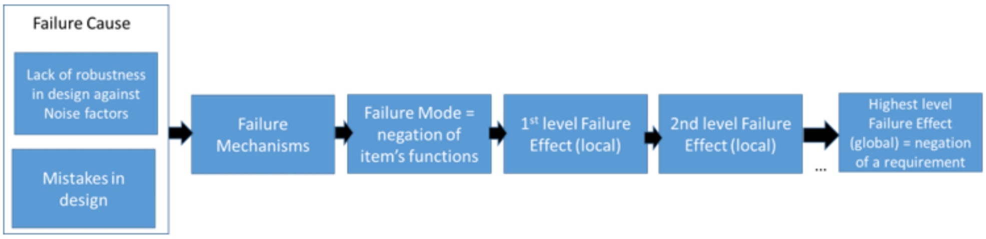


Figure 5.7: Failure event sequence (adapted from O'Halloran et al., 2012)

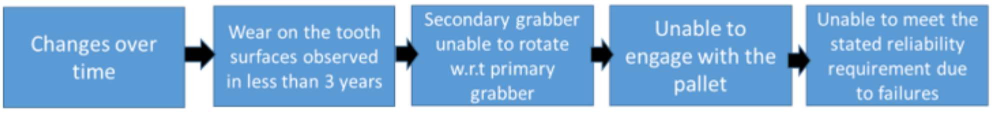


Figure 5.8: Failure event sequence for grabber module for a failure started with a noise factor

failure mechanisms, which then result into the failure modes and the effects. The complete chain of a failure event in engineering design context is given below in Figure 5.7

Since the failure mechanisms acts as the fundamental quantity of information in engineering design, there is a need to have its taxonomy in place. There are various taxonomies available for failure mechanisms. The one that was circulated to the task force by the author were from Scott et al. [2004] because of their ability to cover most failure mechanisms for engineering hardware[3]. The taxonomy helps engineers to identify relevant failure mechanisms, which can be triggered in the presence of noise factors or mistakes. For example, noise factor relating to "external environment (humidity)" may trigger failure mechanism "corrosion". In the context of assembly 'T', an exemplar complete chain of a failure event for the pair of grabber is shown in figure 5.8.

Every failure event is illustrated as individual row on the DFMEA. Therefore, the total number of lines on the DFMEA is governed by the number of failure mechanisms[4]. The DFMEA population is important as it is a standard practice in industries and facilitates the implementation of failure mode avoidance.

[3]Note that the taxonomies used here are for hardware failure modes. Software failure modes require different taxonomies as being developed by researchers such as Ann Marie Neufelder

[4]Note that in Chapter 4, it was demonstrated that the total number of lines in the FMEA are governed by the total number of failure causes. Since in engineering design context, failure mechanism is the fundamental quantity, therefore the total number of lines are governed by the total number of failure mechanisms

Term	Taxonomy (with examples)	Adopted from:
Function	Verb + Noun combination (Refer to Appendix 1 for verbs; Nouns can be energy, material, information) E.g. function of an electrical motor is to <u>convert</u> *electrical energy to rotational energy*	Hirtz et al., 2002
Failure Mode	No Function; Partial Function; Intermittent Function; Degraded Function; Unintended function	Adapted from Ford FMEA handbook version 4.1
Failure Cause	Lack of robustness against noise factors; mistakes	Clausing and Frey (2005)
Noise Factor	Piece to piece variation, customer duty cycle, changes over time, system interaction, external environment	Taguchi et al. (1990)
Failure Mechanism	Wear, fracture, Buckling, corrosion, fatigue	Scott et al. (2004)
Failure Effects (global)	139 TCQ Triangle	Developed in the scope of this research

Table 5.1: Adopted taxonomies in the scope of this work

5.1.3 Execution of the framework in engineering product design

Based on the understanding gained using the p-diagrams, the author alongside with the design engineers agreed to pre-populate a DFMEA for the new design of grabber module. The pre-population was done when the design was around 60-70% complete. The pre-population focused mainly on populating the qualitative columns[5] of the DFMEA using the concept of taxonomies that helped engineers fill the DFMEA rows in a structured manner from top to bottom[6]. Following taxonomies were used in the scope of this case study:

The function and failure mechanism taxonomies used in the study are presented in appendix F in detail. The "function" taxonomy helped facilitate the use of common language across the organisation as well as provided an exhaustive list of functions for the grabber module. The failure mechanism, causes and mode taxonomies helped the team to record potential failure modes in a logical manner. This should

[5]The qualitative columns of the FMEA include item, function, failure mode, failure cause, failure mechanism, failure effects (all levels), prevention control and detection controls.

[6]The FMEAs are very well structured from left to right but not from top to bottom [Saxena et al., 2015]. Taxonomies helps establish a logical thinking, such that FMEAs can be populated in a structured manner whilst also helping the engineers to not miss out on any failure events

Identifier	Module	Component	Function	Comments	Failure Mode Category	Failure Mode
T-000	**Motor +shaft + bearing**	Motor	1. To provide the required torque of xx N-m to engage/disengage the grippers on demand	The failure cause is "mistake" here. Thus, the failure mechanism is motor failure, where motor is treated as a black box as it is an off-the-shelf part with customised shaft having splines	No Function	Unable to provide the required torque to engage/disengage grippers on demand
T-001		Motor			Degraded Function	Unable to provide the required torque to engage/disengage grippers on demand

Table 5.2: A DFMEAs snapshot

be noted that if a function is missed, the associated failure modes will be missed. Therefore, the system engineers were also involved in the pre-population, who helped to produce an exhaustive list of functional and performance requirements for the grabber module. The functions were then populated in the 'function' column of the DFMEA and failure mode taxonomy were used to derive the corresponding failure modes. This step of identifying failure modes is also important because if a failure mode is missed, corresponding failure cause/mechanism will be missed. And, if a failure mechanism is missed, corresponding countermeasure (prevention controls) will be missed. Besides, if a prevention control is missed, the corresponding failure mode will escape into the field and produce unintended output in form of failure effects. Further, in other to develop appropriate prevention control, detection is crucial as it excites and uncover the failure cause/mechanism. Using the detection controls, the team can verify the existence of failure mechanisms/causes and determine the likelihood of the failure event based on the real data obtained from the verification methods.

A simple FMEA spreadsheet adapted from the one shown in Chapter 4 was used to populate the DFMEA. The DFMEA pre-population resulted in many lines of failure events for the grabber module. A snapshot of the DFMEA conducted is provided in tables 5.2, 5.3 and 5.4.

Note that Table 5.2 shows a function and associated two failure modes for the component "motor". Two failure events viz. T-000 and T-001 are shown. Table 5.3 and Table 5.4 shows the extended view of two failure events.

Failure Mechanism	Failure Cause	Occurrence score	Local Effect	Global effect	Severity score	Existing prevention controls	Existing detection controls	Detection score
Solenoid failure	Wrong motor chosen for the application	1	-Unable to open / close grippers on demand -Pallet does not get picked/released	- Unable to achieve the reliability requirement - Poorly perceived at field	8	The same motor is being chosen from the previous version that we know works	Failure is inherently prevented in design	1
- Overloading - Overheating	- Cyclic/repetitive loading operation	3	-Unable to open / close grippers on demand -Pallet does not get picked/released	- Unable to achieve the reliability requirement - Poorly perceived at field	8	None	None	10

Table 5.3: DFMEA snapshot (continued)

Criticality index (=O*S)	Total surprisal	Recommended Actions	Actionee	Action Status (Open/Close)	Due-Date	Date Action close.
8	0.0029					
24	10.4804	1. Further detection control - Develop a motor rig to determine its mean life to replicate loaded pallet scenario 2. Further prevention control - Collect manufacturer's datasheets regarding the motor 3. Include the related tests in the DVP&R 4. Conduct Testing and determine the failure rate of the motor	1. Reliability & verification team 2. Design team	Closed	xx/xx/xxxx	xx/xx/xxxx

Table 5.4: DFMEA snapshot (continued)

After the quantitative columns of the FMEA were populated, a three hour workshop had been arranged with the team members to collectively review the pre-population and simultaneously fill the rest of the columns using the severity, occurrence and detection scales as shown in tables 5.5, 5.6 and 5.7 [7]. The workshop attendees included design (mechanical + electrical + electronics) engineers, reliability engineers, systems engineers, operation and maintenance personnel, manufacturing engineer and the project manager. The author facilitated the workshop and one person from the reliability team was asked to be the FMEA scribe, who took the notes.

The workshop focused on the failure modes of the grabber module. The columns were populated using the method demonstrated in chapter 4. Since the focus is on avoidance of failure modes, the failure treatment has been done using the prevention controls[8]. Thus, other treatment methods such as "transferring the risk to a third party where the failure does less harm" or "adding a compensating device" were not promoted during the workshop by the author, who was acting as a FMEA facilitator in the workshop.

With a simple conditional formatting options on the spreadsheet, the criticality index were determined, which were shown with red, orange, yellow and green banding based on figure 4.21 shown in chapter 4. Since the focus of this case study was on the reliability requirement and not so much on perceived quality levels, the severity levels that had a score of 8 or more were paid more attention in order to develop further prevention and detection control measures. Thus, out of around forty failure rows (N=40) on grabber module, only nine (n=9) were found to have a severity of 8 or above. These nine failure events then became the discussion points. The prevention and detection controls were developed for those that had a high value of the criticality index.

As a result of the workshop, some prevention controls were taken for some failure events, which were found to be detected via design reviews and Finite Element Analyis analysis early in the product design phase, however a lot of the failures were left without prevention measures as the FMEA team (workshop attendees) wanted to first verify the existence of failure via detection controls. Therefore, the focus of the workshop remained on implementing the detection controls. As a result, a major action that was taken after the workshop was to develop two test rigs that were believed to be capable of exciting and uncovering the failure events by replicating the real-life conditions. These two rigs were: 1) motor rig and 2)grabber module

[7] The scales were prepared and distributed by the author using their engineering judgment and knowledge gained from literature search in Chapter 2

[8] The prevention control in the context of design implied changing the material, geometry and/or mechanics of the product in concern.

SEVERITY of Effects of Failure Mode		
Effect	**Criteria**	**Ranking**
Hazardous-without warning	· The failure affects the safe product operation and/or involves non-compliance with government regulation. The failure occurs without any warning.	10
Hazardous-with warning	· The failure affects the safe product operation and/or involves non-compliance with government regulation. The failure occurs with some warning.	9
Very High	· The deviation from the reliability requirement and/or perceived quality levels are observed because of the Product / item being inoperable, with loss of core functionality of the product	8
High	Item operates with high reduction in perceived quality levels	7
Moderate	Item operates with moderate reduction in perceived quality levels	6
Low	Item operates with low reduction in perceived quality levels	5
Very Low	Item operates with very low reduction in perceived quality levels	4
Minor	Item operates with minor reduction in perceived quality levels	3
Very Minor	Item operates with very minor reduction in perceived quality levels	2
None	· No effect on reliability requirement or perceived quality levels	1

Table 5.5: Severity scale

OCCURRENCE of Failure Cause		Probabilistic set	Probabilities	
Probability of Failure	**Ranking**	**Probabilistic set = {probability of prevention (p1), probability of non-prevention (p2)}**	**Probability of preventing the failure**	**Probability of not preventing the failure**
Very High: Failure is almost inevitable	10	{0.001, 0.999}	0.001	0.999
	9	{0.1, 0.9}	0.1	0.9
High: Repeated failures	8	{0.2, 0.8}	0.2	0.8
	7	{0.3, 0.7}	0.3	0.7
Moderate: Occasional failures	6	{0.4, 0.6}	0.4	0.6
	5	{0.5, 0.5}	0.5	0.5
	4	{0.6, 0.4}	0.6	0.4
Low: Relatively few failures	3	{0.7, 0.3}	0.7	0.3
	2	{0.8, 0.2}	0.8	0.2
Remote: Failure is unlikely.	1	{0.999, 0.001}	0.999	0.001

Table 5.6: Occurence scale

Opportunity for detection	Description	Rank	Likelihood of detection	Probabilistic set = {probability of detection (d1), probability of non-detection (d2)}	Probability of detection	Probability of non-detection
No detection opportunity		10	Absolute uncertainty	{0.001, 0.999}	0.001	0.999
Not likely to detect at any stage		9	Very remote	{0.1, 0.9}	0.1	0.9
Post design freeze and prior to launch		8	Remote	{0.2, 0.8}	0.2	0.8
		7	Very Low	{0.3, 0.7}	0.3	0.7
		6	Low	{0.4, 0.6}	0.4	0.6
Prior to design freeze		5	Moderately	{0.5, 0.5}	0.5	0.5
		4	Moderately High	{0.6, 0.4}	0.6	0.4
		3	High	{0.7, 0.3}	0.7	0.3
Virtual analysis - correlated		2	Very High	{0.8, 0.2}	0.8	0.2
Detection Not Applicable: Failure Prevention		1	Almost certain	{0.999, 0.001}	0.999	0.001

Table 5.7: Detection scale

FM⁹#	Occurrence	prevention probability	Detection	detection probability	Severity	Criticality index (CI)	ISSUE category Critical (Red) = 3 Major (Orange) = 2 Ordinary (Green/Yellow) = 1 Wi= 1,2,3	Surprisal (1st iteration)
1	3	0.7	10	0.001	8	24	1	0.5160165897
2	1	0.999	1	0.999	8	8	1	0.002886833739
3	5	0.5	2	0.8	9	45	2	1.321928095
4	9	0.1	4	0.6	8	72	2	4.058893689
5	3	0.7	2	0.8	8	24	1	0.8365012677
6	6	0.4	2	0.8	8	48	2	1.64385619
7	9	0.1	7	0.3	8	72	2	5.058893689
8	8	0.2	10	0.001	10	80	3	12.28771238
9	5	0.5	10	0.001	8	40	2	10.96578428
					Average CI=	45.88888889	Average surprisal (Su) =	5.892 bits

Table 5.8: CI and surprisal values after 1st iteration

rig, which continuously actuated the motors and the grabbers respectively in an accelerated manner.

Based on the first pass of the DFMEA, the following analysis as shown in table 5.8 was undertaken. A surprisal value of around 5.9 bits was calculated. This is shown below:

After the accelerated testing of six motors[9] and six grabber modules on the rigs were conducted, the existence of all the identified failures were confirmed and no other failures were discovered either. The occurrence score were revised based on the failure rates observed in testing and the new surprisal value had been calculated. The implementation of some prevention controls and detection controls was able to bring the surprisal value down to 2.6 bits. The 2nd iteration of analysis is shown in table 5.9.

Since the aim of the proposed failure mode avoidance framework is to bring the surprisal value as close to zero as possible, design engineers were recommended that further prevention controls for failure events FM#3, #4, #8 and #9, out of which they were able to successfully develop prevention controls for FM#3, #8 and

[9]The author together with the reliability team requested a sample size of 10 that was based on the Weibull++ software calculator, however only six were given by the project manager due to budgetary and project constraints. In order to compensate for this loss, the testing time was increased.

FM#	Occurrence	prevention probability	Detection	detection probability	Severity	Criticality index	ISSUE category Critical (Red) = 3 Major (Orange) = 2 Ordinary (Green/Yellow) = 1	Surprisal (2nd iteration)
1	3	0.7	2	0.8	8	24	1	0.8365012677
2	1	0.999	1	0.999	8	8	1	0.002886833739
3	9	0.1	2	0.8	9	81	3	3.64385619
4	6	0.4	2	0.8	8	48	2	1.64385619
5	3	0.7	2	0.8	8	24	1	0.8365012677
6	3	0.7	2	0.8	8	24	1	0.8365012677
7	4	0.1	3	0.7	8	32	1	3.836501268
8	8	0.2	8	0.2	8	64	2	4.64385619
9	8	0.2	5	0.5	8	64	2	3.321928095
					Average CI=	41	Average surprisal =	2.61 bits

Table 5.9: CI and surprisal values after 2nd iteration

#9 (refer to Table 5.9). The further analysis was re-run by the researcher that showed a further decrease in the surprisal value due to change in the occurrence scores for the failure events FM#3, #8 and #9. The surprisal value for the 3rd iteration was calculated to be around 1.45 bits. The 3rd iteration analysis is shown in Table 5.10.

The results show that the application of failure mode avoidance using the prevention controls and detection controls result in a decrease in average criticality indices as well surprisal values (refer the graph shown in figure 5.9 and figure 5.10). Further iterations were not run due to project deadlines and the findings were considered acceptable by the task force.

Although the performance of the new grabber module in the field is unknown (considering the product is not yet launched into the field), the feedback from the task force received by the author on applying the framework in product design had been positive. Based on the feedback, author approached the NPD practitioners of the company to help them apply the framework in a project domain.

5.2 Applying the Framework in context of an NPD project

The task force of the grabber module study could see the benefits of the proposed framework in the product design domain. The project manager, who was involved

FM#	Occurrence	prevention probability	Detection	detection probability	Severity	Criticality index	ISSUE category Critical (Red) = 3 Major (Orange) = 2 Ordinary (Green/Yellow) = 1	Surprisal (2nd iteration)
1	3	0.7	2	0.8	8	24	1	0.8365012677
2	1	0.999	1	0.999	8	8	1	0.002886833739
3	4	0.6	2	0.8	9	36	2	1.058893689
4	6	0.4	2	0.8	8	48	2	1.64385619
5	3	0.7	2	0.8	8	24	1	0.8365012677
6	3	0.7	2	0.8	8	24	1	0.8365012677
7	4	0.1	3	0.7	8	32	1	3.836501268
8	4	0.6	8	0.2	8	32	1	3.058893689
9	2	0.8	5	0.5	8	16	2	1.321928095
					Average CI=	27.11111111	Average surprisal =	1.45 bits

Table 5.10: CI and surprisal values after 3rd iteration

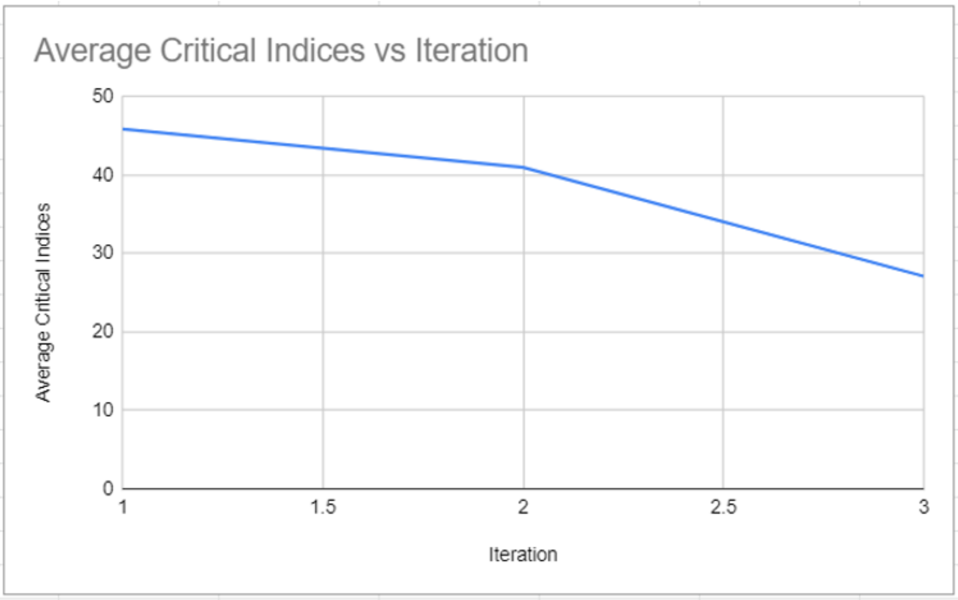


Figure 5.9: Decreasing CI values after implementing countermeasures

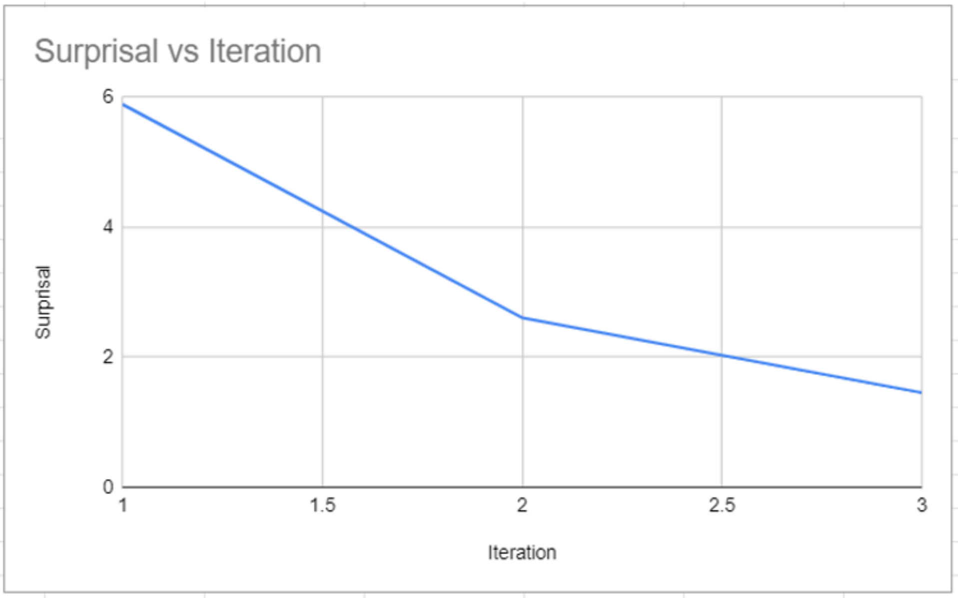


Figure 5.10: Decreasing Surprisal values after implementing countermeasures

in grabber module case study had highlighted that the framework was able to give them analytical insights about the technical risks associated with the product. They also believed that the framework can generate useful insights about individual and overall project risks, when applied in the context of NPD projects.

The findings of the grabber module case study were presented to NPD practitioners of the organisation, who had shown interest in the study carried out by the author. The following main benefits of the framework were presented:

- Genuine Proactive approach to avoid and mitigate failures: The methodology highlighted the importance of detecting the failure events immediately after they are created and/or preventing the failure events as soon as they are identified. It was also highlighted that the early detection is key to early prevention.

- Resolving structural problems with the FMEA: The use of taxonomies enabled the task force to think about the failure events in a logical manner.

- Ability to prioritise the failure events: The use of criticality index and associated banding together with surprisal values for individual failure events enabled the task force to systematically rank the failure modes.

- The Plots: The plotting of average CI and surprisal values w.r.t number of iterations indicated the progress made by implementing the countermeasures in a visual form.

The general feedback on the framework had been very positive, however the NPD practitioners had highlighted that the training may be required to train the individuals who use the framework in future projects. Also, the process of implementing the framework was found too be a bit time-consuming considering the amount of iterations involved. Despite some of these limitations, the NPD practitioners highlighted that these early efforts can save them a lot of money in the long run and therefore they agreed to implement the framework in the context of project domain. They suggested to apply the framework in the concept stage (or premise stage) of a new NPD project.

The selected new project was about the development of a new automated guided vehicle (AGV) and was at the end of stage '2' ("build business case") of Cooper's stage gate model at the time of this research. Theoretically speaking, the developed framework should be able to uncover most failure modes associated with product development and launch stages, providing a holistic view of project issues to develop a right-first-time project. However, due to limited information available at the time and resource constraints, the project manager wanted to just run a first pass of the project FMEA to tackle some obvious issues that had previously been recorded in the risk register. The main motivation for the project manager was: 1) to be able to assess and prioritise the known issues from risk register in an analytical manner using the criticality index and surprisal values, 2) to be able to support the author in validating that parts of the framework can be executed in the premise stage of an NPD project.

Due to time and resource constraints, a p-diagram was not constructed as the project manager emphasized that the information needed to pre-populate the project FMEA is available in the risk register. The author was able to segregate the information gained from the risk register into different columns of the FMEA. The author also had to arrange several meetings with the project manager in order to fill some gaps that existed whilst pre-populating the qualitative columns of the FMEA. The gaps were mainly around the information about failure effects, detection and prevention controls. The project manager highlighted the that the detection and prevention control columns should be populated collectively in a workshop with the stakeholders. Furthermore, the functions (or the objective) of each stage were also brainstormed with the project manager and filled in the FMEA table.

After the pre-population was considered complete, a workshop had been conducted with the project manager along with representatives from various teams including design, manufacturing, procurement and marketing. The author acted as the FMEA facilitator and the project manager acted as the scribe. Each identified row in the project FMEA was then scored in the workshop on the basis of the severity, occurrence and detection scales, which were distributed by the author to all the participants before the workshop. The same scales as presented in chapter 4 were used in the AGV project study. The qualitative of the developed project FMEA are shown in tables 5.11, 5.12 and 5.13 .

Using the severity, detection and occurrence scores, the values of criticality index and surprisal were calculated for the existing iteration, whereby no actions had been take to prevent or detect the failure events. These are shown in table 5.14.

The first iteration of analysis shows a total surprisal value of around '60' for the ten failure modes discussed in the workshop. FM#1 came in the red region, followed by FM#3,4,5,7,9, 10 in orange and FM#2 in yellow and rest others in green. Since it was considered as a high surprisal index and a lot of failure modes had been in red and orange category. A decision was taken to take mitigating actions against all the failure modes and re-run the analysis after the actions had been implemented. The actions that were taken for each failure event are shown in Table 5.15 and Table 5.16.

After the actions were taken, the scores were revised and the analysis was re-run for the second iteration. The results from the second analysis have been shown in Table 5.17.

From the first and second analysis done above, it is evident that the implementation of the corrective actions were able to bring the surprisal value down to around 10 from an initial value of around 60. Besides, all the failure modes are now falling in yellow and green regions, meaning that the project managers were able to accept the second iteration as the final one. However, there is still some scope to make further improvements as the surprisal values can still be brought down to zero in an ideal case scenario. Thus, a third analysis was not run as part of this work as the project manager and the stakeholders suggested to re-run the third iteration after the project progress to detailed stages of product development. Having said that, the adoption of parts of the framework using the project FMEA as the underlying tool have proven to be a useful a strategy for making improvements in the projects domain and potentially produce new projects right-first-time.

The project manager found the findings very helpful to develop the countermeasures in a focused and logical manner. However, there were still many aspects of the framework that were not adopted in the chosen project, which include:

- The use of p-diagram to develop a detailed understanding of the project in the environment it operates in. The p-diagrams were not developed as the project manager highlighted it may need more time and resource to illustrate a theory.
- The use of taxonomies to identify more failure events than just the ones available

FM#	Stage	Function	Failure Mode	Failure Cause	Failure Effect	Prevention control	Detection Control
1	Business case	Document the New Product Introduction plan and make it visible to the stakeholders	The plan is not documented until the development kicks off on a specific date (No function)	Project engineer sorting out other project issues and may not have dedicated time available to document everything (resource planning risk)	Development team unsure of the design and build requirements (Time, cost, quality affected in the worst case)	Interviews ongoing to recruit another dedicated project engineer	Project manager is arranging regular meetings with the current project engineer to oversee the progress of the document
2	Business case	Document the New Product Introduction plan and make it visible to the stakeholders	The plan is not properly communicated	Absence of a communication plan (communication risk)	Development team unsure of the design and build requirements (Time, cost, quality affected in the worst case)	RACI has been constructed to know who needs to be informed Modes of communication has also been identified by the project manager	Design team's feedback to the project manager
3	Concept product development	To select a hardware and software solution from various solutions available across the board	Software solutions may not be understood by the hardware team	Lack of communication between the teams (communication risk)	The hardware may not align with the software control making the item inoperable. Several design iterations may be needed to resolve the issues. Project timeline may be affected	None	None

Table 5.11: AGV project FMEA columns

FM#	Stage	Function	Failure Mode	Failure Cause	Failure Effect	Prevention control	Detection Control
4	Concept product development	To select a hardware and software solution from various solutions available across the board that represent the final design	Software solutions may not be available	Software team work with different agile methodology and their priorities and timelines may not align with the hardware team (lack of strategy)	Proof of concept testing may not start on time (The project time and quality may be affected)	None	Emails to the software project manager
5	Concept product development	To select a hardware and software solution from various solutions available across the board that represent the final design	Hardware solution radically differs from the initial proposed concept	Design team continues to change the design uncontrollably without assessing implications on other aspects of the project such as build, testing, compliance etc. (Lack of implementation of process and skills)	Testing result and build quality measures may become outdated. This severely affects the quality of the underlying product. Several iterations of design, build, test will have to be carried out. This may pose adverse effect on cost and time too.	None	DCN (design control note) process to be followed during pre-production stage
6	Concept product development	To select a hardware and software solution from various solutions available across the board	Hardware solution not accepted by the stakeholders	Hardware solution poses the IP risk (legal risk)	The design team will need to go back to the drawing board to propose a new solution	None	Regular design reviews with the legal team
7	Proof of concept build	To build the first proof of concept (PoC) to reflect the design team of the AGVs	Unable to build the PoC on time	Parts may not arrive on time due to Covid-19 impact (Procurement risk)	The build and testing may not start on time. The project may be delayed	None	Project manager getting regular updates from procurement manager

Table 5.12: AGV project FMEA columns (continued)

FM#	Stage	Function	Failure Mode	Failure Cause	Failure Effect	Prevention control	Detection Control
8	Proof of concept build	To build the first proof of concept to reflect the design team of the AGVs	Unable to build the PoC	Poor quality parts that may not represent the drawings (build risk)	The testing is delayed due to the time taken for the build issue resolution. The project schedule may be delayed	The integration supplier is trusted and generally produce good quality parts Manufacturing engineers guide the development of the build SOPs (Standard Operating Procedures) for the supplier	Inspection conducted before testing
9	Proof of concept test	To make a design verification plan and execute it as soon as build is ready	Design verification plan is not executable	Testing team may come up with some tests that requires sophisticated software controls that may be not ready (communication risk)	Some features may remain untested and can only be tested in later developmental stages. It may be expensive to fix the failure modes during the late development stages	None	None
10	Proof of concept test	To make a design verification plan that uncovers all potential modes with the proposed and executed it as soon as the PoC is built	Design verification plan is not exhaustive	Testing team's DVP misses out the verification methods for one or more failure modes (testing risk)	Some features may remain undetected and untested through the project. Undetected failure modes may escape onto the production site compromising the project cost, time and product quality	None	Testing at several development stages e.g. prototype stage and pre-production stage

Table 5.13: AGV project FMEA columns (continued)

FM#	Occurence	Probability of prevention	Detection	Probability of detection	Severity	CI	weight	Surprisal	Surprisal * weight
1	8	0.2	5	0.5	10	80	3	3.321928095	9.965784285
2	3	0.7	5	0.5	10	30	1	1.514573173	1.514573173
3	6	0.4	6	0.4	7	42	2	2.64385619	5.28771238
4	7	0.3	2	0.8	5	35	2	2.058893689	4.117787378
5	6	0.4	6	0.4	8	48	2	2.64385619	5.28771238
6	1	0.999	1	0.999	9	9	1	0.0028868337	0.002886833739
7	7	0.3	2	0.8	5	35	2	2.058893689	4.117787378
8	3	0.7	3	0.7	5	15	1	1.029146346	1.029146346
9	5	0.4	6	0.2	7	35	2	3.64385619	7.28771238
10	5	0.5	10	0.001	10	50	2	10.96578428	21.93156857
								Total surprisal	**60.5426711**

Table 5.14: First iteration for undertaken NPD project FMEA

FM#	Failure Mode	Failure Cause	Action	Comments
1	The plan is not documented until the development kicks off on a specific date (No function)	Project engineer sorting out other project issues and may not have dedicated time available to document everything (resource planning risk)	Project manager to ensure that the documentation is prioritised over other less critical tasks. More regular meetings before the design development kicks off. Accelerate the interview process	The detection control is rated higher because the NPI documentation is overlapping with the design process. This means there may still exist lack of clarity for the designers. The severity is rated higher as the lack of documentation may lead to confusion for the design team and they miss out on safety critical features etc. The recommended actions should bring the occurrence, detection down.
2	The plan is not properly communicated	Absence of a communication plan (communication risk)	Project manager to set up requirements review with the design team	The design team's feedback to the project manager may be late in the process. The recommended actions will bring the detection down.
3	Software solutions may not be understood by the hardware team	Lack of communication between the teams (communication risk)	Set up regular reviews with the software project manager Various hardware streams' representative to attend regular software demos to keep up with the progress software team has made	The occurrence is scored on the basis of experience with the past projects. The detection is scored higher as some software and hardware features may still not align and may be detected post design freeze only. The recommended actions should bring the occurrence and detection down
4	Software solutions may not be available	Software team work with different agile methodology and their priorities and timelines may not align with the hardware team (lack of strategy)	Contact the program manager to guide the alignment of hardware and software C-level project plans, such that common timeline for delivery may be agreed Escalate the issues to the program manager as necessary	The occurrence is scored on the basis of experience with the past projects. The recommended actions should bring the occurrence down

Table 5.15: Actions taken after the first iteration of project FMEA

FM#	Failure Mode	Failure Cause	Action	Comments
5	Hardware solution radically differs from the initial proposed concept	Design team continues to change the design uncontrollably without assessing implications on other aspects of the project such as build, testing, compliance etc. (Lack of implementation of process and skills)	Develop a process to capture design changes. Designers to be trained for early information based analysis of design, which takes into account manufacturability, reliability, maintainability of the product, such that right-first-time design can be developed.	The detection is scored higher due to the DCN process coming in play in the late design stages The recommended action should bring the detection and occurrence down.
6	Hardware solution not accepted by the stakeholders	Hardware solution poses the IP risk (legal risk)		almost prevention
7	Unable to build the PoC on time	Parts may not arrive on time due to Covid-19 impact (Procurement risk)	Design team to work closely with the procurement team to procure long lead time items	The recommended action will bring the occurrence score down
8	Unable to build the PoC	Poor quality parts that may not represent the drawings (build risk)		
9	Design verification plan is not executable	Testing team may come up with some tests that requires sophisticated software controls that may be not ready (communication risk)	Testing team to liaise with software teams for tests execution	The severity is based on the costs involved for correcting the failure modes The recommended actions will bring the occurrence down
10	Design verification plan is not exhaustive	Testing team's DVP misses out the verification methods for one or more failure modes (testing risk)	Start capturing potential failure modes in the FMEA document. Conduct DFMEAs workshop when design is 60 to 70% mature and construct a DVP&R based on it	The detection is high because there exists no detection opportunity for unidentified failure modes. As a result of this, failure modes will escape into the field. The intention is to identify and detect the failure modes in the PD process.

Table 5.16: Actions within project FMEA (continued)

FM#	New Occurence	Prevention probability	New Detection	Detetion probability	New CI	weight	New Surprisal
1	4	0.6	2	0.8	8	1	1.058893689
2	3	0.7	2	0.8	6	1	0.8365012677
3	3	0.7	4	0.6	12	1	1.251538767
4	4	0.6	2	0.8	8	1	1.058893689
5	4	0.6	5	0.5	20	1	1.736965594
6	1	0.999	1	0.999	1	1	0.0028868337:
7	3	0.7	2	0.8	6	1	0.8365012677
8	3	0.7	3	0.7	9	1	1.029146346
9	4	0.6	5	0.5	20	1	1.736965594
10	2	0.8	5	0.5	10	1	1.321928095
						Total surprisal =	**10.87022114**

Table 5.17: Second and final iteration for undertaken NPD project FMEA

in the risk register. This was again due to the reluctance of the project manager to apply the taxonomies to project FMEA as they were time-pressed to deliver the project and thought that the usage of taxonomies to uncover more failure events than just the ones listed in risk register, may be a time-consuming process.

- The ability to apply the framework to the holistic NPD process in order to uncover all potential failure events.

Like the benefits availed in the grabber module case study, the author suggests that the framework could yield several benefits to the AGV project too, if the concept of p-diagrams and taxonomies (as proposed in chapter 4) were also adopted by the project manager of the AGV project. Moreover, if the analysis could be run at several stages of the NPD process rather than just at the concept stages, it is expected that there are high chances that the AGV project would be able to achieve its objectives right-first-time. These arguments proposed by the author about developing the AGV project right-first-time should be validated in future by applying all parts of the proposed framework to the project, such that none of the failure events and associated countermeasures are missed during the holistic NPD process.

Chapter 6

Conclusions and Future Work

6.1 Research contribution

A right-first-time project is an output of a successful NPD process, where a tangible product is received at the end of the process. The right-first-time development can be understood as a philosophy in new product development, where an NPD project achieves its target requirements including time, cost and quality without having to re-iterate back to the NPD process. In other words, a right-first-time development of an NPD project means there is no need to re-iterate back to the NPD process for resolving the escaped failure modes that get inevitably introduced during the new product development process.

The risks arising due to escaped failure modes can be mild to fatal depending upon their severity and there is a need to minimise highly severe risks in the NPD process. The escaped failure modes can be costly for the product-based companies, therefore potential failure mode avoidance is crucial to guarantee the success of the NPD projects.

An NPD project that follows any NPD process model can be split into three main high-level stages viz. premise, product development and launch. The aim of this research was to examine the feasibility of applying the failure mode avoidance approach in the early information stages, i.e. premise stages of an NPD project in order to identify and treat all possible failure modes that may occur in the holistic NPD process.

Traditionally, the failure mode avoidance approach has been applied to the product development stages of the NPD project in order to achieve a right-first-time product design and a right-first-time product manufacturing. However, none of the conventional failure mode avoidance frameworks have utilised the approach in the context of holistic NPD process. Moreover, the traditional frameworks uses the core tools such as the FMEA, which has been criticised in literature for its structural problems relating to populating the qualitative columns of the FMEA table from top to bottom and the RPN limitations. Therefore, this research has mainly been about developing a new framework that can be applied to the premise stages of an NPD project to foresee all potential failure modes pertaining to the complete NPD process in order to achieve a right-first-time project, whilst also addressing the issues with the FMEA tool that enable NPD failure mode avoidance.

A new failure mode avoidance framework has been developed as part of this thesis. The framework has been developed keeping Cooper's stage gate model in mind. The fundamental basis for the framework is symmetry in the NPD process, which dictates the philosophy of achieving target requirements for the project right-first-time. The symmetry principle emphasize that the achieved output of an NPD project will look exactly the same as the expected NPD project's output at the premise. The best practices from tools such as p-diagrams and FMEA have been adopted to develop the framework. The author also took the opportunity to address the issues pertaining with the FMEA whilst developing the framework. The concept of taxonomies was used to resolve the structural problems with the FMEA, whilst a new method that used two indices namely 'Criticality Index' and 'Surprisal' in conjunction was proposed to analyse and prioritise the failure modes.

The usage of a symmetry principle, adopted from the domain of mathematics and sciences, is the first ever attempt to apply the concept in the context of NPD process. A p-diagram tool is used to illustrate symmetry in the NPD process. It provides a new outlook to conservation laws in the NPD process via treating the failure causes as the fundamental quantity of information. The identification of failure causes (or underlying failure mechanisms) is mandatory as it directly influences the development of countermeasures. According to the proposed framework, the key to implementing the countermeasures is to prevent and detect the failure causes.

The tangible contributions of the developed framework include the development of the new: 1) failure identification methods and 2) failure evaluation methods. For the failure identification, several failure taxonomies have been proposed and discussed. These include failure taxonomy for failure effects (e.g. 139 TCQ triangle), failure modes (e.g. no function, partial function etc.) and failure causes (e.g. mistakes in project management, mistakes in strategic management, external factors etc.).

The identification for the failure events is crucial, such that corrective actions can be implemented to avoid the NPD failure modes from happening. The key to identification of a failure modes is to identify the functions. The NPD functions are defined by the target project requirements for a specific NPD project written in terms of the dimensions on the NPD project triangle. An inability of the project team to miss a NPD stage's function means a missed failure mode and the corresponding effects. Similarly, an ability to miss a failure mode means missed corresponding causes. And if the causes are not identified, the countermeasures cannot be taken. Therefore, in order to make as many failure causes as possible known to the project manager, the taxonomies should be used by them, as they provide a logical way to think about the failure events in the NPD process.

An extension of NPD project triangle is proposed in the scope of this work, which is referred to as 139TCQ triangle. The 139 TCQ triangle is named after 1, 3 and 9 sub-dimensions for time, cost and quality respectively. The 139TCQ triangle helps the project managers and sponsors define the requirements for the NPD project in a systematic manner, such that an exhaustive list of project requirements can be produced. A deviation from the 139TCQ triangle is considered as the NPD failure mode (or simply put as a failure event) for the NPD project [1]. The 139TCQ triangle defines the taxonomy for the failure effects in the NPD project domain. Similarly, a new taxonomy for NPD failure causes has also been proposed.

The usage of taxonomies is beneficial for failure identification, however their analysis and evaluation is another important step too, so that the failure modes and causes can be prioritised. The avoidance and mitigation controls (or countermeasures) taken for a prioritised list of failures makes the Failure Mode Avoidance methodology a pragmatic one, because treating all failure causes (no matter how severe they are) with countermeasures is a costly affair and there may exist a need to not treat specific failure causes if they do not do too much harm to the project.

Once the framework was developed, it was then tested in two domains: 1) In product design sub-stage of an NPD project and 2) In premise stage of an NPD project. The first application is not novel since the traditional frameworks had already been applied into this domain. However, the application of the framework gave author an opportunity to test and validate the framework in an already tested domain, whilst also realizing all possible benefits offered by the framework in the product design domain. Interestingly, the new framework was able to yield several benefits including the following:

- The framework provided a genuine proactive approach to avoid and mitigate failure modes in the early design phases of the product development.
- The framework helped engineers to resolve structural problems with the FMEA in order to populate product-related failure modes in a logical manner.

[1] A failure event as discussed in the scope of this thesis, depicts the pathway of a failure from failure cause to failure mode to failure effects.

- The framework was able to prioritise the failure events in an analytical manner.
- The framework was able to provide analytics to generate visual plots that demonstrated the progress made by applying the countermeasures.

The second application of the framework was novel as it was the first attempt known so far to apply the failure mode avoidance in the premise stages of NPD project. The original intention was to foresee all possible failure events pertaining to several stages of an NPD project. However, due to time and resource limitations, only the part of the framework could be applied to part of the NPD process to highlight the potential risks known at the time of "business planning" stage of the NPD project. The verbal feedback collected from the users of the framework after the execution of the frameworks in two separate domains highlighted the effectiveness of the development framework in project as well as product domain. Also, it was agreed between the author and the users that the framework should be implemented after every stage-gate of the project to plan ahead and treat all foreseeable failure modes associated with the project. Both the case studies were terminated by their respective project managers as they deemed the process time-consuming and suggested that they are satisfied with the amount of residual risk present in the project after the countermeasures were implemented.

6.2 Limitations and future work

The developed framework was considered as a time-consuming process. Besides, the case studies were terminated by their respective project manager and the author on the basis of their intuitions. There was no set target surprisal value that could dictate when to stop using the method dictated by the framework. Also, it was highlighted that the individuals of the organisation need to be trained to adopt the principles of the framework. Considering the current practices in the NPD industry encourages the use of tools and methods like risk registers, Monte Carlo simulations and traditional project FMEA, it is not clear if the proposed framework is better than the current ones in practice. The comparative study between the existing tools that evaluate the project risks and the developed framework can be undertaken as part of future research.

The NPD Failure Mode Avoidance framework is generic and can be implemented at project, design or manufacturing levels to produce right-first-time project, design and manufacturing respectively. In the scope of this work, the framework has been applied in engineering design phase and the concept phase of the NPD process. Due to the time limitations, only part of the framework could be applied to premise stages of the NPD project. Therefore, further work is needed to expand the application to the holistic NPD process. A future opportunity exists to apply it in various stages of NPD project and yield all possible benefits. Since the framework was able to work in at least two domains viz. project design and product design of the NPD process, it is expected that the framework is likely to work in the holistic context of NPD process too. Care should however be taken to adapt the taxonomies based on where the framework is being applied.

Based on the experience gained whilst conducting this research, the author recognises few limitations in this work. In reality it might be a difficult task to fully implement Failure Mode Avoidance methodology due to various technical and cultural challenges involved [Campean and Henshall, 2013b]. The technical challenges are related to identifying and preventing all failures early. Also, it may not be possible to identify the failure modes due to their complex nature. Hillson [2016] illustrates four reasons for inability of removing all risks, which author believes are also in line with inability of removing all failure modes during the NPD process. The reasons for this inability are related to five types of failure modes that are discussed below.

- *Foreseeable knowable*: This type of failure modes are the ones that can be foreseen at a given time and, in principle, are complete known to a team evaluating failures, such that mitigating actions can be taken against them to prevent them going forward to the later stages of NPD process.
- *Time-dependent knowable*: These failure modes cannot be foreseen at given point in time, however become known as time passes by. These type of failure modes can be prevented from escaping into the field if failures and risks are evaluated at regular intervals of time such that mitigation actions [2] can be taken before product is released to the market.
- *Side-effects knowable*: These failure modes are response-dependent, which arise as a result of fixing another known failure mode. It may be possible to identify such kind of failure modes through detailed failure analysis carried out every time as soon as a mitigation action is taken against another failure mode, but may require tremendous efforts to do so.
- *Interaction knowable*: These failure are progress-dependent, which means that they emerge as a result of integration of two or more sub-systems or modules. This integration is essential as it enable progress of an NPD project. For instance, there may be generation of some "interaction" failure modes when

[2] Mitigation action (or countermeasure) is any specific preventative control taken by a product-based company against a known failure mode as soon as they are identified to either: 1) eliminate it completely or, 2) reduce the likelihood of its occurrence or, 3) lessen its severity.

two functional modules of a system are joined together. The module themselves may or may not have a known failure mode associated with them, however the integration of one with other may result in another set of failure modes. Since these types of failure modes are mostly unforeseeable until the progress have been made, they can be difficult to be prevented anytime earlier.

- *Unknowables*: Some failure modes are inherently unknowable, which remain invisible throughout the NPD process and cannot be identified by the manufacturer as a failure until they appear as a surprise in the field.

Failure to miss any of five types of failure modes may serve as the main reason for "escaped failure modes". Out of five types of failure modes discussed above, failure modes that are inherently unknowable will always come as a surprise even though expert failure analysts take extraordinary efforts to identify the failures [Hillson, 2016]. This means no matter how many efforts have been undertaken to identify and treat failure modes early in the information stages of NPD process, there will always be a small percentage of failure modes that will progress to the next stages of development.

The inability to identify all failure modes arise due to: 1) complex nature of failure modes and; 2) the complexity involved in identifying them in early information stages. Considering the vast amount of challenges involved, an application of the framework in the complex multi-disciplinary systems will serve as an interesting future piece of work for the research community.

Apart from the technical challenges, there are organisational and cultural challenges that may restrict the companies from applying Failure Mode Avoidance principles. These are related to: 1) costs needed to adopt the Failure Mode Avoidance methodology, which can also be understood as cost of good quality, 2) companies' reluctance to invest costs and time on something that they are not able to see physically as the Failure Mode Avoidance principles demand the organisations to start improving the quality of projects right from the information based phases, where much of the hardware is not available and; 3) companies not having a system engineering focus and a disciplined framework in place that enable the companies to apply the Failure Mode Avoidance principles in a structured and systematic manner.

The company where the framework has been implemented is an innovative company that believes in trialling out new things that drive improvement. However, there may be other companies who may disregard adopting the Failure Mode Avoidance framework, as it is a modern approach that requires people to change their mind-set and think in a set logical pattern. Besides, it is also observed that the Failure Mode Avoidance implementation requires more time and efforts in the information based phases of the NPD process. However, some companies may want to progress to the material stages of the product development, without spending much time in the information stages. Thus, the implementation of Failure Mode Avoidance approach requires strong business case in order to influence the adoption of the new change required in the company. As part of future work, academics and NPD practitioners are encouraged to adopt the method in different industry sectors such as food, petroleum, finance; such that more NPD organisations may benefit from the effectiveness of the proposed Failure Mode Avoidance method.

Some projects may be incredibly large and complex as there may be several phases through which the product need to go through. For more complex projects, systems engineering approach need to be adopted to break the project down into clusters, such that each cluster may benefit from the implementation of the proposed framework.

The implementation of framework is currently made possible due to coded spreadsheets, however the process of failure identification had been cumbersome based on the manual entries made by the researcher during brainstorming sessions with design and manufacturing engineers and project managers. Thus, there exists a need to develop a knowledge based system that that can automatically retrieve the failure causes and modes information as soon as an NPD stage or a product function or an item is entered into the system. This is possible via the use of taxonomies presented in the scope of this work. The taxonomies can be coded into a software system that acts as the knowledge based reservoir for the NPD practitioners. As an initial version of the software, the information gained through this work can be coded, however as soon as more information is gained via the application of the framework, the software can be updated accordingly.

Another interesting future work include the cost association with the developed Failure Mode Avoidance framework. Future research can be undertaken to understand the amount of costs that can be saved by applying the Failure Mode Avoidance framework in an industrial context.

Overall, the framework has proven to be highly beneficial for the chosen company as it provides the first steps to the NPD practitioners to develop right-first-time projects and products. The application of NPD Failure Mode Avoidance framework avoids the failure modes to escape into the field that are detrimental to company's success and helps the companies to save costs and time plus ensure quality of their products.

The key points to remember whilst applying the proposed failure mode avoidance framework are as follows:

- Failure Mode Avoidance, which is a method and not a process focuses on minimizing the surprisal and criticality index associated with the failure events that are found in the NPD process. The surprisal index in conjunction with the criticality index gives an indication of the overall project risk. More the surprisal value, more are the chances of having unpleasant surprises in the field. In an ideal case of symmetry, a surprisal value of zero will be observed.

- In order to minimise the asymmetry in the NPD process, the failure causes should be ideally treated with prevention controls (in conjunction with early detection controls) as soon as they are identified or immediately after they are created.

- In order to achieve a symmetry transition from one stage of NPD project to another, the stage gate should be treated as a Gateway not a Milestone. This means that the framework should be applied at each gateway to foresee several ways the project can go wrong and to implement the countermeasures against the identified failure modes.

The developed framework and its application have also revealed that "a visible risk is better than an invisible surprise".

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Appendix A

NPD models

Over the years a lot of researchers (Booz, Allen, and Hamilton, 1982; Cooper, 2001; Crawford, 2001; Ulrich and Eppinger, 2011; Wind, 2001) have developed various NPD processes/models that can assist organisations to successfully introduce new products in the market. However, even though each of these NPD models detail various stages that organisations will have to go through when developing new products, each of these models encompass basic stages of developing a new product. For example, each of the NPD process models introduced in the past years reveal that having a NPD strategy, idea generation, screening, business analysis, product development, testing, and commercialisation are some of the basic stages that all organisations must go through when developing a new product. Prior research (Booz, Allen, and Hamilton, 1987; Cooper, 1999) has confirmed that firms that have some kind of formal NPD process in place perform better than the ones that have no NPD process at all. This is mainly because a NPD process/model facilitates interaction and coordination across different departments of the organisation and ensures that there is careful planning when it comes to NPD. All of these factors, it has been found, not only lead to successful NPD but also allow firms to remain in control of high-risk projects, and fast-track the NPD process (Nicholas and Ledwith, 2006).

The process of developing new products is critical for the success of any company (Westerbeek, 2016). However, in this fast-changing world where customer demands keep evolving continuously, developing new products is not an easy process. But there are various new product development (NDP) models or processes that have been created over the years that can help companies in their quest of introducing new products in the market (Dhargalkar et al., 2016). Let us explore the NPD models that have been introduced over the years and examine which NPD model is still relevant today and suitable to create products for the 21st century.

In the last few decades, a number of NPD processes have been introduced

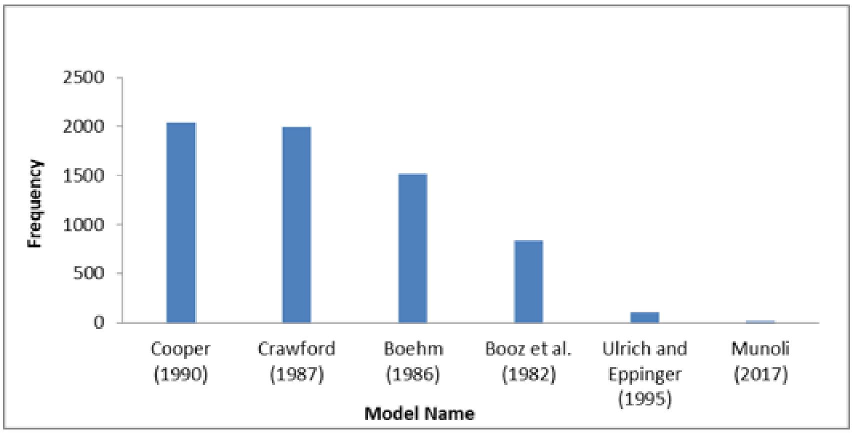

Figure A.1: Frequency of usage of NPD models

and evolved over the years. Some of widely cited NPD process models are the ones introduced by Pahl and Beitz (1996), Blanchard and Fabrycky (1981), Booz et al. (1982), Boehm (1986), Crawford (1987), Cooper (1990, 2001, 2008), Ulrich and Eppinger (1995). Besides, other models such as 3D Hybrid Model by Munoli (2017) and Asimow (1962), can also be found, however their frequency of usage is comparatively less as compared to the models by Booz, Pahl and Beitz, Cooper etc., therefore they will not be discussed further in detail (refer figure A.1).

Let us now discuss some widely cited NPD models one by one.

Booz et al. (1982), also known as the BAH model, underlies most other NPD models that have been created over the years (Bhuiyan, 2011), and has served as a guide for managers seeking to develop new products (Dhargalkar, 2016). The BAH Model consists of seven steps (See Figure A.2) namely new product strategy, idea generation, screening and evaluation, business analysis, development, testing, and commercialisation. As per this model, all the seven stages must occur in linear sequence (Booz et al., 1982). This process has been criticised for leading to a lot of sunk costs because testing of the product occurs only at the end of the process or at a time when all the costs have been incurred (Dhargalkar, 2016).

After Booz et al. (1982) introduced their model; Boehm (1986) introduced a new NPD process known as Spiral Process. This model was developed and largely used to manage large government software projects. The spiral model begins with identification of objectives, offers alternative means of implementation and application of alternatives. When doing so, the designers are able to identify and eliminate any risks they come across and come up with cost-effective alternatives to counter the risks and then test prototypes. Even though the model provides a definite structure to develop complex innovative products, it has been criticised for not accommodating any kind of software enhancement and maintenance that may arise during the life

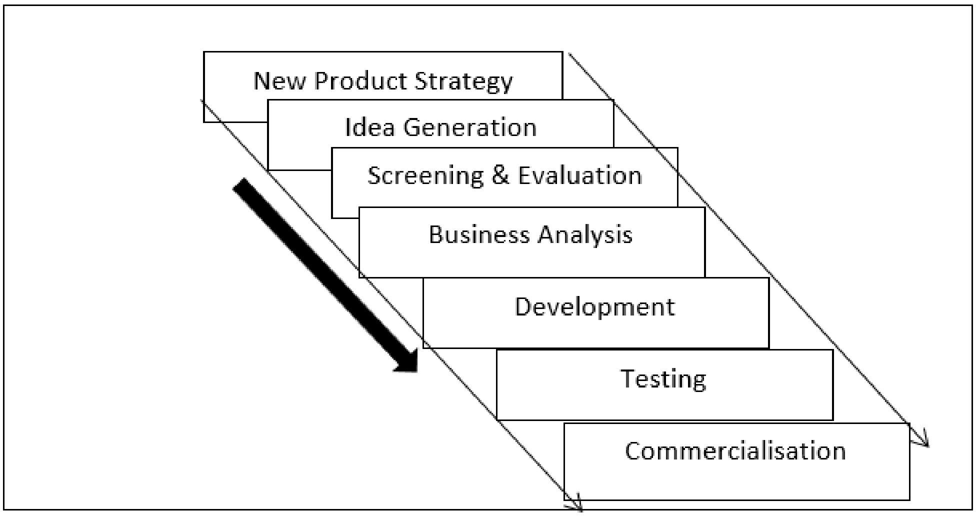

Figure A.2: New Product Development Process (Booz et al., 1982)

cycle of the software (Munoli, 2017). Since the model was originally developed for software development, it is still commonly used in the software industry as an agile methodology where dedicated project teams develop software in different short development cycles (Li et al., 2017).

In the year 1987, Crawford (1987) introduced an NPD process which was divided into five categories namely: Opportunity Identification and Selection, Concept Generation, Concept/Project Evaluation, Development and Launch (Crawford, 1987). Even though this model was largely based on the model introduced by Booz et al. (1982), in his model, Crawford (1987) highlighted the drawbacks that may arise from implementing a linear or sequential process. The author indicated that the various stages in the NPD process are less linear and more flexible and often overlap each other. Unlike the NPD process introduced by Booz et al. (1987), Crawford (1987) also highlighted the importance of introducing review points throughout the NPD process.

Another widely recognised NPD process is the one introduced by Cooper (1990). Known as the Stage-Gate Model, the NPD process is structured mainly with five stages namely discovery, scoping, business case creation, development, testing and validation, and launch. Each Stage of the model is followed by Go/Kill Decision Gates which serve as quality-control checkpoints to ensure the quality of the product. In other words, the Stage-Gate model, in its simplest form, consists of (1) a series of stages and (2) gates, where go/kill decisions are made to make sure whether to go ahead or invest in the project or kill the project. The gates often consist of cross-functional teams which carry out activities within each stage in parallel (Cooper, 2008). It is worth noting that this model has evolved and improved over

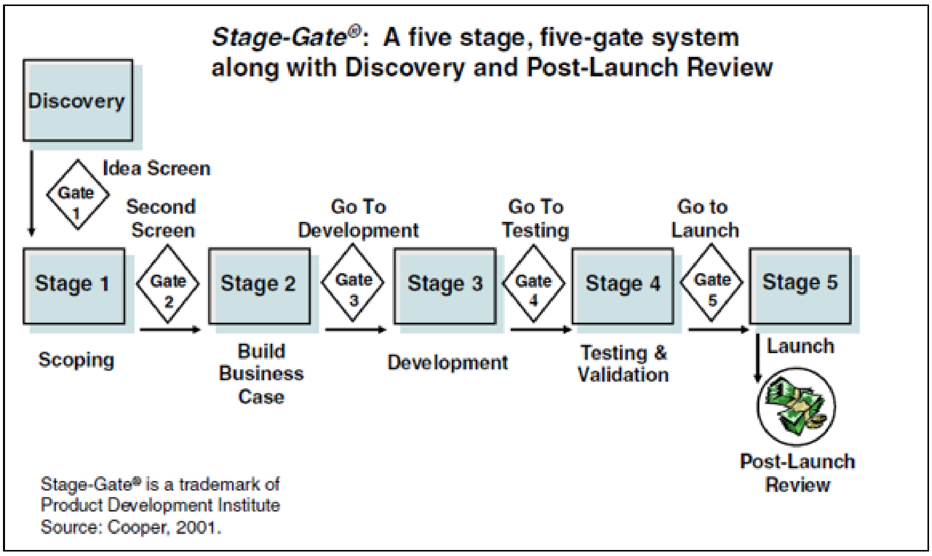

Figure A.3: Cooper (2001) NPD model

the years. For example, when it was first introduced by Cooper in the year 1990, the model started with the idea generation but did not mention how to come up with the idea. Therefore, Cooper (2001) refined the model and came up with the Discovery phase and Post Launch review phase (See Figure A.3).

The traditional stage-gate model has been further refined by Cooper (2014) where a triple 'A' system has been introduced and integrated to the stage-gate process (see figure 5). The triple A system has mainly 3 elements viz. "Adaptive and flexible", "Agile" and "Accelerated". To make the traditional stage-gate model adaptive and flexible, Cooper (2014) indicates mainly two approaches: 1) A spiral development of a new product that might be less than 50% defined with several iterations of build, test, feedback, revise cycles. This type of development aims to get customer ideas and feedback at every stage of the development wherever possible; and 2) A scalable NPD process that focuses on merging two or more stages of new product development in one. This approach may be needed to suit individual project needs as one size of NPD model chosen for the organisation may not be the best fit for all the projects (Cooper, 2019).

To make the traditional stage-gate model agile in order to speed up the processes and minimize waste at the same time, Cooper (2014) introduced a hybrid agile stage-gate model that emphasizes on the integration of time-boxed sprints/scrums and demos as part of every stage. This type of model may be relevant for the development of smart products of today's era where software and hardware teams can work together effectively and efficiently. To summarise the paragraphs around stage-gate model, Cooper's (1990, 2001, 2008, 2014) has been continuously evolved

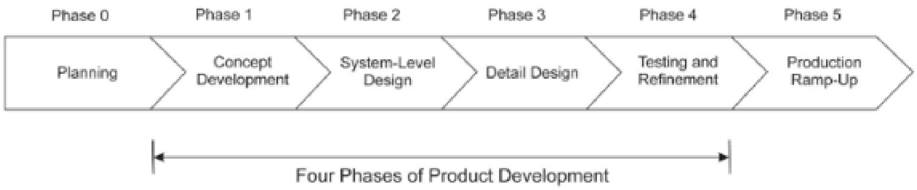

Figure A.4: NPD Ulrich(1995) Model

and has been highly appreciated for speeding up the product life cycle, reducing rework and other forms of waste (Dhargalkar, 2016). The Stage-Gate model not only became a popular system for driving new products but also served as the basis for new NPD models such as the one introduced by Ulrich and Eppinger (1995) and Schilling and Hill (1998). The NPD process introduced by Ulrich and Eppinger (1995) is a well-adopted stage-gate model for physical product development and consists of six high-level steps (see figure A.4) and helps coordination between cross-functional teams at every stage. This feature of the model helps in identifying opportunities for improvement and evaluates the costs of the product (Westerbeek, 2016). However, this NPD process has been criticised for being too design-specific and aimed at mostly creating the industrial products (Dhargalkar, 2016). On the other hand, in their model, Schilling and Hill (1998) suggested a more parallel process without gatekeepers that stimulated more communication across cross-functional teams as a way to shorten cycle teams and decrease the risk of failures in the NPD process.

Some other popular models include Pahl and Beitz (1996), Pugh (1991), Rozenfeld et al. (2006) and Back et al. (2008).

Recently in 2017, Munoli (2017) introduced a NPD process model known as the 3D Hybrid Model for NPD. The NPD process comprises four phases that include: a) Need Cycle; b) Technology Solution Cycle; c) Design Solution Cycle and; d) Manufacturing Solution. According to Munoli (2017), the 3D Hybrid Model incorporates the structures from already existing NPD processes such as Stage-Gate Model and the Spiral Model. The author adds that similar to the other existing NPD processes, the 3D Hybrid Model has the potential to eliminate some issues that may arise during the product development process, but still needs to be tested further to know if it can eliminate all the shortcomings and issues that existing NPD processes face.

As can be seen from the discussion above, different NPD processes have been introduced over the years. There is no doubt that each of these processes has different stages but each of these NPD processes relies on the same basics i.e. generation of new ideas to the launch of the product (Westerbeek, 2016). In table A.1, the most widely used models have been summarised and some similarities within the models can be identified. Almost all the widely used models have common pattern namely starting with: a) Premise – comprising of pre-development stages pertaining to fuzzy front end (FFE), project planning and idea generation; b) Product Development comprising of product building stages such as product design, testing and production; and c) Market Launch comprising of activities such as commercializing the product, marketing, and post launch review.

It can now be noted that the NPD models share commonalities as their respective stages can be broadly fitted into premise, development and launch categories. However, out of several models that exist, which one of them is most suitable for right-first-time development is still a question. Besides, the emergence of new information and communication technologies (ICTs) over the years have dramatically changed traditional products towards intelligent, connected "Smart Products" and created a need for developing radically new engineering processes (Abramovici et al., 2016; Li et al., 2019). In their work Nunes et al. (2017) term these new NPD processes as smart products development (SPD) approaches. The recent ICT innovations have given rise to new SPD approaches that no longer concentrate only on the early phase of product life cycles or fuzzy front end, (Westerbeek, 2016; Li et al., 2019) but also on the product use phase (Abramovici et al., 2016).

Owens (2009) analyses the usefulness of existing NPD processes discussed above. In his analysis, the author states that all the NPD models are good examples of different ways of modelling the product development process but there is no one single NPD model that is exhaustive and can guarantee NPD success. However, the author states that knowing which NPD model may work for a company is a question of practicality and that if a company somehow captures the importance of the diversity that exists in each area of NPD, it has a better understanding of how to improve the process, and follows the path that any NPD process takes can reap tangible benefits that come with following formal NPD processes. The author also adds that to make any product successful or to ensure that the NPD processes really work; they not only need to be much more flexible, but also emphasise on addressing the needs of the customers throughout the product development process. Based on these lines, it can be said that the Stage-Gate Model introduced by Cooper (1990) remains relevant even today as it has been continuously evolved and upgraded to meet the changing needs of the consumers.

Name of Model	Stages Relevant to **Premise**	Stages Relevant to **Product Development**	Stages Relevant to **Market Launch**
Booz et al. (1982)	New Product Strategy, Idea Generation	Screening & Evaluation, Business Analysis, Design & Development	Commercialisation
Crawford (1987)	New Product Opportunity	Concept Generation, Concept/Project Evaluation, Development	Launch
Cooper (1990)	Discovery/Scoping/Business Case	Development, Testing and Validation	Post Launch Review
Ulrich and Eppinger (1995)	Planning	Concept Development System-Level Design, Detail Design, Testing and Refinement	Production Ramp-up
Schilling and Hill (1998)	Opportunity Identification,	Concept Development, Product Design, Process Design	Commercial Production
Pugh (1991)	Market, specification	Concept design, detail design, manufacture	Sell
Pahl and Beitz (1996)	Clarification of the task	Conceptual design, embodiment design, detail design	-
Back et al. (2008)	Project planning	Informational design, conceptual design, preliminary design, detail design, preparing the product production	Launching, validation
Rozenfeld et al. (2006)	Strategic product planning, Project planning	Informational design, conceptual design, detail design, preparing the product production	Launching of the product

Table A.1: Categorisation of NPD model stages in 3 phases

Appendix B

Complexity in identifying ALL failure modes

It might be a difficult task to fully implement Failure Mode Avoidance methodology due to challenges involved in five types of failure modes (Campean and Henshall, 2013b; Hillson, 2016).

The classification of failure modes based on the complexity of identifying them is shown in Figure B.1 below.

Failure to miss any of five types of failure modes serve as the main reason for "escaped failure modes".

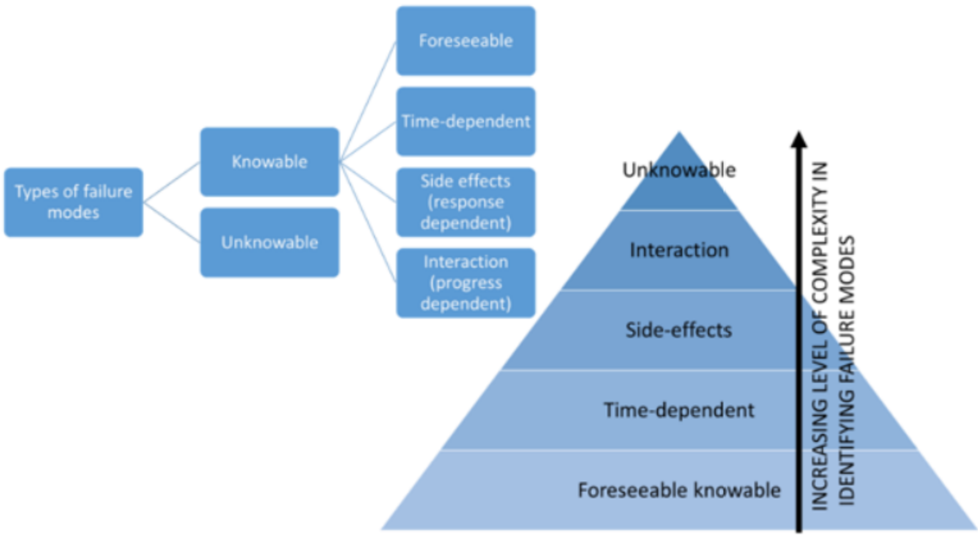

Figure B.1: Types of failure modes-classification based on their nature (Source: adapted from Hillson, 2016)

Appendix C

Ethics Approval

Biomedical and Scientific Research Ethics Committee
Kirby Corner Road
Coventry
CV4 8UW

Tuesday, 05 November 2019

Mrs Anamika Nigam
WMG
University of Warwick
Coventry
CV4 7AL

Dear Mrs Nigam,

Ethical Application Reference: BSREC 22/19-20
Title: Right-first-time development of new products using Failure Mode Avoidance

Thank you for submitting your revisions to the Biomedical and Scientific Research Ethics Committee (BSREC) for consideration. We are pleased to advise you that, under the authority delegated to us by the University of Warwick Research Governance and Ethics Committee, **full approval for your project is hereby granted.**

Before conducting your research it is strongly recommended that you complete the on-line Research Integrity training:
www.warwick.ac.uk/ritraining. Support is available from the BSREC Secretary.

In undertaking your study, you are required to comply with the University of Warwick's Research Code of Practice:
https://warwick.ac.uk/services/ris/research_integrity/code_of_practice_and_policies/research_code_of_practice/

You are also required to familiarise yourself with the University of Warwick's Code of Practice for the Investigation of Research Misconduct:
https://warwick.ac.uk/services/ris/research_integrity/research_misconduct/codeofpractice_researchmisconduct/

You must ensure that you are compliant with all necessary data protection regulations:
https://warwick.ac.uk/services/idc

Please ensure that evidence of all necessary local permissions is provided to BSREC prior to commencing your study.

Please also be aware that BSREC grants **ethical approval** for studies. The seeking and obtaining of all other necessary approvals is the responsibility of the investigator.

Any substantial changes to any aspect of the project will require further review by the Committee and the PI is required to notify the Committee as early as possible should they wish to make any such changes. The BSREC Secretary should be notified of any minor amendments to the study.

May I take this opportunity to wish you the very best of luck with this study.

Yours sincerely

pp.

Professor James Covington
Deputy Chair, Biomedical and Scientific Research Ethics Committee

Appendix D

Consent Form

CONSENT FORM

Participant Identification Number for this study:

Title of Project: Right-first-time development of new products using Failure Mode Avoidance

Name of Researcher(s): Anamika Nigam, Prof. Jeff J. Jones, Prof. Jane Marshall, Prof. Tim Davis

Please initial all boxes

1. I confirm that I have read and understood the participation information leaflet (*version 3, 03/11/19*) for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my *rights* being affected. ☐
3. I understand that data collected during the study, may be looked at by individuals from The University of Warwick, from regulatory authorities, where it is relevant to my taking part in this study. I give permission for these individuals to have access to my data. ☐
4. I understand that data collected will be used to derive research findings. The findings will be presented via a research thesis (submitted to University of Warwick) any other academic publication written by the researcher ☐
5. I am happy for my data to be used in future research. ☐
6. I agree to take part in the above study. ☐

____________________	____________________	____________________
Name of Participant	Date	Signature

Anamika Nigam	____________________	______________
Name of Person taking consent	Date	Signature

Appendix E

Participant Information Leaflet

Participant Information Leaflet

Study Title:	Right-first-time development of new projects using Failure Mode Avoidance
Investigator(s):	Anamika Nigam

Introduction

You are invited to take part in a research study. Before you decide, you need to understand why the research is being done and what it would involve for you. Please take the time to read the following information carefully. Talk to others about the study if you wish.

Please ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Who is organising and funding the study?

The study is being organisation by Mrs. Anamika Nigam, who is a PhD researcher at University of Warwick. The PhD was funded by the International Chancellor's Scholarship and currently being funded by researcher herself.

What is the study about?

The project is focussed on right-first-time development of new products. A "right-first-time" product is defined as a product that is delivered right in terms of quality, cost and time to its customers. Any unintended deviation from these three dimensions of project triangle are referred to as an "escaped failure mode". Escaped failure modes are result of one or more failure modes that are inevitably introduced in the New Product Development (NPD) process. The failure modes in the NPD process arise due to inability of treating all associated risk factors throughout the process. Therefore, NPD based risk management seems to be a strong candidate for achieving success in the NPD process and delivering a right-first-time product. However, literature studies (including Cooper (2019), Kahn et al. (2012) and many others) suggests that the NPD-based risk management is not the only contributing success factor for enhancing NPD performance.

Several other success factors exists, however their contributions towards the right-first-time development of new products is still unknown. Therefore, there is need to carry out a quantitative evaluation of each success factor, such that their rankings and % contributions can be established. This will eventually help NPD organisations to understand where they should be focussing most efforts for ensuing right-first-time development of their products. Besides, this will help the researchers to establish whether or not risk management is the highest contributing factor. An "NPD best practice" framework is also proposed as part of this work, together with which the derived % weightings of each success factor will help evaluate NPD performance of a specific organisation quantitatively. The NPD performance evaluation may act as a KPI for the organisations, such that continual efforts can be made in all possible directions to improve the performance metric to the maximum of organisation's potential.

What would taking part involve?

Taking part in this study will involve the following

- Filling out a questionnaire. The survey will take approximately 9 minutes to complete. Please note your name, email address and current designation will be collected at this time, however this will be kept confidential and will not be disclosed at any time.
- Attend a face-to-face interview. The interview will last for about an hour.

Do I have to take part?

No. Participation in this study is completely voluntary and choosing not to take part will not affect you in any way. You can also choose to withdraw your participation at any time, without giving a reason by contacting one of the research team. Further details about withdrawing from the study are provided later on in this document.

What are the possible benefits of taking part in this study?

The findings from the questionnaire followed by one-to-one NPD expert interviews of ten NPD practitioners can be used by the organisations for the following:

1) It will help your organisation to understand which factors are the highest contributing NPD success factors, such that organisation's management may choose to put more efforts in those areas.
2) To establish an NPD best practices framework, which will be able to quantitatively evaluate NPD performance for your organisation.

What are the possible disadvantages, side effects or risks, of taking part in this study?

There is a slight risk that the participant starts discussing a company specific matter, which is not what researcher is interested in and she is seeking only generic information around the topic. The company-specific matters may be sensitive and confidential. Therefore, it is advised NOT to disclose any company specific matter during the interviews.

Expenses and payments

No payments will be made to the participants for this study.

Will my taking part be kept confidential?

The collected data (in form of physical and electronic copies) will be held securely in researcher's systems and USBs (both password protected) and will remain completely confidential. The collected data (except any personal data such as name, email address) will be shared with researcher's supervisors and will remain intact within researcher's thesis held in University of Warwick Library in the form of electronic as well as hard copies, normally for a period of at least 10 years from the date of thesis publication, which should be no later than May 2020.

The data collected through the questionnaire needs to be linked up with the follow-up questions that will be asked in interviews, therefore there is a need to identify the participants, but this should be noted that none of the personal data including names, associated organisation and email address will NOT be disclosed as part of any publication.

What will happen to the data collected about me?

As a publicly-funded organisation, the University of Warwick have to ensure that it is in the public interest when we use personally-identifiable information from people who have agreed to take part in research. This means that when you agree to take part in a research study, such as this, we will use your data in the ways needed to conduct and analyse the research study.

We will be using information from you in order to undertake this study and will act as the data controller for this study. We are committed to protecting the rights of individuals in line with data protection legislation. The University of Warwick will keep information related to finding for 10 years after the project has finished in May 2020.

Personal data (Name, email address) will be **pseudonymised** as quickly as possible after data collection. This means all direct and indirect identifiers will be removed from the research data and will be replaced with a participant number. The key to identification will be stored separately (for a temporary time period until May 2020) and securely to the research data to safeguard participant's identity.

Research data that may be collected as part of interview process will be **anonymised** as quickly as possible and it will not be possible to withdraw your data after two weeks from your interview.

Your rights to access, change or move your information are limited, as we need to manage your information in specific ways in order for the research to be reliable and accurate. The University of Warwick has in place policies and procedures to keep your data safe.

This data may also be used for future research, including impact activities following review and approval by an independent Research Ethics Committee and subject to your consent at the outset of this research project.

For further information, please refer to the University of Warwick Research Privacy Notice which is available here: https://warwick.ac.uk/services/idc/dataprotection/privacynotices/researchprivacynotice or by contacting the Information and Data Compliance Team at GDPR@warwick.ac.uk.

What will happen if I don't want to carry on being part of the study?

Participation in this study is entirely voluntary, you can withdraw participation from the study without giving a reason and this will not affect you in any way. Please note withdrawing participation is separate to withdrawing data that has already been collected during the study.

If you withdraw from the study, it will often not be possible to withdraw your data which has already been collected, after it has been anonymised. To safeguard your rights, we will use the minimum personally-identifiable information possible and keep the data secure in line with the University's Information and Data Compliance policies.

Participants have the right to withdraw at any point during the study, for any reason, and without any prejudice. Participants may request a withdrawal via emailing Anamika.saxena@warwick.ac.uk and the data (if identifiable) will be deleted from systems immediately. Please note that it will be impossible to withdraw the data after 15/12/2019, as the study and the related findings will be finished by then.

What will happen to the results of the study?

The results of the study will be presented in the thesis submitted to University of Warwick and later to any journal publications related to the topic.

Who has reviewed the study?

This study has been reviewed and given favourable opinion by the University of Warwick's Biomedical & Scientific Research Ethics Committee (BSREC): SREC 22/19-20

Who should I contact if I want further information?

Please contact the corresponding author at Anamika.saxena@warwick.ac.uk and researcher's supervisor at j.a.jones@warwick.ac.uk

Who should I contact if I wish to make a complaint?

Any complaint about the way you have been dealt with during the study or any possible harm you might have suffered will be addressed. Please address your complaint to the person below, who is a senior University of Warwick official entirely independent of this study:

Head of Research Governance
Research & Impact Services
University House
University of Warwick
Coventry
CV4 8UW
Email: researchgovernance@warwick.ac.uk
Tel: 024 76 522746

If you wish to raise a complaint on how we have handled your personal data, you can contact our Data Protection Officer, Anjeli Bajaj, Information and Data Director who will investigate the matter: DPO@warwick.ac.uk.

If you are not satisfied with our response or believe we are processing your personal data in a way that is not lawful you can complain to the Information Commissioner's Office (ICO).

Thank you for taking the time to read this Participant Information Leaflet

Appendix F

Function and Failure mechanism taxonomies

Appendix

Function (verb) taxonomy from Hirtz et. al (2002)

Class	***Secondary***	***Tertiary***	**Correspondents**
Branch	Separate	Separate	Isolate, severe, disjoin
		Divide	Detach, isolate, release, sort, split disconnect, subtract
		Extract	Refine, filter, purify, percolate, strain, clear
		Remove	Cut, drill, lathe, polish, sand
	Distribute	Distribute	Diffuse, dispel, disperse, dissipate, diverge, scatter
Channel	Import	Import	Form entrance, allow, input, capture
	Export	Export	Dispose, eject, emit, empty, remove, destroy, eliminate
	Transfer	Transfer	Carry, deliver
		Transport	Advance, lift, move
		Transmit	Conduct, convey
	Guide	Guide	Direct, Shift, steer, straighten, switch
		Translate	Move, relocate
		Rotate	Spin, turn
		Allow DOF	Constrain, unfasten, unlock
Connect	Couple	Couple	Associate, connect
		Join	Assemble, fasten
		Link	Attach
	Mix	Mix	Add, blend coalesce, combine, pack
Control	Actuate	Actuate	Enable, initiate, start, turn-on
	Regulate	Regulate	Control, equalise, limit, maintain
		Increase	Allow, open
		Decrease	Close, delay, interrupt
	Change	Change	Adjust, modulate, clear, demodulate, invert, normalise, rectify, reset, scale, vary, modify
		Increment	Amplify, enhance, magnify, multiply
		Decrement	Attenuate, damper, reduce
		Shape	Compact, compress, crush, pierce, deform, form
		Condition	Prepare, adapt, treat
	Stop	Stop	End, halt, pause, interrupt, restrain
		Prevent	Disable, turn-off
		Inhibit	Shield, Insulate, protect, resist
Convert	Convert	Convert	Condense, create, decode, differentiate, digitise, encode, evaporate, generate, integrate, liquefy, process, solidify, transform
Provision	Store	Store	Accumulate
	Supply	Contain	Capture, Enclose
		Collect	Absorb, Consume, fill, reserve
		Supply	Provide, replenish, retrieve
Signal	Sense	Sense	Feel, determine
		Detect	Discern, perceive, recognize
		Measure	Identify, Locate

	Indicate	Indicate	Announce, show, denote, record, register
		Track	Mark, time
		Display	Emit, expose, select
	Process	Process	Compare, calculate, check
Support	Stabilise	Stabilise	Steady
	Secure	Secure	Constrain, hold, fix, place
	Position	Position	Align, Locate Orient

Failure Mechanism Taxonomy from Scott et al. (2004)

Primary Identifier	Failure Mode	Definition
Buckling (High and/or point load geometric configuration)	Buckling	An increased deflection of a member after a slight change in load as a result of the geometrical configuration and the combination of magnitude and/or point of load.
Corrosion (Material deterioration due to chemical or electrochemical interaction with environment)	Biological corrosion	The corrosive process resulting from the food ingestion and waste elimination by microorganisms or macro organisms. The waste products of these living organisms act as corrosive media.
	Cavitation erosion	A form of chemical corrosion caused by differences in vapor pressure. Bubbles and cavities within a fluid collapse adjacent to the pressure vessel walls and cause particles of the surface to be expelled thereby baring the material below the surface to the corrosive medium.
	Corrosion fatigue	A failure mode in which corrosion and fatigue combine with each process accelerating the other. The corrosive process forms pits and surface discontinuities that act as stress raisers and accelerate fatigue failure. Cyclic loads or strains lead to cracking and flaking of the corrosion layer baring the material below the surface to the corrosive medium.
	Crevice corrosion	A form of corrosion that occurs within crevices, cracks or joints. Small volume regions of stagnant solution are trapped in contact with the corroding metal.
	Direct chemical attack	A common form of corrosion that occurs when the surface of the machine part exposed to the corrosive media is attacked more or less uniformly over its entire surface. The result is a progressive deterioration and dimensional reduction of load-carrying net cross section.
	Erosion corrosion	A form of chemical attack that occurs when abrasive or viscid material continuously flows past a surface thereby baring the material below the surface to the corrosive medium.
	Galvanic corrosion	Electrochemical corrosion of two dissimilar metals in electrical contact. Current flows through a connecting pool of electrolyte or corrosive medium and leads to corrosion.
	Hydrogen damage	Any damage to a metal caused by the presence of hydrogen or the interaction with hydrogen. Such damage includes hydrogen blistering, hydrogen embrittlement, hydrogen attack, and decarburization.
	Intergranular corrosion	A form of attack that occurs when the formation of galvanic cells precipitate corrosion at grain boundaries of copper, chromium, nickel, aluminum, magnesium, and zinc alloys due to the alloy being improperly heat treated or welded.
	Pitting corrosion	A form of corrosion similar to crevice corrosion leading to the localized development of array of holes or pits that penetrate the metal. The pit can be initiated by a small surface scratch, a defect, or a momentary attack due to a random variation in fluid concentration.
	Selective leaching	A form of corrosion in which one element is preferentially removed from an alloy to obtain a metal that is more resistant to the intended environment.
	Stress corrosion	Occurs when the applied stresses on a machine part in a corrosive media generate a field of localized surface cracks, which usually occur along grain boundaries.

Mechanical

Primary Identifier	Failure Mode	Definition
Creep (Plastic deformation)	Creep	Occurs when the plastic deformation in a machine member accrues over a period of time under the influence of stress and temperature. The accumulated dimensional changes eventually interfere with the ability of the machine part to satisfactorily perform its intended function
	Creep buckling	A delayed result of creep whereby an unstable combination of the loading and geometry of a machine part exceed the critical buckling limit.
	Stress rupture	Rupture into two pieces as a result of stress, time, and temperature. The steady-state creep growth period is often short or nonexistent.
	Thermal/stress relaxation	The relaxation of a prestrained or prestressed member due to the dimensional changes resulting from the creep process.
Ductile deformation (Ductile material)	Brinelling	A static force induced permanent surface discontinuity of significant size occurring between two curved surfaces in contact as a result of local yielding of one or both mating members.
	Force induced elastic deformation	Occurs when the imposed operational loads or temperatures in a machine member result in elastic (recoverable) deformation such that the machine can no longer satisfactorily perform its intended function.
	Yielding	Occurs when the imposed operational loads or motions in a ductile machine member result in plastic (unrecoverable) deformation such that the machine can no longer satisfactorily perform its intended function.
Fatigue (Fluctuating loads or deformation)	High cycle fatigue	The sudden separation of a machine part into two or more pieces occurring when loads or deformations are of such magnitude that more than 10,000 cycles are required to produce failure.
	Impact fatigue	Failure of a machine member by the nucleation and propagation of a fatigue crack that occurs as a result of repetitive impact loading.
	Low cycle fatigue	The sudden separation of a machine part into two or more pieces occurring when loads or deformations are of such magnitude that less than 10,000 cycles are required to produce failure.
	Surface fatigue	Pitting, cracking, and spalling of contacting surfaces (often rolling surfaces) that occur as a result of cyclic contact stresses and cyclic shear stresses below the contacting surface. The cyclic subsurface shear stresses generate cracks that propagate to the contacting surface and dislodge particles to produce surface pitting.
	Thermal fatigue	Occurs when fluctuating temperature fields in the machine part cause load or strain cycling to the point of failure of the machine part.
Fretting (Small amplitude fluctuating loads or deformations at joints not intended to move)	Fretting corrosion	Surface degradation of the material from which the part is made that occurs as a result of fretting action.
	Fretting fatigue	The premature fatigue fracture of a machine part that occurs as a result of conditions that simultaneously produce fretting action and fluctuating loads or strains.
	Fretting wear	The presence of fretting action causes a change in the dimensions of mating parts. The changes in dimensions become large enough to interfere with proper design function or large enough to produce geometrical stress concentrations of such magnitude that failure ensues as a result of excessive local stress levels.
Galling & Seizure (Sliding surfaces)	Galling	Massive surface destruction by welding and tearing, plowing, gouging, significant plastic deformation of surface asperities, and metal transfer between the two surfaces. Occurs when two sliding surfaces are subjected to such a combination of loads, sliding velocities, temperatures, environments, and lubricants that significant impairment to intended sliding surfaces results.
	Seizure	An extension of the galling process that occurs when the two parts are become welded together so that relative motion is no longer possible.

Primary Identifier	Failure Mode	Definition
Impact (Impact load of large magnitude)	Impact deformation	The intolerable elastic or plastic deformation that occurs as a result of impact and causes failure.
	Impact fracture	The magnitudes of the stresses and strains that occur as a result of impact are high enough to cause separation into two or more parts.
	Impact fretting	The fretting action induced by small lateral relative displacements between two surfaces that are not intended to move as they impact together. The small displacements are caused by Poisssan strains or small tangential "glancing" velocity components.
Radiation (Nuclear radiation)	Radiation damage	When the exposure to a nuclear radiation field result in changes in material properties such that the machine part is no longer able to perform its intended function. Radiation exposure usually triggers some other failure mode and is often related to a loss in ductility.
Rupture (Separate into two or more parts)	Brittle fracture	Primary interatomic bonds being broken as a result of elastic deformation and the member, which exhibits brittle behavior, separates into two or more pieces. The fracture exhibits a granular, multifaceted surface.
	Ductile rupture	The plastic deformation in a machine part, which exhibits ductile behavior, to the point of the member separating into two pieces. A dull, fibrous fracture surface results from the propagation of internal voids.
Spalling (Particle spontaneously dislodged from surface)	Spalling	A particle being spontaneously dislodged from the surface of a machine part and prevents the proper function of the member.
Wear (Undesired change in dimension)	Abrasive wear	Occurs when wear particles are removed from the surface by plowing, gouging and cutting action of the asperities of a harder mating surface or by hard particles trapped between the mating surfaces.
	Adhesive wear	A type of wear caused by high local pressure and welding at asperity contact sites followed by motion-induced plastic deformation and rupture of asperity junctions. The result of this form of wear is metal removal or metal transfer.
	Corrosive wear	Occurs when adhesive wear or abrasive wear are combined with conditions that lead to corrosion.
	Deformation wear	A form of wear caused by repeated plastic deformation at the wearing surfaces. A matrix of cracks are produced that grow and coalesce to form wear particles.
	Impact wear	A form of wear caused by repeated elastic deformation at the wearing surface.
	Surface fatigue wear	An occurrence of wear associated with curved surfaces in rolling or sliding contact. Subsurface cyclic shear stresses produce microcracks that propagate to the surface and cause macroscopic particles to be removed by spalling thereby forming wear pits.