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THE DEVELOPMENT OF METHODS TO ESTIMATE AND REDUCE DESIGN REWORK

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The Development of Methods to Estimate and Reduce Design Rework

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ABSTRACT

Design rework includes unnecessary repetition in design tasks to correct design problems. Resolving design matters in advance, through in-depth understanding of the design planning and rework issues and development of effective predictive tools could contribute to higher business profit margins and a faster product time-to-market. This research aims to develop three novel and structured methods to predict the design rework occurrence and effort at the very early design stage, which may otherwise remain undiscovered until the testing and refinement phase.

The major contribution obtained from the Design Rework Probability of Occurrence Estimation method, DRePOE, is the development of design rework drivers. The developed drivers have been synthesised with data from interview results, direct observations, and archival records obtained from eleven world-class aerospace and automotive components manufacturers. To predict the probability of occurrence, the individual score of each driver was compared against historical records utilising the analogy-based method.

The Design Rework Effort Estimation method, DREE, was developed to interconnect functional structures and identify failure relationships among components. A significant contribution of The DREE method is its capability to assess the design rework effort at the component level under the worst-case scenario.

Next a Prioritisation Design by Design Rework Effort Based method, PriDDREB, was developed to provide a tool to forecast the maximum design rework given the constraint. This method provides a tool to determine and prioritise the components that may require a significant design rework effort.

The three methods developed were validated with an automotive water pump, a turbocharger, and a McPherson strut suspension system in accordance with the validation square method. It is demonstrated that DRePOE, DREE, PriDDREB methods can offer the product design team a means to predict the probability of design rework occurrence and assess the required effort during the testing and refinement phase at the very early design phase.

Keywords:
Design rework, Probability, Effort, Estimation,

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PhD. life is filled with difficulties and happiness. The hardest time is when there are no solutions to progress, while the enlightenment provides hope and cheerful moments. However, both of them happen iteratively throughout this learning period.

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LIST OF PUBLICATIONS

Arundachawat, P., Roy, R., Al-Ashaab, A. and Shehab, E. (2009), "Design Rework Prediction in Concurrent Design Environment: Current Trends and Future Research Directions", Proceedings of the 19th CIRP Design Conference–Competitive Design, Cranfield University Press.

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Arundachawat P., Roy R., Al-Ashaab A., (2011)**, "**An Analogy Based Estimation Method for Design Rework Effort", Journal of Intelligent Manufacturing, Published (December 2011)

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TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

TABLE OF EQUATIONS

LIST OF ACRONYMS

AD	Axiomatic Design
AHP	Analytical Hierarchy Process
APQP	Advance Product Quality Planning
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CE	Concurrent Engineering
CPPD	Concurrent Product and Process Development
CR	Consistency Ratio
CER	Cost Estimation Relationships
CI	Consistency Index
CPM	Critical Path Method
CV	Consistency Vector
DC	Digital Confirmation
DD	Digital Development
DFMEA	Design Failure Mode and Effect Analysis
DIR	Design Investigation Review
DP	Design Parameter
DPl	Digital Planning
DPV	Digital Production Vehicle
DREE	Design Rework Effort Estimation
DRePOE	Design Rework Probability of Occurrence
DRF	Dealer Repair Frequency
DSM	Design Structure Matrix
DWG	Drawing
ECI	Engineering Change Instruction
EGR	Exhausted Gas Recirculation
FAST	Function Analysis System Technique
FEA	Finite Element Analysis
FMEA	Failure Mode and Effect Analysis
FR	Function Requirement

FTA	Fault Tree Analysis
GA	Genetic Algorithm
IPSD	Industrial Power Systems Division
LOC	Level of Consistency
MDM	Multi Domain Matrix
MOP	Multicriteria Optimisation
NJ	Number Being Judged
NL	Novelty Level
NPI	New Product Introduction
NTI	New Technology Introduction
OEMs	Original Equipment Manufactures
PCR	Product Change Request
PD	Product Development
PERT	Project Evaluation and Review Technique
PriDDREB	Prioritise Design by Design Rework Effort Based
QC	Quality Control
QP	Quadratic Programming
RCA	Root Cause Analysis
RI	Random Index
RPN	Risk Priority Number
SA	Simulate Annealing
SOP	Start of Production

CHAPTER 1
INTRODUCTION

The aim of this chapter is to introduce the key initiatives in this thesis as well as the research aim and objectives, while chapters 2 to 7 reveal the approach to develop methods to estimate the design rework occurrence and effort. Later, chapters 8 and 9 uncover the systematic procedure to validate all methods developed in this thesis.

From sections 1.1 to 1.6, the research background, industrial context, research questions, research aim, research objectives and the thesis structure are raised consecutively. The research background provides the key ideas of this research topic as well as the initial areas to investigate based on the available literature. There are four aspects to overview in this chapter: design process, Concurrent Engineering (CE), knock-on effect and industrial context. The design process is introduced and then the CE is reviewed in order to provide the context of design activities. Later, the knock-on effect is discussed because it increases the unexpected design rework effort. Moreover, the industrial context is summarised from the secondary data and the industrial meetings in the very early phases of the research.

Afterwards, the research aim and objectives provide the logical guidelines to respond to the research questions. Finally, the thesis structure is highlighted in section 1.6.

1.1 RESEARCH BACKGROUND

The design rework is an undesirable circumstance in the design process because it causes unnecessary repetitive effort to resolve design problems. This extra effort is called design rework effort (Arundachawat et al., 2009). However, a quantity of a design time unit (hours, weeks, months, or years) completed by one person is acknowledged as design effort. Moreover, the design lead time is convertible to be the design effort (Putnam and Myers, 2002). Therefore, the design rework effort could lead to a disagreeable time delay in the design project. Today, the global market is fiercely competitive; hence, shortening the product design and the development time to market is vital for industries. Moreover, increasing lead time and effort in the product design activity causes more damage to organisations than cost overruns (Ford and Sterman, 2003 a, b), because those increases could lead to a loss of opportunity to earn extra profit by one third (Luh et al., 1999).

Figure 1-1 is a generic design process for the initial analysis. In the planning phase, products have to be well defined, from a marketing point of view, in order to develop requirements. Later, activities are further conducted in the concept development, the system-level design and detail design. The testing and refinement is the final stage which is to confirm the product prototype before production.

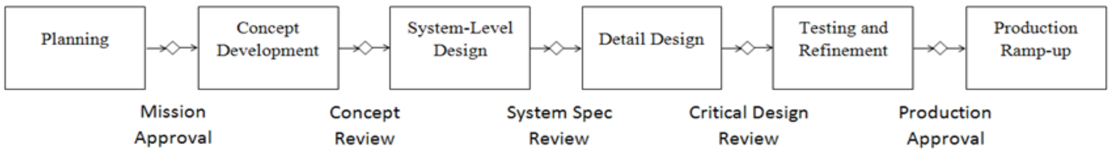


Figure 1-1: Generic design process (Ulrich and Eppinger, 2008)

In summary, every process follows a systematic procedure so that that the individual product fits the customer's needs. However, time taken to reach the acceptable maturity of design in a product depends on each company's core competency.

From Ulrich and Eppinger (2008, p. 15), the testing and refinement phase is an activity in which product prototypes are tested in order to uncover design or other issues and resolve them early on. This is a particularly critical stage because the production ramp-up phase comes immediately afterwards. If completion of the testing and refinement phase is delayed by design failures, it will be risky when the planned schedule for production is reached. If the schedule is maintained regardless of design flaws, the product could confer a high monetary penalty for companies. However, prolonging the production creates the possibility of a lost opportunity, as stated earlier.

Whitney (1991) proposes two alternatives to be investigated in depth, as illustrated in Figure 1-2. Both research directions target to minimse unnecessary iteration or design rework in a product design and development activitiy. It is a best practice that the product design and development must be conducted in collaboration among experts. Therefore, the research in management based intends to eliminate any obstracles related to team work, e.g. communation difficulties among designers and manufacturing engineers.

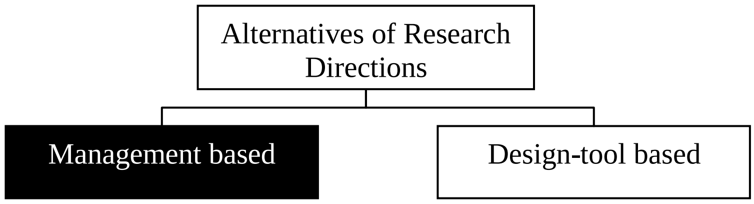


Figure 1-2: Initial paradigm for research directions

On the other hand, a research in design-tool based is focused on the development of methods or techniques to achieve the right first time design concept. For example, a design tool is developed to be able to deliver the design choices providing that each alternative is possible to manufacture.

As a result, both research directions are to enhance the understanding of the state-of-the-art in the design rework effort estimation for the researcher at the very early state of this thesis.

1.1.1 Design rework definition from the state-of-the-art in design rework literature

The definition of the design rework is explicitly reviewed in section 2.1.3. However, the researcher summaries the design rework definition from the state-of-the-art as follows:

"*Design rework comprises unnecessary repetition in design tasks to correct design problems.*"

Moreover, CE and knock-on effect are the additional key words which are found from the state-of-the-art in design rework. Hence, both terms are discussed in sections 1.1.2 and 1.1.3 respectively.

1.1.2 Concurrent Engineering

Both research directions in Figure 1-2 are considered under the CE approach. This approach theoretically aims to reduce design lead time and effort with overlapping design activities, rather than working in sequence (Smith, 1997), as shown in Figure 1-3.

Overlapping induces iterative design within team, and a design solution converges faster than in the sequential design approach (Prasad et al., 1998). However, there are some concerns about optimal overlapping because too much overlapping could cause unnecessary repetition or rework (AitSahlia et al., 1995; Ford and Sterman, 2003b). Accordingly, the design rework effort is one issue that prevents CE from achieving the maximum benefit, and it is one of the key initiatives to be studied in this thesis.

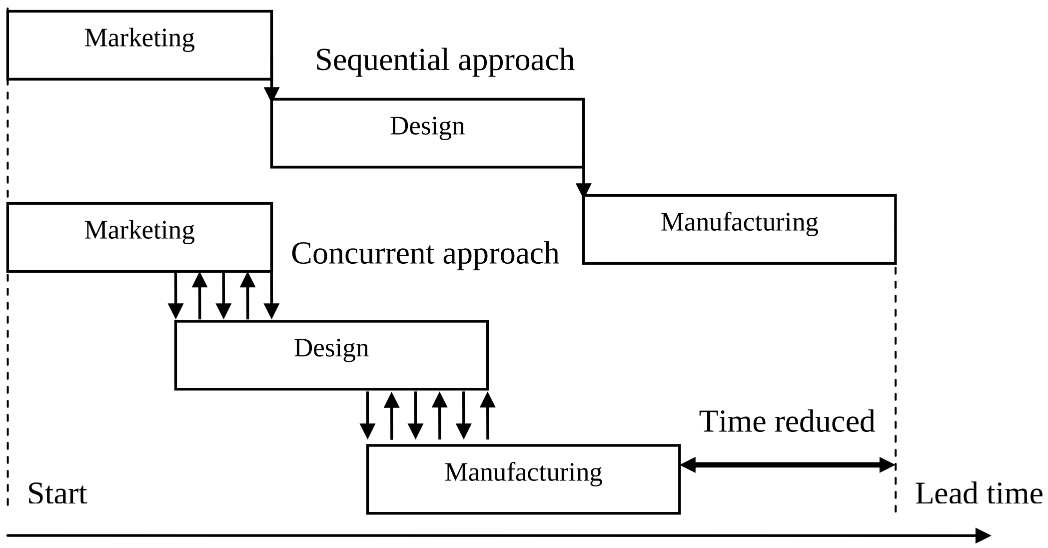


Figure 1-3: Sequential and concurrent design approach (adapted from Yassine et al., 1999)

CE can be cascaded into different levels, as shown in Figure 1-4 (Bowonder et al., 2004). There are three levels in CE: product, project and design concurrencies. Each company can provide a variety of product ranges all of which can be developed in parallel. As a result, this situation is acknowledged as product concurrency.

For example, product 3 in Figure 1-4 is developed from marketing and concept exploration to support process design & development. Moreover, all phases can also be executed concurrently. Finally, the product design & development stage is cascaded to different design activities all of which also work in parallel. This classification makes product design activities complicated. However, it does provide a clearer guideline to analyse the state-of-the-art in design rework.

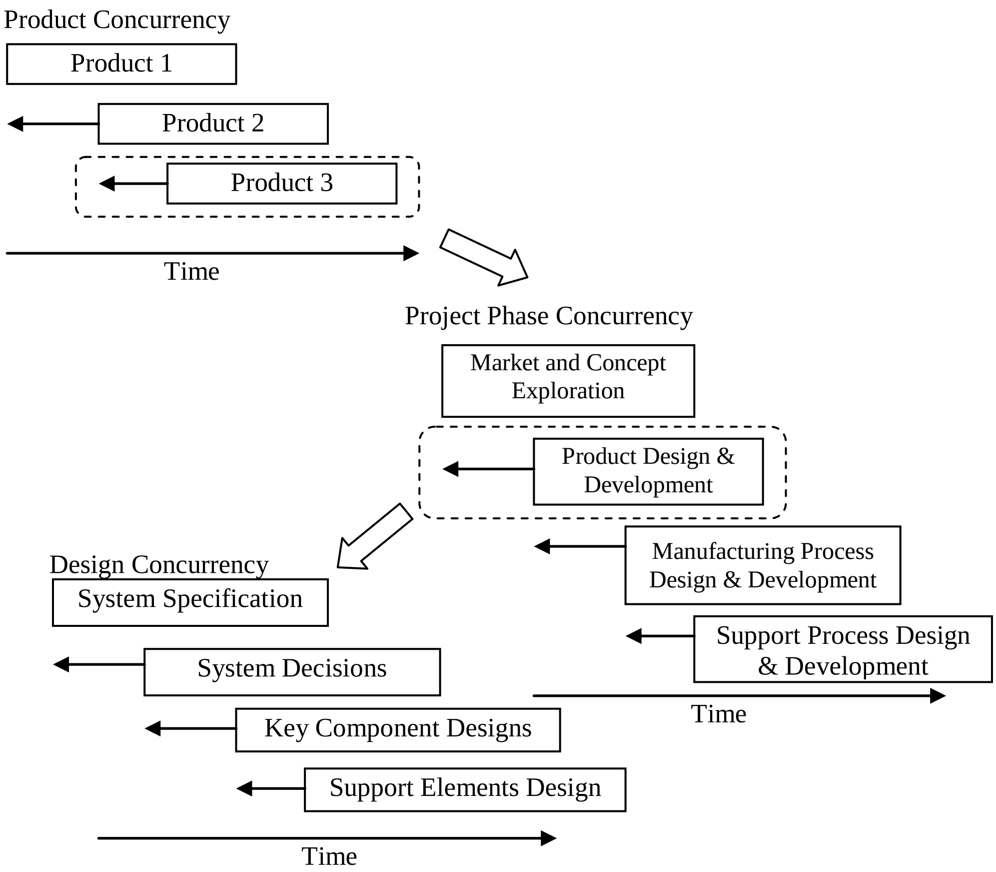


Figure 1-4: The level of concurrent activities within a company (adapted from Bowonder et al., 2004)

1.1.3 Knock-on effect

The knock-on effect is the circumstance when changing from a particular component's design causes the others to alter due to the relationship among them. There are two classifications as follows:

The first is the relationships among design activities in terms of the information exchanged, as shown in Figure 1-3. If customers change their product expectations, any prior design works have to be reworked. As a consequence, every development in manufacturing must be reworked automatically because every activity connects and is executed concurrently. This example is classified as rework from different principles (Clark and Fujimoto, 1989).

The second effect happens among work packages. In principle, changing one entity would impact on another (Hoedemaker et al., 1999, Browning and Eppinger, 2002). Consequently, it makes the design rework problem even more complex.

There is evidence that the delay problems due to design changes cost five times as much as early design alterations (Clarkson et al., 2004).. If the problems are found very late in the programme, they will require a significant design effort to resolve. As a consequence, prolonging the lead time to release of the design is inevitable.

Design rework effort is regarded as a management facet in design because effort allocations are made in the planning phase. Hence, accuracy in the estimation of design lead time and effort is crucial in the early design phase.

1.1.4 90% syndrome

The problem described here is when a project ends up with twice the original project schedule even though it has completed 90% of the planned time. In addition, it is commonly studied in the CE environment (Ford and Sterman, 2003b). Therefore, only the estimated accuracy of design lead time and effort is not enough to overcome the 90% syndrome, but the key challenge is to evaluate the design rework effort. If the design problems and their impacts can be assessed early on, the design flaws can be eliminated proactively. Accordingly, design lead time would be reduced dramatically.

Until recently, there are well known project planning tools such as the Project Evaluation and Review Technique (PERT), Critical Path Method (CPM) and Gantt chart. However, they all have common limitations as follows:

The mentioned tools cannot represent feedbacks (Eppinger et al., 1990); however, the design activities are always embedded with feedbacks (Pugh, 1990). Moreover, the duration of each task is assumed to be prearranged in the existing planning tools. Therefore, the precision of these planning tools relies on the estimated time consumption for each task.

1.2 INDUSTRIAL CONTEXT

This section supports the researcher’s understanding of industrial good practice. Consequently, the data collection can be planned systematically. At present, an extended enterprise is a common industrial practice (see Figure 1-5). At the beginning, each original equipment manufacturer (OEM) receives the customer's requirements, which are then converted into functional requirements (FRs). Later, the product system design is constrained by the FRs. As a result, components in the system are designed to be ready for manufacturing and assembly. Based on the OEMs' strategies, design tasks can be completed either in-house or sub-contracted to suppliers. Therefore, designing a comprehensive product is a collaborative activity.

The extended enterprise is a guideline to the selection of participating companies during the data collection stage. These companies are from the aerospace and automotive industries in order to maintain generalisation. Furthermore, they are from different countries in three continents. Detailed discussions for industrial participants are given in chapter 4.

Two companies provide the industrial case studies in this thesis. Company E offers an automotive water pump and a turbocharger case, while company K proposes a suspension system case. Both companies are introduced in sections 1.2.2 and 1.2.3, respectively.

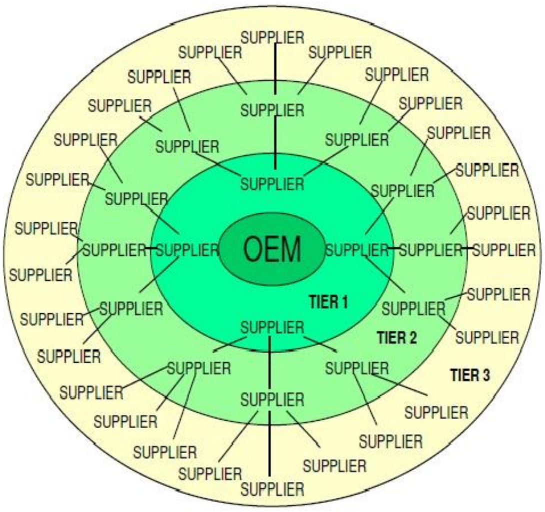


Figure 1-5: Automotive extended enterprise (Oduguwa et al., 2006)

1.2.1 Design rework in industrial context

The correction cost in the product life cycle is insignificant in the early design phase even though the chances of design flaws are significant due to design immaturity. On the other hand, any changes in the later stages are costly and unfavourable. In an industrial context, the preliminary information related to correction cost was derived from the interview with company A’s expert. The design cannot be released unless problems are fully solved. In addition, solving design problems in the stage close to the production deadline results in the significant cost of those corrections (Figure 1-6) and opportunity loss.

Henceforth, the testing and refinement phase is a critical stage because the next phase is the Production Ramp-up or Start of Production (SOP). If any design rework issues occur, there will be a substantial cost of corrections. Not only design effort will be incurred but also other costs, e.g. the cost of modifying the die, opportunity costs, etc. Furthermore, the participants from the aerospace companies suggest that design rework should be controlled to an insignificant level in the development programme. Therefore, industries ideally attempt to eliminate any design flaws in the testing and refinement phase. As a consequence, fulfilling this goal is a real challenge.

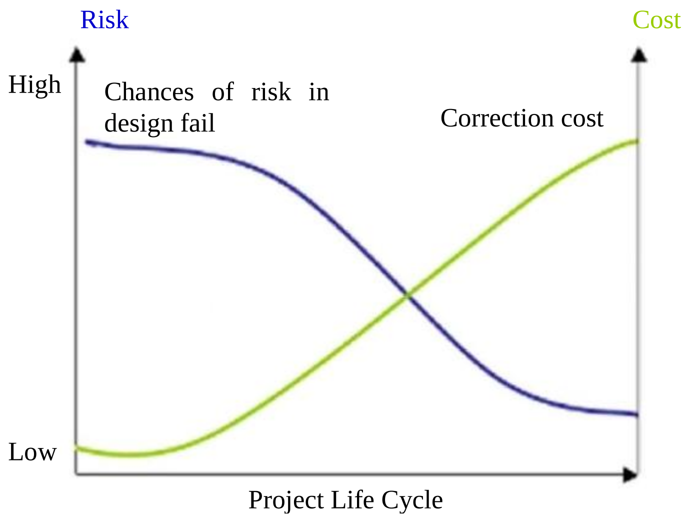


Figure 1-6: Cost of corrections in product design (adapted from Lough et al., 2009)

From the initial understanding, several questions are raised: how to assess the likelihood of design rework occurrence, how to determine the effort required in resolving each design rework problem, and how to enhance a design team to acknowledge design rework upfront. All of these are prepared to be research questions, as shown in section 1.3.

1.2.2 Company E

Company E is a UK automotive OEM. The company provides final products as well as engineering solutions. The main product is an engine as a prime mover for off-highway vehicles and other applications. The engine design and development are constrained by pollution legislations which are acknowledged as the key drivers of product novelty. The distinctive design rework issues are the result of a considerable effort to resolve the problems of the water pump project.

1.2.3 Company K

Company K is a Tier 1 automotive supplier located in Detroit, USA. The company provides engineering solutions as well as parts to Japanese, European and American car OEMs. In addition, there are development centres distributed throughout Europe and Asia.

Company K supplies suspension, chassis and power train parts. Since OEMs' requirements have never been repeated, system and component designs always differ from one OEM to another. Therefore, this variety of demands has become a major driver of the novelty for an individual product being designed. The McPherson strut suspension system is provided as a case study. The design rework issue occurs due to an unidentified failure cause which makes the design team spend additional time and effort to resolve the problem.

1.3 RESEARCH QUESTIONS

The focus of this thesis is to estimate the design rework occurrence and effort in the testing and refinement phase. Moreover, this capability must be available in the early design phase. Accordingly, the key drivers of design rework occurrences must be addressed. In addition, the methodology to assess the likelihood of design rework occurrence is a real challenge.

None of the literature provides a precise method to estimate the design rework effort in the testing and refinement phase. The challenge to achieve this capability is the means to evaluate the knock-on effects in the design rework effort estimation.

The method to evaluate critical components in terms of design rework effort increases designers' level of awareness. However, the challenge occurs when there is relatively minimal experience in the product being designed.

As a last point, validation of all development is necessary. Therefore, the research questions are summarised as follows:

- What are the key drivers of the design rework occurrence?
- How could the probability of the design rework occurrence in the testing and refinement phase be predicted at the early design phase?
- How could a design team consider the knock-on effect from design issues in the testing and refinement phase at the early design phase?
- How could the design team successfully identify groups of components which would incur a significant penalty of the design rework effort?
- How could all of the methods developed in this thesis be validated?

1.4 RESEARCH AIM

The aim of this research is derived from previous sections which is to:

'Develop structured methods for the early design stage to predict the design rework occurrence and effort in the testing and refinement phase.'

1.5 RESEARCH OBJECTIVES

The research objectives are derived from the research questions and the research aim as follows:

- To identify the key drivers for the probability of occurrence of design rework in the testing and refinement phase.
- To develop an estimation method for the design rework probability of occurrence at the early design phase.
- To develop a methodology to estimate the design rework effort with consideration of the knock-on effect at the early design phase.
- To extend the methodology in the third objective to provide a warning about the components which would require the extensive design rework effort to resolve.

- To validate each individual method with industrial experts and case studies.

Objectives 1 and 2 have been consolidated in chapters 4 and 5, while objectives 3, 4 and 5 have been addressed in chapters 6, 7 and 8 respectively. Findings from chapter 4 are further developed in chapters 5, 6 and 7. In addition, the whole research complies with the research protocol, as developed in section 3.8.

1.6 THESIS STRUCTURE

There are nine chapters in this thesis, as illustrated in Figure 1-7. Chapter 2 begins with the keywords to search the literature. The main task is analysing factors that drive design rework issues. The other target to be investigated in this chapter is the estimation methods which allow the prediction of costs in the late stage.

Chapter 3 discusses the research protocol development. The product design activity comprises intellectual properties; hence, few participating companies are expected. Therefore, the research protocol in this thesis must overcome this challenge.

Chapter 4 presents the good practices of industrial design processes. Moreover, issues related to design effort or lead time are analysed. Design rework effort is defined by an industrial context as corrective actions in the testing and refinement phase. In addition, discrepancies between industrial practices and theoretical literature are addressed.

Chapter 5 proposes the Design Rework Probability of Occurrence Estimation (DRePOE) method. It allows estimating the probability of design rework in the testing and refinement phase. In addition, this capability is available for the design team in the early design phase. The detailed developments of the drivers in the estimation are described explicitly. Furthermore, an automotive water pump case is presented in this chapter.

Chapter 6 provides the detailed process to assess design rework effort in the testing and refinement phase named the Design Rework Effort Estimation (DREE) method. In addition, the method allows the design team to perform estimations in the early design phase. The knock-on effects of changing one component to another are considered in this method. In addition, the example of the automotive water pump project is outlined in this chapter.

Chapter 7 reveals the additional development as completed in chapter 6. This chapter establishes the methodology to categorise the components which would deliver the greatest design rework effort. This is called the Prioritise Design by Design Rework Effort Based (PriDDREB) method, and the automotive water pump case is provided as an example.

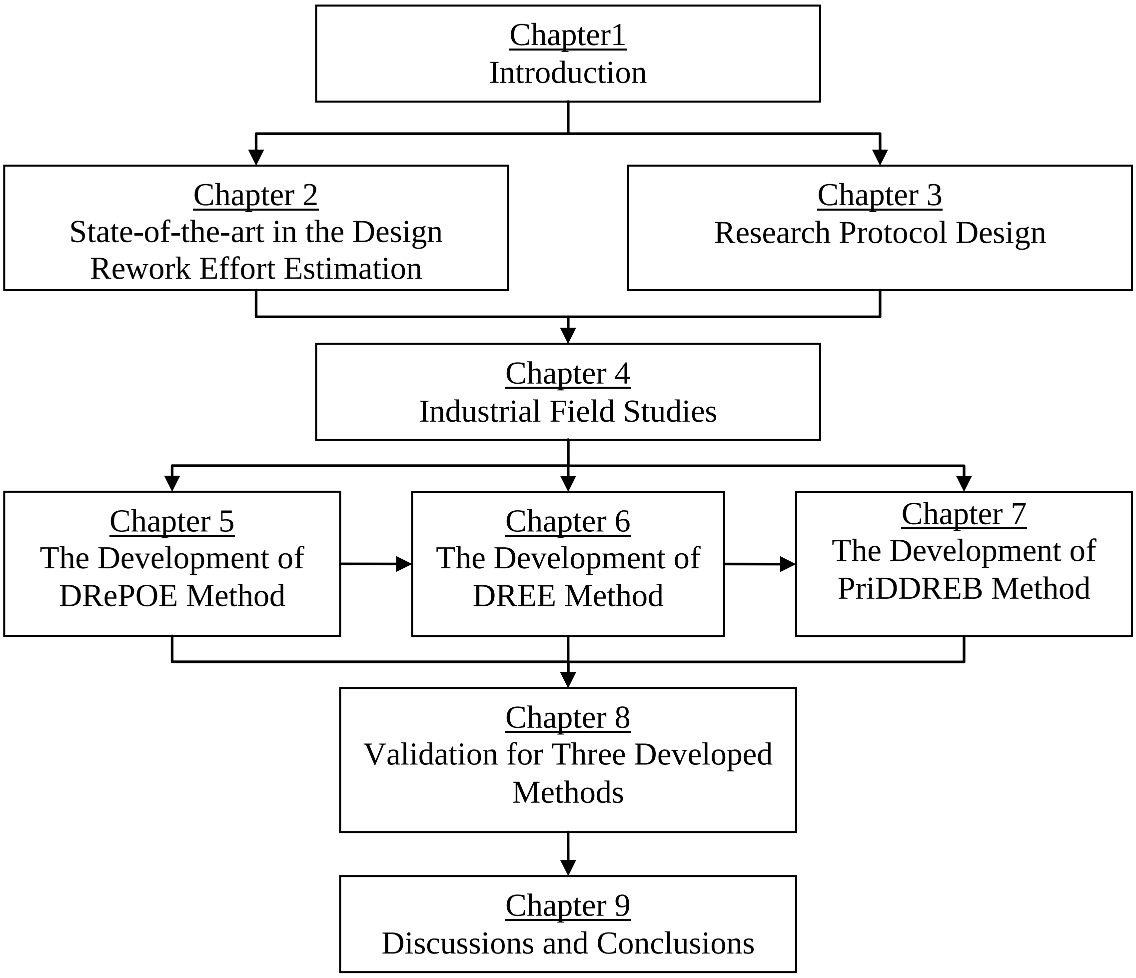


Figure 1-7: Thesis structure

Chapter 8 exposes the validation of all developed methods in this thesis. Industrial case studies, namely the turbocharger and the MacPherson strut suspension system, are additionally assigned to test the methods. Later, all results are discussed by experts from companies E and K.

Chapter 9 reveals the discussions and conclusions of the thesis. The advantages and limitations of each individual method are expressed; furthermore, future works are suggested.

CHAPTER 2
STATE-OF-THE-ART IN THE DESIGN REWORK EFFORT ESTIMATION

The aim of this chapter is to unveil the factors related to design rework issues and review the available tools as well as techniques to develop the design rework estimation methods, both of which are focal points, as detailed in Figure 2-1. Reviewing the state-of-the-art in the design rework was an iterative process. The researcher had focused on the literature related to design rework at the beginning; however, it was later found that there was much fundamental knowledge needed. Therefore, fundamental knowledge and the state-of-the-art in design rework estimation are both required to be investigated, as detailed in sections 2.1 to 2.8.

Sections 2.1 to 2.7 expose the fundamental knowledge which is commonly found in the state-of-the-art in design rework estimation. Moreover, all literature is reviewed through books, journal papers, conference proceedings, theses and the MIT Sloan School of Management Working Paper Series, all of which have been acquired from Scopus and Scholargoogle.

The definitions of design and design rework effort are contrasted in section 2.1. The generic design process and design support tools are reviewed, with the aim of understanding the existing design methods, as shown in sections 2.2, 2.3, 2.4 and 2.5. Furthermore, section 2.6 shows cost and effort estimation methods and how the ability to implement them in the early design phase is the main criterion. Section 2.7 then reviews alternative optimisation techniques for a particular problem. In section 2.8, the state-of-the-art literature related to design lead time and effort estimations is extracted to factors driving design rework. As a result, findings from the literature are outlined in section 2.9.

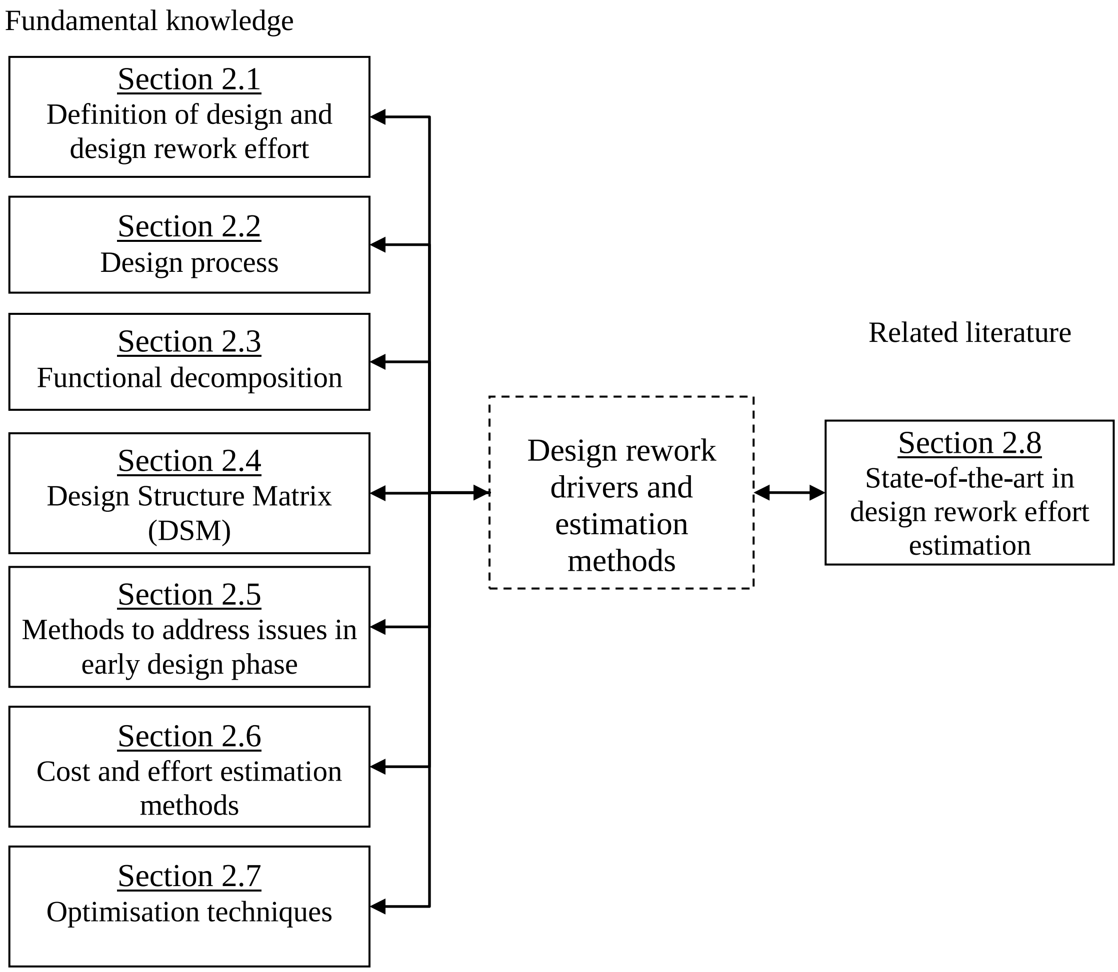


Figure 2-1: State-of-the-art literature related to design rework effort estimation

2.1 DEFINITION OF DESIGN AND DESIGN REWORK EFFORT

The term "*design*" in this thesis covers engineering design only, while other areas such as art work or architecture are not considered. The definition of engineering design is provided in section 2.1.1 while design effort is highlighted in section 2.1.2. Design rework and design changes are discussed in sections 2.1.3 and 2.1.4, respectively.

2.1.1 Engineering Design Definitions

Every physical product must be the outcome of a design process. Since the engineering design is the focus, design and engineering design are used throughout the thesis.

The concept of engineering design can most clearly be understood as a process that links customers to the final products. For example, engineering design is a process to create final products from what customers want (El-Haik and Yang, 1999). To understand what customers want, the problem statements need to undergo stages of synthesis and analysis, and then the specifications of the artefacts are formed (Jin and Chusilp, 2006). The problem statements are derived from finding market needs (Hazelrigg, 2003). On the other hand, the process to convert customers' needs into physical products is composed of decision making stages (Summers and Shah, 2003): product size, shape, configuration, functions and dimensions, etc. (Krishnan and Ulrich, 2001).

Therefore, engineering design is defined as the activities that address the needs of end users and convert them into design specifications or design objectives. Then a design solution is selected from different artefacts aiming to satisfy customer expectations. In summary, designing is the process to create alternatives then select the optimum design to achieve customer requirements (Olewnik and Lewis, 2003).

2.1.2 Design Effort

The term "effort estimation" is widely recognised in costing software development. A man month is determined as a software development effort which is the amount of time spent by one person to complete a software development project (Putnam and Myers, 2002).

Hence, design effort is the duration of time spent by a designer, including management, to finish a design task. It covers the period between the end of the feasibility study until final detailed drawings are released to manufacturing (Bashir and Thomson, 2001). In addition, Roy et al. (2001) define qualitative time and quantitative time in design. The former is the point in time spent to formulate ideas while the latter is the time consumed on modelling the geometry of the physical entities.

In summary, design effort is "*the design time spent by one person to achieve the assigned design task*". In addition, it is considered as time to develop an idea, analysis of design solutions, and time to generate detailed drawings for manufacturing.

2.1.3 Design rework

The term '*design rework*' was noticed early in the construction and engineering design contexts. It is considered as the deviated time plan from real progress in construction projects; moreover, the rework problems are fed back by later activities (Freidrich et al., 1987; Cooper, 1993). At the beginning of this decade, Love and Smith (2003) collected the definition from previous studies, most of which agree with the common definition as being quality deviation from expectations. Furthermore, rework is a result of errors, omissions, failures, damage, and change orders. Therefore, design rework problems cause the unnecessary effort of redoing a process or an activity that was incorrectly implemented the first time.

In an engineering design context, rework is defined as the repetition of a task because it was originally attempted with imperfect information (Smith and Eppinger, 1997). This immature information transferred also happens in a CE context because of overlapping activities in which the preliminary data are sent to the associated tasks in order to begin early. However, any changes or updates cause rework (Krishnan et al., 1997; Loch and Terwiesch, 1998; Qian and Goh, 2008).

Design rework issues, taking into consideration CE and preliminary information exchange, are classified into three types: independent, interdependent, and dependent overlapping (Yassine et al., 1999). From Figure 2-2a, CE gains more benefit from independent overlapping, because there are no relationships among the tasks, so any tasks can start freely. Figure 2-2b illustrates that changing of final information from task *A* causes rework *XB*. Task *A* would also be reworked, if there were feedbacks from task *B* to task *A*. The information updates between tasks *A* and *B* induce design rework effort, as shown as couples of *A1-B1*…*An-Bn*, until mutual results are satisfied. Finally, the downstream fully relies on the upstream which is considered as dependency overlapping execution, as shown in Figure 2-2c. Therefore, dependency among tasks is one major cause of design rework. To emphasise, this classification is fundamental to analysis of the state-of-the-art in design rework, as in section 2-8.

Ballard (2000) mentions the value of iteration in the design process – into positive and negative iterations. Unnecessary iteration is defined as waste in design or negative iteration; for instance design error or design failure due to forgetting or neglecting previously known information or lack of knowledge. This classification is based on the assumption that design is an iterative and generative process by its nature. Negative iteration is what is unnecessary for task completion and value generation; furthermore it can be eliminated without loss of value or having caused failure to complete the project.

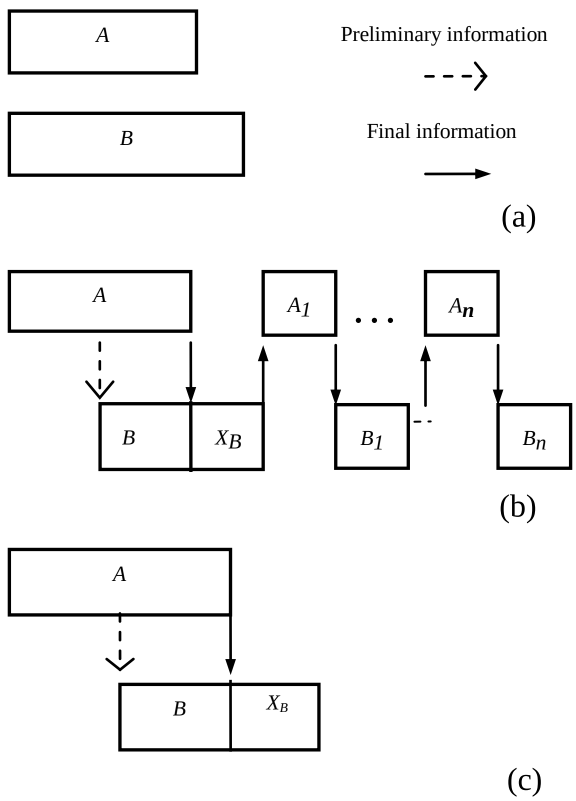


Figure 2-2: Overlapping tasks in CE a) Independent b) Interdependent c) Dependent (adapted from Yassine et al., 1999)

Cho and Eppinger (2001) outlined that rework is triggered by other tasks due to three causes: receiving new information from overlapping tasks, probabilistic change of inputs from other reworked tasks, and probabilistic failure to meet the established criteria. Hence, rework problems are stochastic circumstances; however, dependencies among design activities are still the main drivers of rework.

In summary, design rework occurs due to dependency among design tasks, and incorrect information transferred among design activities is the other key factor stimulating the severity of design rework. Therefore, the definition of design rework is summarised as follows:

"*Design rework comprises unnecessary repetition in design tasks to correct design problems.*" Thus, design effort spent on this rework activity is called "*design rework effort*".

2.1.4 Design change

The purpose of reviewing the literature related to design change is to differentiate it from design rework. Rouibah and Caskey (2003) emphasise that well managed engineering changes lead to shorter lead time and reduced cost. Changes are from iterations during product design and development, and early change requests cost less than those close to the delivery date. The changes would be either due to resolving a design conflict or satisfying emerging requirements.

Clarkson et al. (2004) developed a risk assessment method to predict the impact of changes from one component to another. The root causes of change are either the elimination of mistakes during design or adaptation to new requirements. In addition, evolutionary changes from old to new versions of a product are also considered in this method. Oduguwa et al. (2006) directly focus on the cost impact from requirement changes.

From the definition of design rework in section 2.1.3, design rework complies with changes due to mistakes occurring during design rather than changes due to new requirements.

2.1.5 Key observations from reviewing the definitions of design and design rework effort

Designing is a process that converts subjectively customers' requirements into physical entities. This conversion starts by gathering what the customer requests and interprets those requests into specifications. Later, alternative solutions are created, and subsequently the most suitable design alternative is selected and developed to become a physical product. The human ability spent in terms of analysis and synthesis, either individually or collectively, as well as detailed drawings, is counted as design effort.

However, design rework is an unnecessary design activity triggered by other tasks due to dependency among them, and effort spent in resolving the problems are regarded as design rework effort. In addition, the design rework causes design changes due to design flaws.

2.2 DESIGN PROCESS

This section reveals the design process selected to communicate with industries. Understanding the design process will cement design rework estimation methods in this thesis. Moreover, it will enhance the reviewing activity of the state-of-the-art in design rework estimation.

There are many journal papers and books that propose generic product design processes, for example Pugh (1990), Aurich et al. (2006), Pahl et al. (2007), Ulrich and Eppinger (2008). All these authors explain the design process as a systematic method to ensure the conversion of customers' requirements into physical products. The purpose of selecting a common design process is to use it as a means during discussion with industries. The criteria for selection are shown in Table 2 1.

Table 2-1: Comparison between proposed design process

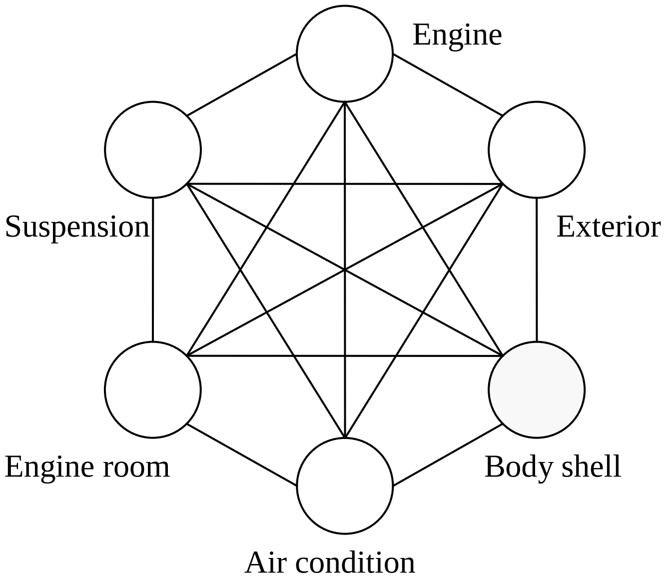
References	Citation (Scholargoogle)	Detailed in design process model	
		Number of Phases	Review Sessions
Pugh (1990)	371	6	No
Aurich et al. (2006)	63	6	No
Pahl et al. (2007)	2,357	6	No
Ulrich and Eppinger (2008)	2,937	6	Yes

Scholargoogle is suitable for obtaining a number of citations for books – compared to Scopus. Therefore, the citation results from the former search engine are listed in column two of Table 2-1. In column three, there are no differences in the number of phases but only Ulrich and Eppinger (2008) provide review sessions in the design process model, as shown in Figure 1-1. The review sessions are important because they are activities to ensure that everything being designed is correct and ready to pass to the next phase. In addition, this reference obtains the greatest number of citations. Therefore, the generic design process from this reference is selected as a means to communicate with industries.

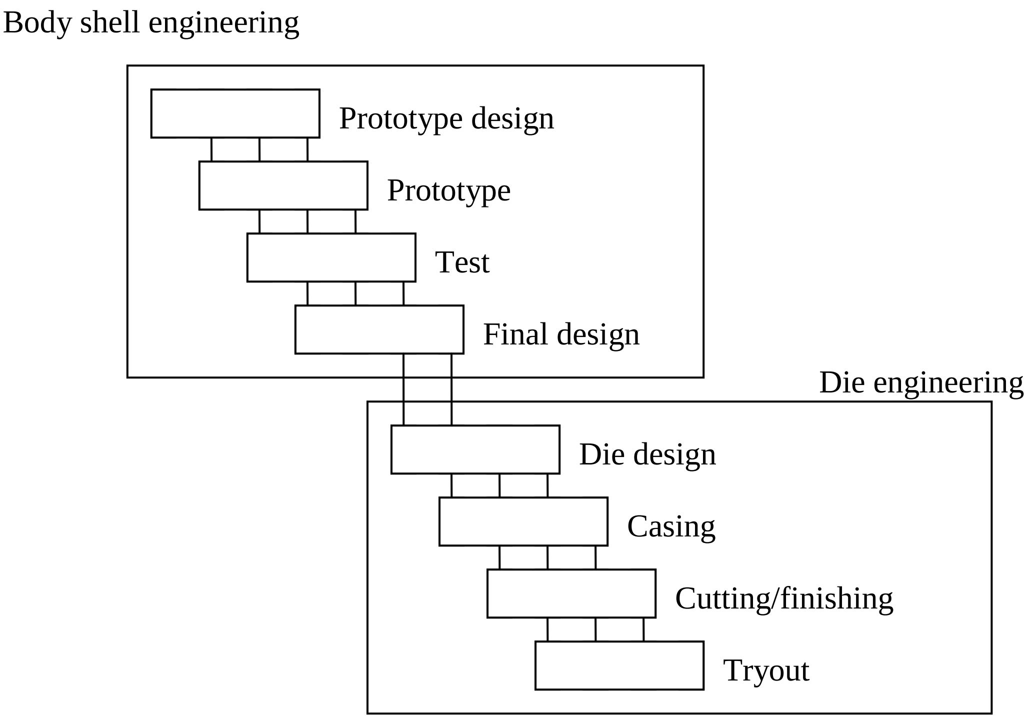
The Planning phase is mainly a marketing activity that gathers requirements from target customers and evaluates internal capabilities. Later, the decisions must be made about whether to start the design of new products or not. Concept Development is a phase where requirements are converted to product-functional structures, and then specifications are developed. Correctly obtaining a conceptual design is of substantial importance. Many more iterations in the later phases will not help to complete a good product, if the concept has been wrong since the beginning (Nepal et al., 2008). In addition, several concepts from different technologies are generated in order that an optimal conceptual design is selected. Later, the design is gradually developed to the system level and then cascaded into the detail level. Close to the end stage, prototypes will be built in order to obtain approval for production. Between stages, a design review ensures that the design is flawless and ready to release to the later stage.

2.2.1 Solving design by Horizontal and vertical directions

This section enhances the researcher's understanding of the design process as it is a problem solving process. Moreover, there are two directions from which to resolve problems: horizontal and vertical (Clark and Fujimoto, 1989), as represented in Figure 2-3.



a)



b)

Figure 2-3: Solving design problems a) Horizontal b) Vertical (Clark and Fujimoto, 1989)

Solving design problems using the horizontal design direction is mainly retrieving the design from the problems of a product's subsystems or work package integrations. Sometimes there are also conflicts among these. For example, in Figure 2-3a, cars need to achieve the top speed required. To satisfy this, a larger engine capacity is one solution. Hence, the engine bay would need to be expanded as a result of an expansion of the body shell. However, once the body shell has been stretched, it would result in a huge drag factor and as a consequence reduce the top speed. Hence, concurrently considering all of the working packages is inevitable.

Solving design problems in the vertical direction involves several disciplines. In Figure 2-3b, the body shell has to be "*engineered*" in the prototype design activity. Later, the physical artefact has to be built as a prototype which is approved by testing. However, body shell engineering and die engineering are in concurrent progress. It could be said that the body shell engineering activity is to confirm the performance and functionality. On the other hand, the die engineering is to ensure manufacturability.

Even though both directions require different definitions in design, they need to be optimised simultaneously in order to achieve the target function of the whole product. Hence, the relationships between horizontal and vertical problems solving are coupled and sophisticated. Any late changes in them could incur a significant penalty.

2.2.2 Key observations from reviewing design process

The design process, which is suggested by Ulrich and Eppinger (2008), to communicate with industries, is the key output in this section. Furthermore, the principle of design solving problems is classified in the horizontal and vertical directions both of which constrain the analysis of the state-of-the-art in design rework literature provided in section 2.8.

2.3 FUNCTIONAL DECOMPOSITIONS

The real challenge in this thesis is to assess the design rework in the testing and refinement phase back in the early design phase. The researcher found that this capability is able to be achieved with functional decomposition. From the concept development in Figure 1-1, the design activity begins from creating product functional structures. Hence, the methods to formulate the product functional structure are focused on here. There are several methods to formulate a product functional structure, for example Function Analysis System Technique (FAST, Bytheway, 2007), Taxonomy in

Mechanical Systems (Kirschman and Fadel, 1998), Axiomatic Design (Suh, 2005), Functional Basis (Stone and Wood, 2000).

FAST is a technique implemented in the Value Engineering (VE), (Miles, 1972). Its concept states that every product has to deliver a function. Each function can be strictly expressed as two words which are a verb and noun combination. Furthermore, high-level functions can be decomposed until each of them cannot be substituted any more. The principle of breaking down a function is that the lower-level function has to satisfy the adjacent higher-level function. However, the stopping criteria are a critical challenge of this method (Sturges et al., 1993).

Another functional decomposition approach evaluates the flow of elements through each function (Pahl et al., 2007). Moreover, elements are composed of information, materials and energy. Again functions can be broken down into lower levels. In addition, adding flow among functions enhances the horizontal connection among them.

Another method is Axiomatic Design (AD), (Suh, 2005). The function in this method is different from the previous two mentioned above. Function Requirement (FR) and Design Parameter (DP) are developed systematically during the decomposition. FR represents the function of the product being designed while DP appears as a physical solution to satisfy FR. The ideal design solution of this approach is one FR mapping with only one DP; and this is recognised as the independent axiom in this approach. In principle, elimination the horizontal relationships among sub functions is the method's target which is the key distinction from Pahl et al. (2007). Furthermore, AD is dissimilar from FAST in terms of breaking down the lower-level functions. FAST creates a structure solely from the function point of view, while AD builds up a functional structure from the coupling activity between FR and DR in each level. Hence, this technique is acknowledged as "zigzagging".

Functional behaviour is another method to develop a functional structure. This approach addresses issues that are multi-disciplinary in design and links the relationships among physical entities in accordance with the laws of physics (Yoshioka et al., 2004; Tomiyama et al., 2007).

There have been many attempts to develop a taxonomy for verb and noun combinations (Collins et al., 1975; Kirschman and Fadel, 1998; Stone et al., 2000; Kitamura et al., 2002). In principle, they allocate their effort to develop an explicit list of action verbs and nouns for their own function decomposition methods. In addition, there has been an attempt to develop a design catalogue to complete a comprehensive list of functions (Hundal, 1990).

FAST and AD are explicitly explained in sections 2.3.1 and 2.3.2, because they form a significant part of the method development in chapters 6 and 7. FAST is maturely developed and well known in industries. On the other hand, AD clearly defines the abstractions (FRs) and physical entities (DPs) both of which are useful for cause and effect analysis.

2.3.1 Functional Analysis System Technique (FAST)

FAST (Bytheway, 2007) is proposed in this section because it is a well established technique and is mature in terms of academic publications (Roy et al., 2008). It aims to increase creativity in design, which is achieved. As a result, thinking in terms of function regardless of physical products is the key achievement.

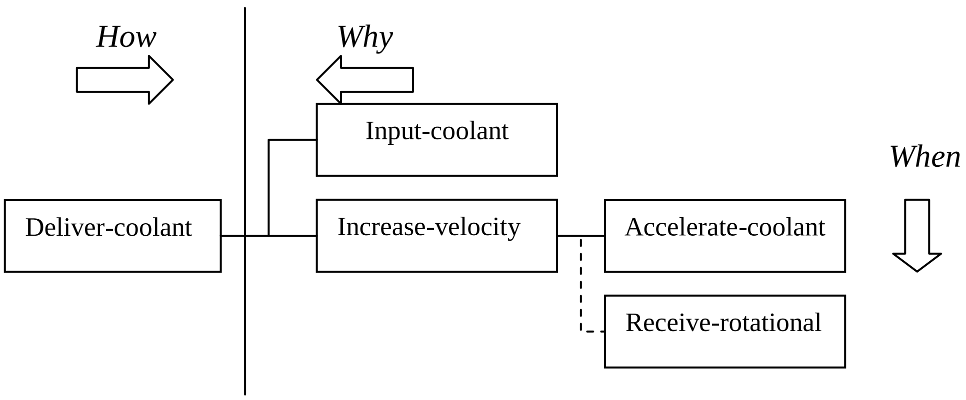


Figure 2-4: Example of FAST for an automotive water pump

Functions start from the left and expand to the right hand side. The left-most function is the one that needs to be achieved – the basic function. A function on the right-hand side explains how to achieve the adjacent left-hand side function. Therefore, reading from left to right explains how to achieve the function on the left-hand side. Conversely, reading from right to left supports the reason for the existence of the functions on the right-hand side. Moreover, the sequence from higher to lower levels reveals functions from a chronological point of view.

Table 2-2: Generic verbal list (McAdams and Wood, 2000).

Function Class	Basic Function	Sub-basic Restricted	Synonyms
Channel	Import		input, receive, *allow*, form entrance, *capture*
	Export		discharge, eject, dispose, remove
	Transfer		
		Transport	lift, move, channel
		Transmit	conduct, transfer, convey
	Guide		direct, straighten, steer
		Translate	
		Rotate	turn, spin
		Allow DOF	constrain, unlock
Support	Stop		insulate, protect, *prevent*, shield, inhibit
	Stabilise		Steady
	Secure		*attach*, mount, lock, fasten, hold
	Position		orient, align, locate
Connect	Couple		join, assemble, *attach*
	Mix		combine, blend, add, pack, coalesce
Branch	Separate		switch, divide, release, detach, disconnect, disassemble, subtract, valve
		Remove	cut, polish, sand, drill, lathe
	Refine		purify, strain, filter, percolate, clear
	Distribute		diverge, scatter, disperse, *diffuse*, empty
	Dissipate		absorb, dampen, dispel, *diffuse*, resist
Provision	Store		contain, collect, reserve, *capture*
	Supply		fill, provide, replenish, expose
	Extract		
Control magnitude	Actuate		start, initiate
	Regulate		control, *allow*, *prevent*, enable/disable,
			limit, interrupt
	Change		increase, decrease, amplify, reduce, magnify normalize, multiply, scale, rectify, adjust
	Form		compact, crush, shape, compress, pierce
Convert	Convert		transform, liquefy, solidify
			evaporate, condense, integrate, differentiate,
			Process
Signal	Sense		perceive, recognise, discern, check, locate, verify
	Indicate		Mark
	Display		
	Measure		Calculate

For example, Figure 2-4 is part of a FAST exercise from an automotive water pump which is the initial case study, as detailed in chapter 6. Reading from left to right, Deliver-coolant function could be satisfied by achieving the Input-coolant and Increase velocity (coolant) functions. While, reading from right to left, the Increase-velocity function exists because it supports the Deliver-coolant function. In more detail, the Increase-velocity function can be cascaded to the Accelerate-coolant and Receive-coolant functions.

Table 2-3: Generic noun list (McAdams and Wood, 2000).

Class	Basic	Sub-basic	Complement
Material	Solid		
	Liquid		
	Human		hand, foot, head, etc
	Gas		
Energy	Human		motion, force
	Biological		pressure, volumetric flow
	Mechanical	Rotational	torque, angular velocity
		Translational	force, velocity
		Vibration	amplitude, frequency
	Electrical		electromotive force, current
	Hydraulic		pressure, volumetric flow
	Thermal		temperature, heat flow
	Pneumatic		pressure, mass flow
	Chemical		affinity, reaction rate
	Radioactive		intensity, decay rate
	Acoustic		pressure, particle velocity
	Magnetic		magneto motive force, flux rate
	Electromagnetic	Optical	intensity, velocity
		Solar	intensity, velocity
Signal	Status	Auditory	tone, verbal
		Olfactory	
		Tactile	temperature, roughness, pressure
			Taste
		Visual	position, displacement
	Control		

Finally, reading from the top downwards shows that the Deliver-coolant function is achieved first by the Input-coolant function and then completes the Increase-velocity function. The Solid line represents the primary link of basic functions, while the dashed line reveals the support functions.

The diagram should be continued through decomposition towards the right-hand side as much as possible. The function formation is strictly displayed as a verb-noun combination. The guidelines for the verbs and nouns of the engineering design are shown in Tables 2-2 and 2-3, respectively, both of which are simplified versions from McAdams and Wood (2000). Using these generic lists has the benefit of enhancing the repeatability in developing functional decomposition for any entities. The verbs written in italic style are repetitive from one class to others. For example, the verb "*allow*" appears in the "channel" and "control" classes.

Column one of Table 2-2 classifies the action verbs into groups, while columns two and three show the specific words of each group, and column four provides synonyms. The classification of verbs is sorted into function, basic, sub-basic and synonym. For example, there are four basic action verbs within the control class and there are two synonyms for "actuate". A similar classification principle is also applied to Table 2-3. However, the last column provides the alternative complements of nouns.

2.3.2 Axiomatic design (AD)

AD is another method to structure product functional structure; however, its advance capability is to connect function to component. In addition, the researcher innovatively applies this method to define components which tend to cause design flaws, as shown in section 6.2.5.

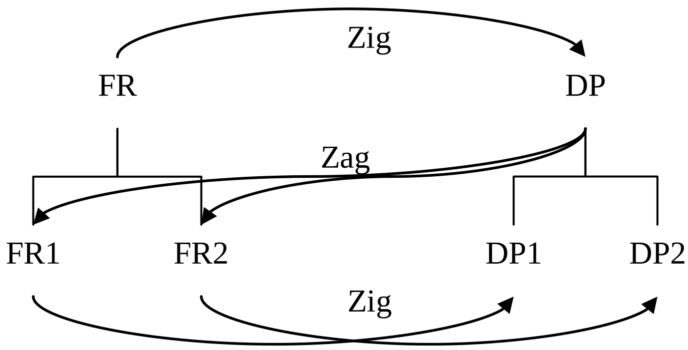


Figure 2-5: The example of a zigzag technique (adapted from Pappalardo and Naddeo, 2005)

In summary, it is a systematic approach to link customer requirements down to components and manufacturing (Ge et al., 2002; Guenov and Barker, 2005); hence, it enhances the improvement of the product design process. AD has two principles: maintaining independence between FRs and DPs, and keeping the lowest contents in design. If these two axioms are conformed to, the design is defined as a good design (Suh, 2005). Reducing product costs is another extended application of AD (Khairi, 2006). One of the nearest applications to design rework issues is to analyse the impact of changes (Xue et al., 2004). However, it focuses on the cost of configuration change on hardware construction but not the design effort.

From Figure 2-5, the zigzag technique begins with a functional requirement (FR) and then seeks a physical solution or design parameter (DP); and this action is called the "Zig". Once the DP is addressed, it then moves to the left-hand side to look for the lower-level FR, which is called the "Zag". This exercise should be continued until functions cannot be broken down to a lower level. Ideally, the number of FRs should equal the DPs but this is not always possible (Pappalardo and Naddeo, 2005).

2.3.3 Key observations from reviewing functional decompositions

There are two points captured in this section. Implementing functional decomposition is a standard practice in the conceptual design phase. There are several approaches to achieving this practice and they are commonly applied to completing the design according to the *"right first time"* concept. Functional structure is implemented in the early design phase, but is not meant to estimate design rework effort. The other challenge is to find out the stopping criteria of functional decomposition. Therefore, these are initiatives for further development in this thesis.

2.4 DESIGN STRUCTURE MATRIX (DSM)

Smith and Eppinger (1997) developed the approach to estimate design effort and the knock-on effect, while the Design Structure Matrix (DSM) is an intermediate means. Therefore, the researcher decided to investigate this in depth. It is a square matrix showing relationships among entities (Steward, 1981). From a design point of view, DSM supports the analysis of relationships within a product being designed in terms of visualising component integration (Pimmler and Eppinger, 1994).

An example of DSM is represented in Figure 2-6 and was initially obtained from company C. The heading of each row is identical to the vertical headings. Designing the bumper is completely dependent on the grille and cooling pack designs, so that reading horizontally will show the influential components on the respective heading of each row by looking at $\times$ in the matrix.

Components		G	Cp	Ag	B	H
Grille	(G)		×		×	×
Cooling pack	(Cp)	×			×	×
Air guide	(Ag)	×	×			×
Bumper	(B)	×	×			
Hood	(H)	×			×	

Figure 2-6: Modelling relationships of the front part of a car bonnet by DSM

There are two types of relationship to signify in a DSM classified by their position: feed forward and feedback. Feed forward appears in the lower diagonal of the DSM, while each entity in the upper diagonal is feedback. The cooling pack design gathers information feeding forward from the grille design. While, it in turn depends on feedback from the cooling pack.

In addition, DSM could represent dependency types, as described in Figure 2-7. In column two, element B depends on element A, so element B will be altered by any changes in element A. Therefore, there is a cross on row B. If there are no relationships between A and B, there would be no ×, as shown in column three. On the other hand, if elements A and B are interdependent, there will be two × on both A and B when reading across each row, as shown in column four. If A and B are design tasks, A needs to start the design with "guess" and then releases information to B. There would be a feedback from B to A; therefore, this coupled relationship performs iterations among design tasks.

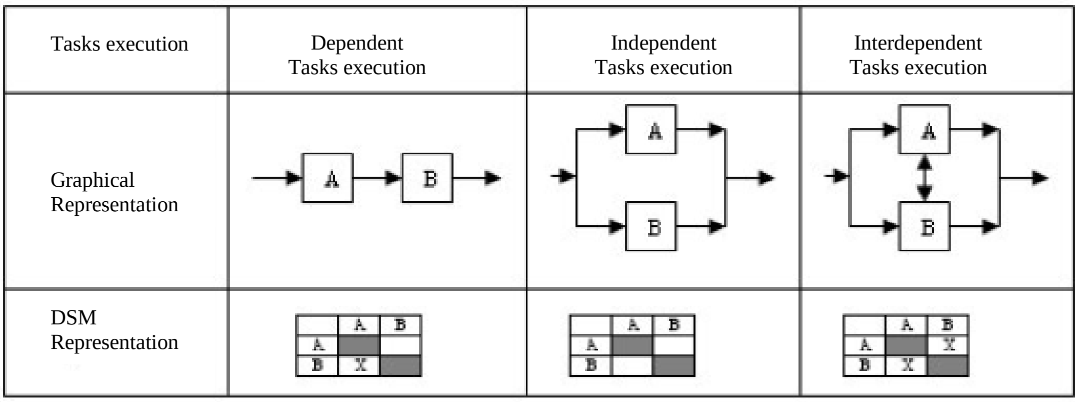


Figure 2-7: Representation of dependencies by DSM (Guenov and Barker, 2005)

A Component-Based or Architecture DSM is very useful to determine the relationship among components of a product being designed and it supports either integrating or decomposing a design. Apart from understanding relationships, the DSM would improve design by reducing feedbacks, because each one makes the design more complex. Browning (2001) classifies the application of DSM into four groups as follows:

"*Partitioning*" is a common practice to eliminate feedbacks. This technique is a process to sequence the design and then relationships will be moved from the upper to the lower diagonal side. The other common practice is "Tearing", which is a process to decompose "*couple activities*", or interrelationships, into smaller tasks and then rearrange them (Kusiak and Wang, 1993).

Class two is a Team-Based or Organization DSM which models the collaboration of team in a complex organisation (Sosa et al., 2004).

Class three, the model Activity-Based or Schedule DSM is applied either to a modelling process or network activities. Furthermore, it is also applied to calculate lead times in projects; however, all activities need to be predefined (Maheswari and Varghese, 2005).

Lastly, Parameter-Based (or Low-Level Schedule) DSM is a means to model interactions of a considered system by parameters or equations.

Defining a proper methodology to determine relationships in DSM is the key challenge. From the researcher's synthesis, DSM could be completed either with direct and indirect methods, as outlined in sections 2.4.1 and 2.4.2.

2.4.1 Obtaining DSM by direct methods

DSM is developed by signifying the relationships directly from the user's perception. For example, DSM, as shown in Figure 2-6, was developed in cooperation with company C's expert in the early phase of this research during the interview session. Therefore, DSM could be developed by either the synthesis of developers or a qualified team. Furthermore, this is an example of a non-numeric DSM, because it is mainly showing relationships. They can be indicated as *High*, *Average* or *Low* dependencies

(McCord and Eppinger, 1993). Pimmler and Eppinger (1994) classify interactions among relationships into spatial, energy, information and material; furthermore, a numeric value ranging from -2 to 2 represents the degree of importance.

Employing DSM together with AD is also applicable (Suh, 1990). Su et al. (2003) combine AD, DSM and the Analytical Hierarchy Process (AHP) to obtain the important level of each DP to achieve any single FR. However, the application of DSM is not applicable when the number of FR is not equal to DP. Acquiring DSM with AD is possible when FR and DP are at the same level only.

Multi Domain Matrix (MDM) is another extended method of DSM. Relationships among components are modelled separately based on the category of relationships, e.g. functionality, assembly or energy transfers etc. Later, they must be combined into one matrix (Danilovic and Sandkull, 2005, Lindemann et al., 2008). The strength of relationships is obtained from counting the possible routes from one entity to the considered element in the final matrix. Therefore, the many more possible ways that are shown represents the higher the strength of relationships (Yassine et al., 2003).

2.4.2 Obtaining DSM by indirect methods

The DSM of relationships among components can be derived indirectly. Obtaining the relationships between components and functions must be acquired first. Later, the linkages must be applied with matrix multiplication (Tumer and Stone, 2003). Eqs. 2-1 and 2-2 represent the formulae to achieve the component-component relationship matrix ($\Lambda_{component}$) and function-function relationship matrix ($\Lambda_{function}$). FC is a binary matrix showing relationships among functions and components which are working together to deliver a particular function. If a component does work to deliver a considered function, it shows “1”, otherwise “0”.

$$\Lambda_{component} = FC^T \times FC \tag{2-1}$$

$$\Lambda_{function} = FC \times FC^T \tag{2-2}$$

For example in $\Lambda_{component}$, the strength of a relationship between two components is not equivalent to the number of functions they work in together. For instance, if a pair of components appears together for two functions, the strength of relationship will be two. As a result of matrix multiplication, a DSM completed by the indirect method is always a symmetric matrix.

2.4.3 Key observations from reviewing DSM

DSM is a well-known tool to analyse design, and it can be achieved by either direct or indirect methods. The critical factor in this section is the possibility of obtaining DSM in the very early design phase. The direct method can be achieved by AD, while the indirect method exploits the function-component relationship matrix. However, these two approaches are in major conflict. AD is trying to eliminate feedback relationships while the indirect method always embeds with feedbacks.

2.5 IDENTIFYING RISKS IN THE PRODUCT DESIGN PHASE

The researcher desires the capability to predict the design flaws as early as possible; hence, the details in this section are given prominence. Identifying potential issues is critical because without them there are no directions to conduct proactive actions to prevent problems (Carrascosa et al., 2004). Design rework issues can be classified as a "risk" because they delay the project schedule (Browning, 1999). Each issue can be assessed by identifying each of them after assigning its probability and impact, then performing multiplication (Browning and Eppinger, 2003). A bigger value corresponds to a greater risk, Eq. 2-3. Therefore, the accuracy in this evaluation is in acquiring the issue list as well as obtaining its probability and impacts numerically.

$$\Re_i = P_i \times I_i \tag{2-3}$$

where $\Re_i$ is the risk outcome from risk i. P_i is the probability of risk i occurrence, while I_i is the impact of risk i (Browning and Eppinger, 2003).

Therefore, this section aims to demonstrate the reviews of methodologies to detect problems early in the design phase as well as the impact analysis. The early proposed methods to analyse issues in products are Fault Tree Analysis (FTA) and Failure Mode and Effects Analysis (FMEA) (Burgess, 1970) both of which are methods used in reliability engineering (Smith, 1985; O'Connor, 1991). However, FTA more extensively generates alternative events of failures through component hierarchy, but FMEA anticipates potential problems in order to evaluate the occurrence and impact of issues (Dale and Shaw, 1990). The other method to identify problems is Root Cause Analysis (RCA); however, it is only suitable to find the root causes of problems. Hence, it is appropriate to look backwards, while FMEA is applied more on a predictive side to address potential problems (O'Connor, 1991). Therefore, FTA and RCA will not be focused on in this thesis. A final point to be made in this section is that Pareto Analysis literature has been studied in order to analyse whether design rework problems would lead to significant impact or not.

2.5.1 Failure mode and effects analysis (FMEA)

The major purpose of this section is to review methodologies to expose failure issues in the design process as early as possible. First of all, the general understanding is presented and then methods to address the failure mode are illustrated in detail as shown in Figure 2-8.

FMEA is a systematic approach to address potential risk in product design and it has the ability to capture issues proactively in the early design phase (Ishii, 1995). It is divided into two groups: “Design FMEA (DFMEA)” and “Process FMEA (PFMEA)” (Teoh and Case, 2004). However, DFMEA is the sole focus in this thesis. In principle, risks registered due to design are derived with scenarios of product failures in operations. The analysis begins from functions. Later, components potentially driving failure modes to the considered function are explicitly discussed. This activity is called identifying “*failure modes*”. After accomplishing a list of failure modes, occurrence, detection and severity have to be scored and 10 is the strongest score. All numbers are judged based on what would happen if each problem were to occur in operation. Later, all of these scores have to be combined by multiplication, so the Risk Prioritise Number (*RPN*) is achieved. Thus, the interpretation is that a greater *RPN* leads to more critical risk within a particular failure mode. Finally the results are useful in action planning to reduce or control risk. In brief, there are three activities that must be completed in FMEA, which are: Identify issues (*Failure Mode*), Analyse issues (*RPN*), and Act (controlling issues), (Steven et al., 1999).

FMEA has limitations in not covering risk associated with scope changing, budgeting, and especially risks resulting in potential delays in product design and development (Segismundo and Miguel, 2008). However, there is plentiful literature that improves FMEA by considering costs incurred as consequences ensuing from failures (Rhee and Ishii, 2003; Curran et al., 2003; Dong, 2007; Von Ahsen, 2008). It seems that design effort to resolve failure modes is not clearly mentioned yet in the literature.

The development in FMEA is aimed either at improving the method to acquire *RPN* (Bevilacqua et al., 2000; Franceschini and Galetto, 2001; Sankar and Prabhu, 2001; Chang et al., 2001; Bowles, 2004; Segismundo and Miguel, 2008) or a means to identify failure modes. However, only the latter is reviewed in depth because there is a fundamental curiosity about how failures are linked to design rework effort. In general, each failure mode is classified as either an independent event, as interactions or as a sequence event (Hunt et al., 1993; Price and Taylor, 1998; Krasich, 2007; Nepal et al., 2008), as shown in Figure 2-8. Therefore, the literature is sub-divided by these classifications.

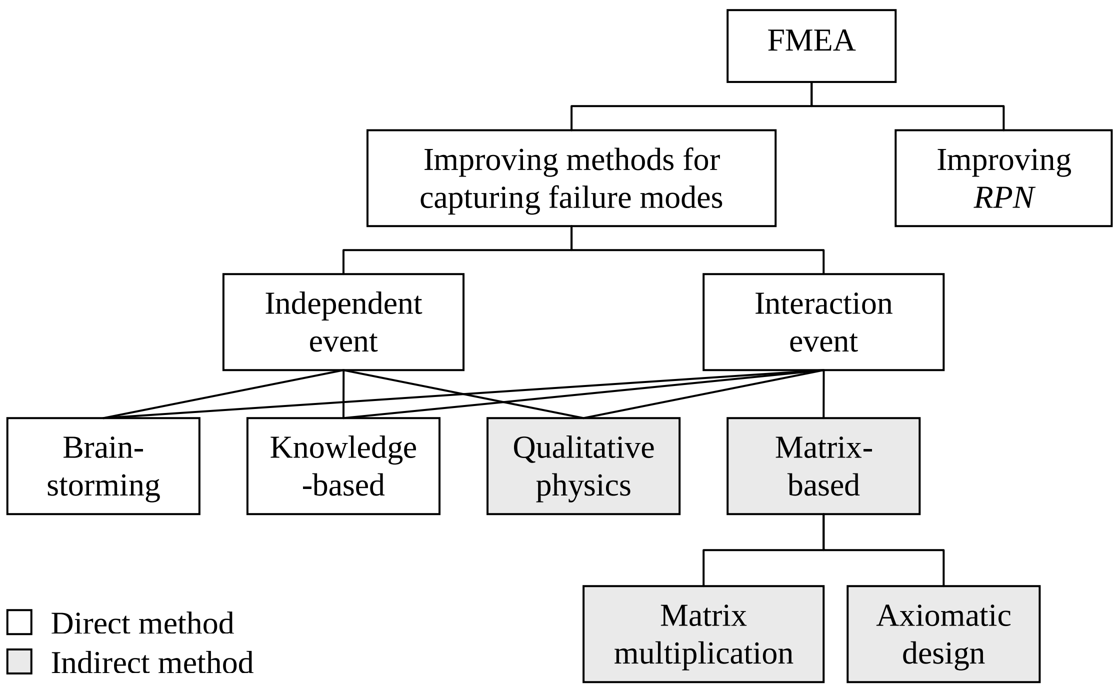


Figure 2-8: FMEA literature classification

Independent Failure Modes

There are several means to obtain a failure mode list. The earliest method is brainstorming by a qualified team (Hari and Weiss, 1999). In order to standardise failure modes, developing a failure taxonomy is the ultimate goal of various studies. Collins et al. (1976) are recognised for their early endeavours to build up a failure taxonomy for a helicopter design; however, the failure list is limited to mechanical parts. Later, Uder et al. (2004) improved the mechanical failure taxonomy of the previous study and made a significant development for electrical failure modes in spacecraft design.

The other approach to acquire a failure mode list is the implementation of a knowledge-based system. In principle, this technique re-uses historical failure data within a new project (Teoh and Case, 2004). Obtaining failure modes from brainstorming and knowledge-based systems is considered to be a direct method, because those modes have either emerged directly from a team or been retrieved from historical projects.

On the other hand, the indirect method exploits intermediate means to develop failure modes. For example, qualitative physics or causal reasoning is recognised as an indirect method. Failure modes of systems or components are evaluated by the behaviour of functions which lead to problems (Bell et al., 1992; Eubanks et al., 1996; Hughes et al., 1999).

Interaction Failure Modes

Interaction failure modes may cause either immediate or gradual degradation failures from one component to others (Sun et al., 2006). An indirect method such as qualitative physics is also implemented to address failure modes (Price and Taylor, 2002).

A matrix-based method is another means to acquire failure modes indirectly, as described earlier in 2.4.2. Function-component and component-failure mode relationship matrixes must be prearranged first. Later, both matrixes are multiplied together as a result of the function-failure mode relationship matrix (Tumer and Stone, 2003). However, this method still requires a lot of judgement in order to complete the initiated two matrixes, but it helps to visualise the dependency among failure modes.

Arunajadai et al. (2004) enhance the capability to identify groups of failure modes which always occur together by matrix-based analysis. In addition to the matrix-based operation, Pappalardo and Naddeo (2005) adapt AD for capturing relationships among failure modes; however, there are no concrete methods to extract the relationships between failure causes and failure modes. Nakao et al. (2009) claim that design failures are from complexity due to coupling in design as defined in the AD principle. In addition, complexity prevents people from anticipating problems; however, there are no concrete methodologies linking couple design problems and failure modes.

2.5.2 Pareto Analysis

Pareto Analysis states that significant outcomes (approximately 80%) are caused by a small number of inputs (about 20%), (Ebert and Baisch, 2001); therefore, this principle is very useful to prioritise subsystems or components which are prone to encounter problems in order to stratify preventive effort (Paulk, 1999; Cross and Sivaloganathan, 2005). Consequently, the literature in this section was constrained when searching for "*Pareto Analysis*", "*Failure Mode*" and "*Design*".

Pareto Analysis is always expressed as a frequency plot among various inputs against outputs. Subsequently, the greatest influence input is highlighted (Dale, 2003 pp. 325-328). This method is widely used as a quality tool for product design and development (Booker, 2003), software (Iqbal and Rizwan, 2009), automotive (Dale and Shaw, 1990) and aerospace (Vassilakis and Besseris, 2009). It is suitable for developing a database from historical projects (Starr et al., 1999; Buchheim, 2000; Kumar et al., 2007; Shang and You, 2009). Moreover, it is always mentioned as a key element in Total Quality Management (Ahuja and Khamba, 2008) and Six Sigma (Conger, 2010).

Prioritising the impacts of design failures, such as costs, is one application of Pareto Analysis (Abdul-Rahman, 1993; Schiffauerova and Thomson, 2006). Chao and Ishii (2007) apply this approach to prioritise potential design errors. In brief, Pareto Analysis has been applied for a wide range of purposes, so it has the potential to deal with design rework issues.

2.5.3 Key observations from identifying risks in the product design phase

Risk analysis in design can be achieved by distinguishing potential problems and assigning the impact of each of them. FMEA is a potential method to capture design issues in the late design process by performing an assessment in the early design phase. However, this method does not cover the effort required to resolve problems. Hence, FTA or RCA would be required to enhance FMEA. However, the challenge is developing an effective tool to capture failure modes.

Pareto Analysis is widely applied in quality tools. The potential design problems are prioritised by their impacts. Hence, it is a potential method to proactively react to design rework issues. Consequently, efforts to resolve problems can be allocated effectively. However, its limitation is that a problem list must be predefined.

2.6 COST AND EFFORT ESTIMATION METHODS

The purpose of this section is to review cost and design effort estimation methods of any design project. In addition, the ability to estimate the entire product costs from the beginning onwards is the focus. Roy (2003) and Xu et al. (2006) posit that parametric and analogy-based estimation methods are suitable for the estimation of the entire project costs in the early design phase. Therefore, parametric and analogy-based estimation approaches are further investigated in this section.

2.6.1 Costs incurred in the design phase

Design effort is recognised as a cost incurred in the design phase. Bashir and Thomson (2002) propose three methods to estimate design effort from a global viewpoint. Complexity of product being designed is a driver in the estimation. Roy et al. (2001) differentiate design time to be qualitative time which is the duration to think about the design, while quantitative time is the duration spent on CAD modelling.

Xu et al. (2006) introduce several more cost elements in the design phase, as follows: engineering design cost, drawing cost, computer processing cost, design modification cost, production preparation cost and management cost. However, an estimation of the extra effort or time required in the testing and refinement phase is the focus in this thesis. Thus, the design modification cost is further investigated in the industrial field study (chapter 4).

This section introduces a method to estimate design effort from a global viewpoint. Nonetheless, there is no evidence to show a relationship between complexity and design rework effort. Therefore, the methods to estimate the design lead time and effort from a specific viewpoint are reviewed in section 2.8.

2.6.2 Parametric-based estimation

The parametric-based estimation has the capability to estimate the entire product cost and design effort, even though the project is still in the very early design phase. The approach is achieved by considering the cost drivers of the product being designed.

The cost estimation relationship (*CER*) or cost driver is used to calculate products being designed. In addition, the CER or cost driver explains the relationship between physical features of a product and a related cost. For example, the cost driver for building construction is units of money spent per one unit of area, as an example: £/m^2. The relationships can be either linear or non-linear. The strength of *CER* can be explained statistically by a % of correlation (*R*). The greater the value of *R* means the better explanation of the cost driver or *CER* to the cost of products.

Parametric-based estimation has the benefit of utilising *CER* effectively (Niazi et al., 2006). This method has been used in a wide range of cost estimations, such as life cycle costing (Liu et al., 2009) or detailed product cost analysis (Qian and Ben-Arieh, 2008). Moreover, Bashir and Thomson (2001) employed this method to estimate design effort for products.

However, this method is not suitable for a low sample number of historical data due to the limitation of the statistics principle (Duverlie and Castelain, 1999). Furthermore, the *CER* must be well defined before estimation.

2.6.3 Analogy-based estimation

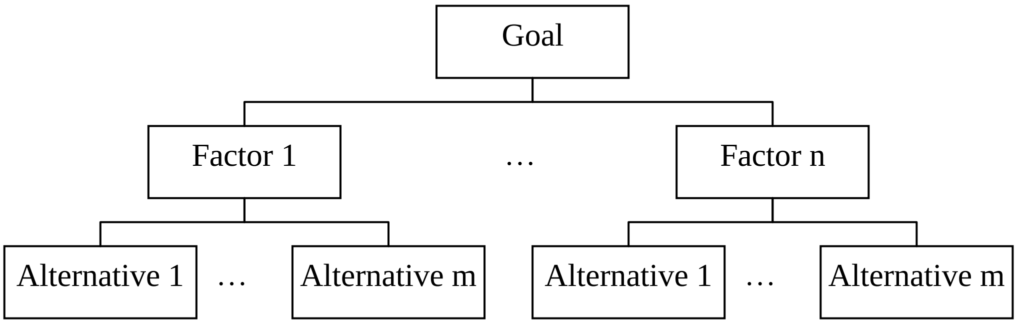
General aspects: Analogy-based estimation is a technique to estimate costs or effort by comparing common characteristics among products being designed as against historical products (Xu et al., 2006). The analogy-based method is also used in the conceptual design phase to retrieve historical products. This method has the capability to provide a similarity score. The quality of the similarity score is defined by mathematic principle (Duverlie and Castelain, 1999; McAdams and Wood, 2002; Lai and Gershenson, 2008).

The analytical hierarchy process (AHP) is one technique used to quantify comparisons, and it is widely used in many applications (Vaidya and Kumar, 2006). Furthermore, it is employed in the early design phase, especially in the conceptual design stage (Yeo et al., 2004).

The advantage of analogy-based estimation is that it does require much historical data in order to develop equations, as is needed in the parametric-based estimation. It compares the similarity between historical and upcoming entities. However, the main disadvantage of this method is that it relies heavily on subjective judgements (Asiedu and Gu, 1998).

Analytical Hierarchy Process: AHP has been developed from multi-criteria decision making technique (Yeo et al., 2004). Later, this method has been extensively implemented for analogy cost estimation, because the cost is impacted on by a variety of factors. Bashir and Thomson (2001) implement AHP to estimate design effort and their results are considerably accurate. However, their methodology did not reveal other factors that influence design lead time, e.g. experience of designers, coordination etc.

Drivers or factors to make decision choices have to be predefined in the hierarchy as shown in Figure 2-9a. The top level describes the overall decision goal. The middle level describes drivers or factors which have an influence on the top level. Finally, the lowest level is composed of alternatives being compared. There will be more than two factors in level two and each of them can have more than two alternatives being compared. Moreover, there will be more levels in the hierarchy depending on the applications. The comparisons in pairs and structures in the hierarchy prevent decision makers from the confusion created by having too many criteria to think about.



(a)

Factors	Factor 1	Factor 2	Factor 3
Factor 1	1	$\frac{1}{2}$	4
Factor 2	2	1	6
Factor 3	$\frac{1}{4}$	$\frac{1}{6}$	1

(b)

Figure 2-9: AHP example a) Hierarchy structure b) Matrix for factor level

In the comparison activity, two questions are required. The decision on which entity has a greater influence must be made and then the strength of importance requested. The guideline for scoring is shown in Table 2-4. For example, in Figure 2-9b, the comparison has to be analysed in a pair of rows against column headings. The results of comparison factors 1 and 2 is ½, which means that factor 1 has less influence on the goal than factor 2 by the strength order of 2. However, factor 1 has a higher influence on the goal than factor 3 by the strength order of 4. The scoring activity only has to be completed for the upper diagonal of the matrix, because the lower diagonal is a reciprocation of the upper diagonal part.

Table 2-4: Influence rating scale (adapted from Bashir and Thomson, 2001)

Numerical values	Value definition
1	Equal influence
3	Vaguely more influence
5	More influence
7	Severe influence
9	Tremendously severe influence
2, 4, 6, 8	Intermediate values to reflect compromise

Once the scoring has been completed, the weighted average for each entity is obtained from the principle Eigenvalue of the AHP matrix as illustrated in Eq. 2-4.

$$Aw = \lambda_{\max} w \tag{2-4}$$

where *A* is the AHP matrix as shown in Figure 2-9b. $\lambda_{\max}$ is the principle Eigenvalue for matrix *A*. *w* is a vector.

An alternative method to obtain the weighted average score is the weighted average method (Render et al., 2003 pp. 519-536). If a_{ij} is the numeric value in the matrix, the weighted average score (w_i) for each factor is obtained by Eq. 2-5.

$$w_i = \frac{\sum_{j=1}^{n} a_{ij}}{n \times \sum_{i=1}^{n} a_{ij}} \tag{2-5}$$

Each weighted score provides the true measurement among the entities being analysed due to comparisons with each other. The true measurement is ensured with a ratio scale of which the interval between each entity is quantifiable (Sankar and Prabhu, 2001; Bowles, 2004). Therefore, it is very useful to deal with qualitative factors. Scoring is tested to be consistent or transitive by the Consistency Ratio (*CR*) as shown in Eq. 2-6. If the scoring activity has no pattern in terms of sequence, the average of scoring or *CI* will be close to a random average or *RI*. $CR \le 0.1$ is preferred; however, $0.1 < CR \le 0.2$ is still acceptable (Wedley, 1993). In principle, *CR* evaluates whether the judgement on the scoring from each pair-wise comparison has transitivity or not. If $CR > 0.2$, transitivity is not reserved, because the judgements on scoring are close to random judgements. If $CR = 1$, the judgements on the scoring results are perfectly random. On the other hand, $CR = 0$ means the matrix is perfectly transitive (consistent). *CI* and *RI* are represented in Saaty (2000).

$$CR = \frac{CI}{RI} \tag{2-6}$$

$$CI = \frac{\lambda - n}{n - 1} \tag{2-7}$$

where *CI* is the consistency index, *RI* the random index, *n* the number of entities being compared, and λ is the maximum Eigenvalue of the matrix.

λ Can be calculated with the weighted average. It is modified from Eq. 2-8 to Eq. 2-10 (Render et al., 2003, pp. 530-536).

$$\lambda = \frac{\sum_{i=1}^{n} CV_i}{n} \qquad (2.8)$$

$$CV_i = \frac{W_i}{w_i} \qquad (2.9)$$

$$W = PC \times w \qquad (2.10)$$

where *CV* is the consistency vector, *n* is the elements being compared, *W* is the weighted sum vector, *w* is the weighted average vector, *PC* is the pair-wise comparison matrix, and *i* is denoted as elements in the vectors.

The weighted average is used because it is spreadsheet-friendly, e.g. Excel, while this is not the case for the Eigenvalue and Eigenvector. The critical characteristics of the AHP technique are that the total weighted score for each level is always equal to one. Therefore, it is useful for resource allocation (Ramanathan and Ganesh, 1995; Vaidya and Kumar, 2006).

Incomplete comparison matrix: Information overload is a potential problem that makes AHP impractical, because the full scoring matrix requires an exhaustive scoring effort when the elements being compared (*n*) increase, as shown by Eq. 2-11 (adapted from Harker, 1987b). For example, if 10 elements are being compared, there are 45 scores that need to be evaluated.

$$Number \quad being \quad judged(NJ) = \frac{n(n-1)}{2} \qquad (2\text{-}11)$$

Moreover, if there are five factors and nine choices in the AHP structure, it needs to be answered 190 times. Hence, this procedure would be a very exhaustive exercise and lead to dramatic errors (Harker, 1987a). An incomplete comparison matrix is one solution to solve the information overload. Harker (1987a, b) shows an early attempt to develop the method, allowing “I don’t know” or “I’m not sure” into AHP, but the method to measure consistency is not available. The other early development could reduce the judgements dramatically, but the consistency measurement is not shown in a concrete methodology, such as that of Shen et al. (1992), and Lim and Swenseth (1993).

Wedley (1993) developed a method to predict a consistency ratio based on the numbers being judged in an incomplete comparison matrix. However, this study does not reduce the number of comparisons significantly in order to preserve the *CR*’s precision.

The numbers being judged is reduced down to only $n+1$, as developed by Triantaphyllou (1999); however, consistency measurement is not provided. Ra (1999) proposes a Chain-wise Paired Comparisons method to obtain the weighted average with only n comparisons; moreover, a concrete method to measure consistency is also provided. There are further developments to decrease the comparison such as those of Su et al. (2003), but they lack a clearly-defined method to measure consistency compared with Ra (1999). Another approach is that of predicting missing elements scores in the AHP matrix, as shown in Feddrizzi and Giove (2007), and Chiclana et al. (2008). However, this method increases the endeavour needed to operate compared with Ra (1999). The summary for the incomplete pair-wise comparison methods is shown in Table 2-5. Significant reduction of *NJ* and Availability of method to measure consistency are two key criteria to evaluate.

Table 2-5: Summary for incomplete pair-wise comparison methods

Authors	Significant reduction of *NJ*	Availability of method to measure consistency	Note
Harker (1987)	Yes	No	
Shen et al. (1992)	Yes	No	
Lim and Swenseth (1993)	Yes	No	
Wedley (1993)	No	No	
Triantaphyllou (1999)	Yes	No	
Ra (1999)	Yes	Yes	
Su et al. (2003)	Yes	No	
Feddrizzi and Giove (2007)	Yes	No	Both methods require more steps to acquire weighted scores compared with others.
Chiclana et al. (2008)	Yes	No	

Ra's (1999) method has better characteristics compared with the others; therefore, it has been selected for implementation in this thesis. The algorithm to calculate the weighted average for each entity is shown in Table 2-6. Only *n* comparison is required for this method. The necessary scoring in this method comes from the upper diagonal of the AHP matrix and the bottom cell of column one in the AHP matrix. Each $w_1 \ldots w_n$ is the true weighted scores for individuals, but the fraction form represents the relative measurement of a considered entity with the adjacent individual. Columns two to four are an in-depth explanation of the method, while column five is for the estimated weighted score obtained from the algorithm.

Table 2-6: Chain-wise paired comparison algorithm (Ra, 1999)

i	R_i	D_i	$\tilde{R}_i$	M_i	w_i^*
1	$R_1 = w_1/w_2$	$D_1 = R_1$	$\tilde{R}_1 = D_1 / \sqrt[n]{\prod D_i}$	$M_1 = \prod_{i=1}^{n} \tilde{R}_i$	$w_1^* = M_1/M$
2	$R_2 = w_2/w_3$	$D_2 = R_2$	$\tilde{R}_2 = D_2 / \sqrt[n]{\prod D_i}$	$M_2 = \prod_{i=2}^{n} \tilde{R}_i$	$w_2^* = M_2/M$
3	$R_3 = w_3/w_4$	$D_3 = R_3$	$\tilde{R}_3 = D_3 / \sqrt[n]{\prod D_i}$	$M_3 = \prod_{i=3}^{n} \tilde{R}_i$	$w_3^* = M_3/M$
⋮	⋮	⋮	⋮	⋮	⋮
n-1	$R_{n-1} = w_{n-1}/w_n$	$D_{n-1} = R_{n-1}$	$\tilde{R}_{n-1} = D_{n-1} / \sqrt[n]{\prod D_i}$	$M_{n-1} = \tilde{R}_{n-1}$	$w_{n-1}^* = M_{n-1}/M$
n	$R_n = w_n/w_1$	$D_n = R_n$	$\tilde{R}_n = D_n / \sqrt[n]{\prod D_i}$	$M_n = 1$	$w_n^* = M_n/M$
		$\prod_{i=1}^{n} D_i$	$\prod_{i=1}^{n} \tilde{R}_i = 1$	$M = \sum_{i=1}^{n} M_i$	

For example, w_1/w_2, w_2/w_3, w_3/w_1 are shown as ½, 6 and ¼ in Figure 2-9b, respectively. However, this method is implemented for more than four elements being compared.

In addition, Level of consistency (*LOC*) replaces *CR* in terms of measuring the quality of scoring by using Eq. 2-12. More entities being compared necessitate a higher *LOC* as recommended in Table 2-7. The applications for this algorithm and *LOC* are given in section 5.3.4.

$$LOC = e^{-\left|\ln\left(\sqrt[n]{\prod D_i}\right)\right|} \quad (2\text{-}12)$$

Table 2-7: Acceptable *LOC* against the number of elements being compared (Ra, 1999)

N	Acceptable *LOC* (%)	*N*	Acceptable *LOC* (%)
3	76.3	12	94.3
4	81.9	13	94.8
5	86.4	14	95.1
6	88.9	15	95.5
7	90.4	16	95.7
8	91.6	17	96.0
9	92.4	18	96.2
10	93.2	19	96.4
11	93.8	20	96.6

2.6.4 Key observations from reviewing cost and effort estimation methods

Parametric and analogy-based estimation is suitable to estimate cost and effort. In addition, both methods have the capability to estimate the entire project, even though the assessment is still in the early design phase. However, to use parametric estimation with high confidence requires a considerably higher sample number which may not be suitable in limited participant circumstances. On the other hand, analogy-based estimation is a proper alternative, because it does not expect many samples of historical products to perform estimations, as requested by the parametric method. Therefore, the analogy method is selected for further development in this thesis.

2.7 OPTIMISATION TECHNIQUES

The aim of this section is to enhance the knowledge of optimisation techniques, because many of them are applied in the state-of-the-art in design rework literature. Each of them aims to search the maximum overlapping design task duration with the minimal design rework effort, e.g. Roemer et al. (2000), Yassine et al. (2008). Selecting the proper optimisation technique affects the quality of solutions, as well as computational time and cost (Holden et al., 2002).

Optimisation means searching for the maximum or minimum results from an equation composed of variables. The equation to be optimised is considered as the objective function which describes, or is modelled on, a problem, whereas the variables are explicitly shown individually in ranges or equations acknowledged as constraints (Levy, 2009, pp. 1-24). In addition, the constraints can be written in either equality or non-equality format. Hence, understanding the characteristics of objective functions, constraints and variables is vital towards selecting the suitable optimisation technique.

The critical activity in this section is classifying the optimisation technique, because there are optimisation techniques available for a wide range of applications (Floudas and Pardalos, 2008). There are several rationales to categorise the optimisation approach, as follows: Antoniou and Lu, (2007, p. 2) group the methods as analytical, graphical, experimental and numerical; moreover, there are many more methods embedded in each group. Chong and Żak (2008, p. 73) divide optimisation into constrained and unconstrained.

Holden et al. (2002) separate the optimisation approach broadly into local and global searches. Roy et al. (2008) provide categorisations of the engineering design optimisation (EDO) into five groups: design variables, constraints, objective functions, problem domain and environment; however, the authors do not cover the organisation and management of the design process. Unfortunately, the design rework issues are identified as management-based in shown in Figure 1-2.

Salvendy (2001, pp. 2521-2650) classifies optimisation techniques into six groups: linear, nonlinear, network, discrete, multicriteria, and stochastic; furthermore, there are several techniques to search for solutions within each of them. The researcher decided to use this classification as a starting point, because this literature focuses on decision making. In addition, the heart of the design process is decision making (Olewnik and Lewis, 2005).

2.7.1 Classification of the optimisation technique

Linear optimisation: This method is commonly known as linear programming. The objective function must be described in linear form by variables. Moreover, constraints can be expressed as a set of linear equations or inequalities. Some examples of techniques to search for a result are the graphical method, simplex method and interior point method (Venkataraman, 2002, pp. 93-104). However, the linear optimisation becomes complex when the variables and constraint reach 10 and 20 respectively (Ferris et al., 2007, p. 14).

Nonlinear optimisation: If the objective function cannot be expressed in a linear equation, nonlinear optimisation is necessary to solve the problem. The constraints represent the feasible region of the solution, while the objective function is represented as a contour. From these characteristics, the nonlinear optimisation could provide the solution at any point in the feasible region, while there is only one in the linear optimisation.

Neither the global maximum nor minimum result is confirmed in nonlinear optimisation, unlike in linear optimisation. Hence, only the local maximum or minimum is achieved. The searching methods are, for example, the graphical method, quadratic programming (QP), and genetic algorithm (GA). However, QP will be difficult when dealing with a significant number of constraints.

Network optimisation: The network optimisation is classified as a special case of linear optimisation, because it is used in modelling real-life issues such as transportation problems, and minimum cost flow problems (Bertsekas, 1998, pp. 1-3). The reason for classifying it as special linear programming is because the variables and constraints make the model huge and complicated as a result of long computational time issues. The Simplex method is one method for solving transportation problems, while dynamic programming is recommended for the shortest path problems.

Discrete optimisation: When the variables in the optimisation model are not continuous, discrete optimisation is implied. In addition, it is acknowledged to be a challenging area, especially for nonlinear discrete optimisation, because derivatives or gradients do not apply to the formerly mentioned discrete optimisation (Venkataraman, 2002, p. 320). Total enumeration, relaxation technique and heuristic or approximate optimum are recommended in order to search a solution.

Multicriteria optimisation: If the considered problems have to be optimised for more than one objective, multicriteria optimisation (MOP) is involved. There are two suggested groups of methods to search a solution: composing generating and preference-based methods (Chong and Żak, 2008, p.187).

Stochastic optimisation: Making decisions when there are unknown factors or a lack of confidence within variables leads to stochastic optimisation. The commonly used methods for searching for a result are stochastic programming and dynamic programming.

2.7.2 Key observations from reviewing optimisation techniques

From the literature, optimisation is clustered by considering the characteristics of the objective functions and constraints. Therefore, this is the first filter when looking at the proper optimisation problems. Later, the detailed technique to solve optimisation problems can be selected.

2.8 STATE-OF-THE-ART IN DESIGN REWORK ESTIMATION

The aim of this section is to identify factors related to design rework in order to develop the design rework drivers in chapter 4. Hence, prior to identifying factors, the definition of a driver has to be examined. The definition of a driver is derived from the "cost driver" (Blocher et al., 2005, p. 903), as follows:

"*A cost driver is any factor that causes a change in the cost of any activity.*"

Hence, *the factor that causes a change in the effort of design activity* in each different literature is the target to look for. Moreover, the assumptions and limitations in the literature are identified as parts of the method development in chapters 5, 6 and 7.

At the beginning, the design effort estimation is the keyword to search the literature. Hence, the literature matching this keyword is that of Bashir and Thomson (2002). This literature develops the design effort estimation using parametric, analogy and neural network methods. In addition, product complexity is the major input. Its aim is to establish an accurate estimation method. However, this publication does not consider design rework.

From this understanding, the criteria to select the state-of-the-art in design rework are from the combination of "*design effort*" and "*rework*". In addition, all literature is collected by searching publications related to "*product development (PD)*", "*product design*", and then focused with the keyword "*estimation*". Another important keyword is Concurrent Engineering (CE) because it is understood from the researcher's point of view that CE is widely implemented in industry.

The first impression from all the literature is that it takes into consideration design rework effort as an inherent part of the total design effort or design lead time. However, none of the literature reviews design rework specifically. Dependent and interdependent types of design activities (defined in section 2.1.3) classify state-of-the-art into sections 2.8.1 and 2.8.2. Afterwards, the gap analysis is represented in section 2.8.3. In addition, all of them are sorted chronologically and are represented as summaries and limitations.

2.8.1 Design rework effort for dependent tasks

One of the early studies of the estimation method that incorporates overlapping in the CE environment is from Krishnan et al. (1997). Early decision making on the exchange of information to downstream can cause unnecessary iteration due to upstream information evolution and downstream sensitivities. Upstream evolution and downstream sensitivity are identified by how uncertainty decreases during the period of overlapping. Moreover, there are recommendations to alleviate the effects of evolution and sensitivity in this method. Conceptual design and design for the manufacturing phases are modelled with a probabilistic principal to estimate lead time, but the actual challenge is that there are more than two activities involved.

Loch and Terwiesch (1998) extended Krishnan et al.'s (1997) work. They still consider overlapping duration and organisation capability into a probabilistic model to estimate design lead time. The additional factor in the model is pre-communication. It is defined as the actions towards reducing upstream uncertainty before the design process begins; and it could be graded as a communication policy.

Downstream rework occurs because overlapping processes make downstream design tasks rely on uncertain upstream preliminary information. Once the upstream process changes, the downstream has to be reworked proportionally to the degree of modifications required. Hence, many more changes that are made lead to an increase in the design rework effort required. Thus, design rework effort deduces the benefit gained from overlapping. The impact function is developed to explain the relationship between upstream and downstream. Consequently, design rework is influenced by an overlapping period, pre-communication intensity, and concurrent communication policy.

Hoedemaker et al. (1999) identify the limitations of overlapping activities in CE. There is the hypothesis that rework due to overlapping would prolong the lead time in CE when compared with a sequential strategy. The optimal number of tasks required to perform overlapping is around 11 to 15. If the number of task exceeds this threshold, it is difficult to integrate everything under the CE approach as a result of reducing the benefits of overlapping.

Yassine et al. (1999) conclude that downstream design rework occurs because of an overlapping period and design change. Information from upstream is transferred twice in the model. Downstream design tasks begin with the first batch of information derived from the upstream design task. The probability of occurrence is representative of knowledge accumulation. The design change is calculated from the weighted average which is either from the probability of a drastic design change or a small design change. Both probabilities are from judgements and the probability of knowledge accumulation. However, the rationales in supporting each probability are not represented.

Roemer et al. (2000) provide a model to calculate time and cost trade-offs when the product development (PD) is overlapping. The shortest lead time would not necessarily to be the lowest cost of rework. Therefore, the optimisation technique has the role of discovering the optimal solution. The whole PD process is modelled as consisting of more than two design tasks. The downstream rework is called extended design time, which is caused by the evolution and sensitivity as taken from Krishnan et al.'s (1997) basis. However, this method is for management purposes rather than estimation.

Chakravarty (2001) uses risk to modify the design work in predicting rework on building a mock-up. This risk is defined by the probability of incompatibility design. The degree of rework is driven by the risks of requiring the design modifications. This literature proposes three overlapping strategies: interrupt-build overlapping, continuous build overlapping, and pre-empt build overlapping. Moreover, the optimisation model incorporates all of these to achieve the lowest possible costs for design and building a mock-up. However, the method is for two tasks that are overlapping.

Browning and Eppinger (2002) developed a model to find out how design rework cascades throughout a PD process. In this work, PD is modelled as a network of tasks, so an output from one task is an input for another. Design rework is induced by changes in particular inputs in their model. However, input changes are driven either by the upstream task itself or the knock-on caused by upfront tasks. Afterwards, the probability of any input changes that may be required is a product of multiplication from the probabilities of both situations. Unfortunately, all probabilities used in this model are gained from experience, but there is no detailed explanation for what triggers changes.

Xiao and Si (2003) combine the benefits from a strategic approach dealing with the concept of evolution-sensitivity in transferred information, as taken from Krishnan et al. (1997). In addition, the concept of information uncertainty awareness is derived from Loch and Terwiesch (1998). The solution for both issues is to create batches of preliminary information that are transferred in order to lower the risk from downstream rework. Moreover, optimisation plays a role in finding the optimal batch number.

Roemer and Ahmadi (2004) resolve the impact of the rework function from Roemer et al. (2000) by increasing work intensity or resources. The aim of their paper is to find out whether increasing resources or overlapping have a greater influence on reducing lead time and cost. It is found that combining both effects will achieve the highest effectiveness. However, this work only models two tasks.

Jun et al. (2005) model the entire PD process by including extensive task patterns. They consist of feedback, branch & merging, non-overlapping, interaction, overlapping, cycle, and communication. The downstream design rework effort is estimated by a non-homogeneous Poisson process with fine tuning from historical data, while the degree of rework estimation is estimated by a sensitivity concept.

Bogus et al. (2006) provide guidelines to determine overlapping strategies because overlapping of design tasks is neither risk-free nor at no cost to design rework. Strategies given are as follows: overdesign, early release of preliminary information, prototyping, no iteration/optimisation, standardisation, and set-based design. All strategies are selected by the scenario evaluation which is from a degree of upstream design evolution and downstream design sensitivity to changes.

Yassine et al. (2008) implement dynamic programming to estimate the design lead time to find an optimal policy in transferring information, because too much information can lead to an unnecessarily extended lead time. Design rework issues are from the time spent on outdated information that has been received. Probability of rework is obtained from the Monte Carlo simulation. However, all probabilities used in this model are derived from experience.

In summary, all the literature considers design rework issues as embedded in the PD process. Factors inducing design rework are collected into five groups: project complexity, dependency, information exchange, pre-communication and crashing.

Project complexity refers to the integration among elements within a design project. A design project can be separated into modules or components, as defined in Hoedemaker et al. (1999). Dependency and information exchange are the most dominant factors found in this section. Dependency itself explains relationships between each pair of design tasks through upstream evolution and downstream sensitivity of change, while information exchange describes upstream changes, and number of overlapping tasks. Pre-communication is the factor reflecting the capability to reduce uncertainty of the product being designed at the early design phase which was proposed by Loch and Terwiesch (1998). Crashing or increasing resource intensities to PD can compensate design rework effort, as proposed by Roemer and Ahmadi (2004). All factors are summarised in Table 2-8.

2.8.2 Design rework effort for interdependent tasks

Smith and Eppinger (1997) developed a work transformation matrix (WTM), which is the extension of DSM, to model the design iteration process. The concept of Eigenvalue is used to solve the matrix. The method can model either dependent or interdependent relationships among design tasks. Once numeric relationships are defined, the method allows the lead time to be estimated analytically. The interesting point is that iterations within the design process are covered in the WTM. The assumption of this method is that each element has to start concurrently. Once the initial presumption design effort is assigned to each component, this method can model the knock-on effect iteratively. In addition, the final design effort is always greater than expected. However, obtaining numeric relationships is still not clearly defined. Moreover, there are no concrete guidelines to define the initial design effort input.

Cho and Eppinger (2001) assume that each design rework issue occurs for the following reasons: (1) new information is obtained from overlapped tasks after it has started working with preliminary inputs, (2) inputs change when other tasks are reworked, and (3) outputs fail to meet the established criteria. DSM clarifies dependency among tasks, amount of overlapping and impact of overlapping on the design lead time. Design rework is classified into feedback rework and feed-forward rework. Feedback rework occurs due to the change of information from a downstream task or by the failure of a downstream task to meet the established criteria, so an upstream design task needs to be reworked. For feed-forward rework, the downstream task needs to be reworked, since the upstream task has generated new information. A couple of relationships between two design tasks is called iterative rework. The assumption is that the development processes converge to their final solutions with iterative rework. Hence, there are fewer chances of either altering or emergent errors because of gaining more experience, along with the time needed to conclude this exercise. Therefore, the rework probability tends to decrease due to iterations. Therefore, stochastic simulation is implemented to estimate the design lead time. The probability of rework and expected duration of rework are derived from experience, but there are no detailed explanations on how to acquire this experience.

Yan and Wu (2001) introduced a genetic algorithm (GA) to find the shortest design lead time. Feedback from downstream will cause an upstream design to be reworked. Therefore, arranging design tasks with the optimisation method, which provides the shortest design lead time, is the target. The priority number among tasks needs to be assigned; however, how to obtain the numeric value is not well illustrated.

Yan et al. (2002) developed a branch-and-bound optimisation algorithm with a heuristic rule to minimise the lead time for product-process design-activities under CE. Product design is upstream while the process design takes place downstream. The factors triggering design rework are either from upstream changes or upstream faults discovered by downstream. The branch-and-bound algorithm optimises both effects and recommends the optimised overlapping time. Although this literature provides a major contribution to the methodology to estimate mean duration, the method to achieve the relationship between upstream and downstream is not clearly defined.

Joglekar et al. (2001) explored the performance of coupled development activities by proposing a performance generation model (PGM). Two coupled design tasks are modelled. It is assumed that there are limitations in the development time and resources. Therefore, managers need to strike a balance between time reduction, resulting from overlapping, and time increasing due to design rework. Design rework is either from upstream changes triggering downstream rework or downstream alterations forcing upstream rework. The output from this literature is an optimal policy for two overlapping tasks which is constrained by lead time and resources. However, in validation, the design time for each engineer is very difficult to allocate because each one has to work on more than one project simultaneously. Hence, it is quite difficult to calculate the exact time duration for each project.

Wang and Yan (2005) modelled a design activity group, which is composed of an upstream product design activity and several downstream process design activities. Optimisation time and cost are the two main objectives. The interdependency relationship in this model is classified into two possible patterns: fault detection by downstream and upstream changes. The main contribution is finding a constraint to optimise concurrent design activities. The constraint is defined as progress in development with time and there are two types of progress: convex and concave. the former is a fast development progress while the latter is a slower one. Their model is validated by testing with an assigned cost function. It is found that the exponential concave progress makes this assumption factual. However, this literature is not validated by real case studies.

Mitchell and Nault (2007) proposed that cooperative planning can reduce uncertainty in a concurrent design environment. Furthermore, this literature confirms evidence that design rework in a concurrent design can be controlled. Uncertainty is from lack of experience in the projects and this increases the magnitude of upstream instead of downstream rework.

Upstream rework induces downstream rework as a result of project delay. Rework is defined as frequency (number of change iterations) and a magnitude dimension (degree of changes) relative to the original design. Mitchell and Nault (2077) studied 120 business processes (BP) redesign and information technology (IT) development projects in the healthcare and telecommunications sectors. Upstream BP design and downstream IT platform design are interdependent upon each other. Their paper does not offer an estimation-method for either design lead time or design rework, but it provides a clear overview on how design rework occurs. In summary, for interdependent relationships, a fault in upstream design can be found during performance downstream which then necessitates design rework upstream.

2.8.3 Summary for factors related to design rework

The factors under investigation are taken from the analysis results in sections 2.8.1 and 2.8.2 and they are summarised in Table 2-8. The factor definitions are shown as follows:

Project complexity: In a concurrent design project, integrating a product being designed is increasingly difficult compared with a small number of design activities. Therefore, this is viewed as Project complexity.

Dependency: Dependency explains how design activities are related to each other. Evolution and sensitivity are assessed by the strength of dependency among design tasks.

Information exchange: Interconnected tasks exchange information with each other during design. Moreover, there are three categories: upstream changes, faults found downstream, number of overlapping tasks. Upstream changes definitely originate from progress in design, or they can be derived from outside the design team; for example, customer requirement changes. In addition, the number of changes to evaluate the consequences and extensive number of changes lead to substantial design rework effort. Overlapping of design tasks is a generic procedure to reduce design lead time and cost, inoptimal overlapping would lead to a greater design rework effort required. Faults found downstream means that design tasks have to be reworked when design failures are captured within downstream activities; for example, engineers in the testing and refinement phase provide feedback related to engine part failures to the design team.

Pre-communication: This is any action required to reduce upstream uncertainty before the design process begins, and it is determined as a communication policy.

Crashing: A reactive activity to compensate for design rework by increasing work intensity and resources.

2.9 KEY OBSERVATIONS FROM STATE-OF-THE-ART IN DESIGN REWORK ESTIMATION

The key observations from the state-of-the-art in design rework estimation are to address the potential to conduct research as follows:

- All the literature looks at design rework as embedded in the product design effort or lead time.
- Most of the literature is simulation and optimisation based. Moreover, either to achieve lead time estimation accuracy or to manage resources and overlapping to achieve the target lead time is the main focus. The probability of upstream changes or evolution is assumed to be predefined for simulation purposes, but there are no clear linkages to real-life applications.
- Concurrent Engineering is a basis for most state-of-the-art in design rework estimation.
- Assigning numeric values to relationships is a good means to identify the dependency among design tasks. However, only Smith and Eppinger (1997) use this approach, and there are no clear guidelines to obtain any such relationships.
- Only Loch and Terwiesch (1998) and Mitchell and Nault (2007) have considered the effect of the knowledge and experience of the development team; therefore, there should be more investigation in this direction.
- There is only one literature from Roemer and Ahmadi (2004) looking at increasing resources to compensate design rework. Hence, further exploration in this direction would provide a vast opportunity to develop the contribution to knowledge.

Table 2-8: Factors induce design rework for dependency and interdependency design tasks

Literature	Factors under investigation in the literature							Dependency types	
	Project complexity (Integration)	Dependency	Information exchange			Pre-communication	Crashing		
			Upstream Changes	Faults found by downstream	Number of overlapping tasks			Dependent	Interdependent
1.Krishnan et al (1997)			✓		✓			✓	
2.Loch and Terwiesch (1998)		✓	✓		✓	✓		✓	
3.Hodemaker et al. (1999)	✓							✓	
4.Yassine et al. (1999)		✓	✓					✓	
5.Roemer et al. (2000)			✓					✓	
6.Chakravarty (2001)			✓					✓	
7.Yassine et al. (2001)			✓					✓	
8.Browning and Eppinger (2002)			✓					✓	
9.Terwiesch et al. (2002)	✓	✓	✓					✓	
10.Xiao and Si (2003)			✓					✓	
11.Roemer and Ahmadi (2004)							✓	✓	
12.Jun et al. (2005)			✓		✓			✓	
13.Bogus et al. (2006)			✓					✓	
14.Yassine et al. (2008)		✓	✓					✓	
15.Smith and Eppinger (1997)		✓	✓						✓
16.Cho and Eppinger (2001)	✓	✓							✓
17.Yan and Wu (2001)				✓	✓				✓
18.Joglekar et al. (2001)		✓							✓
19.Yan et al. (2002)			✓	✓					✓
20.Wang and Yan (2005)				✓					✓
21.Mitchell and Nault (2007)	✓								✓

- Only Loch and Terwiesch (1998) and Smith and Eppinger (1997) consider design effort and rework in a horizontal problem-solving direction.
- All the literature does not direct any concrete guidelines to estimate the quantity of design rework in the testing and refinement phase.

2.10 CHAPTER SUMMARY

The next chapter explains the development of the research protocol in this thesis. Moreover, chapter three is concurrently developed along with chapter two. Once the research protocol of this thesis is established, the factors related to design rework, as summarised in Table 2-8, are used to develop design rework drivers in section 4.6.1.

The key observations are addressed in section 2.9. There is a potential area to develop design rework effort estimation methods for multi-design tasks. Moreover, the interaction among work packages should be the focus in the development. In addition, design rework effort should be considered solely and especially in the testing and refinement phase. Additionally, this key observation is aimed at addressing research gaps identified in section 4.6.2.

CHAPTER 3
RESEARCH PROTOCOL DESIGN

This chapter illustrates the design of the research protocol which is adapted from Robson (2002, p. xxi), shown as follows:

- Make decision on focus
- Build up the research questions
- Identify types of research
- Select research strategy
- Choose research method
- Data collections
- Analyse and report data

All these elements are conceptually equivalent to other states-of-the art, such as Blaxter et al. (2006, p. 7), Kothari (2008, p. 11), Gray (2009, p. 4). In addition, this chapter proposes the process to validate the research findings. To develop scientific research, maintaining generalisation is a major key challenge. However, the design itself is a process to convert requirements, from end users into a physical product. Therefore, quantitative validation only would be insufficient to confirm findings (Pedersen et al., 2000). In addition, another challenge is the limited number of participants, since designing is the core competency of every business and obviously deals with commercially secret information. Keeping these two challenges in mind, this chapter follows the procedure stated earlier, so that selecting a suitable research method from alternatives could be achieved.

Making a decision on focus is derived from the research background and industrial context to form the research aim and objectives, as stated in sections 1.4 and 1.5.

After research questions and objectives are raised, they satisfy the Making a decision on focus. Then it is cascaded to research strategy and research method. Hence, section 3.1

provides alternatives types of research. Moreover, the rationales to select the optimal choice are discussed.

Later, the research strategy is reviewed and chosen in section 3.2. Section 3.3 reveals the alternatives of the available research methods. The candidate must allow conducting research with a limited number of participants, as stated earlier.

Sections 3.4 and 3.5 provide the details of data collection and the data analysis methods successively. Finally, the explicit discussion of the research protocol of this thesis is proposed in section 3.8.

3.1 IDENTIFY TYPES OF RESEARCH

Classifying types of research against research questions is crucial for designing a research protocol. Kumar (2005, p.9) defines types of research into three viewpoints, as shown in Figure 3-1.

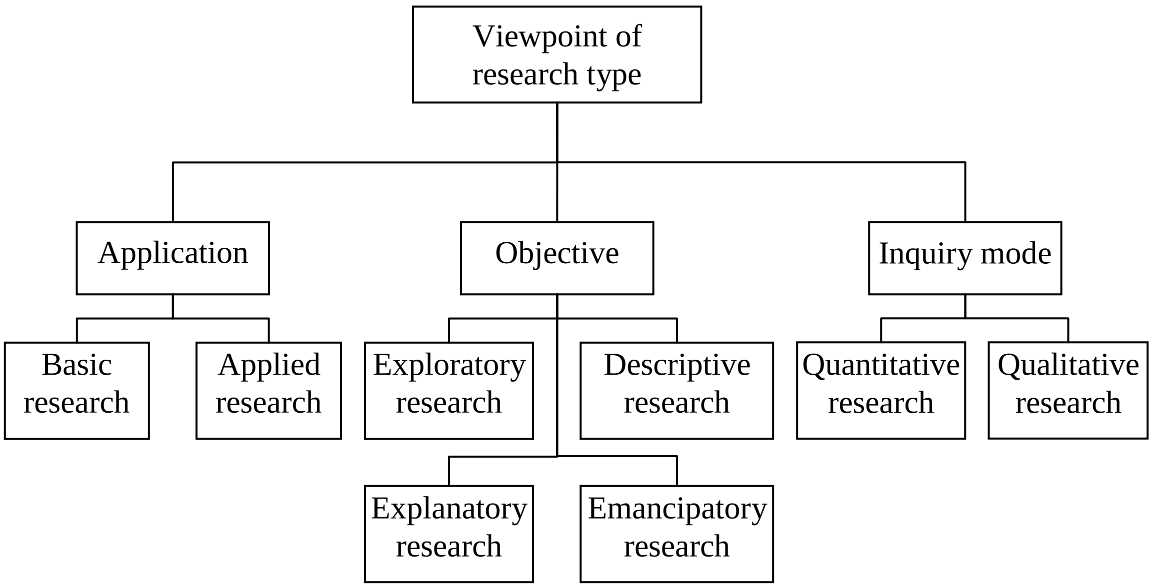


Figure 3-1: Viewpoints of research types (adapted from Kumar, 2005, p.9)

3.1.1 Application viewpoint

O'Leary (2004, p. 134) defines that the main purpose of basic and applied research is different. Basic research aims to produce and expand knowledge to better understand the world. So, applying knowledge is not the key accomplishment. In brief, building a theory is its goal; hence, it can be applied to either a specific organisation or others (Creswell, 2009, p. 2). On the other hand, the direct purpose of applied research focuses on using knowledge in order to find solutions for real-world problems. Moreover, a solution from one case is not necessarily applicable to others.

Key observations

The design rework issue is a real-world problem in product design and development projects. Thus, in a wider view, it is considered as applied research. But in each research question, the knowledge that is developed aims to be generalised. Hence, this thesis has a combination of Basic and Applied researches.

3.1.2 Inquiry mode viewpoint

Creswell (2009, p. 8) classifies quantitative research as being focused on finding the relationships among variables through a set of questions or hypotheses. These include experiments or quasi-experiments in order that correlations can be examined; as a consequence, it requires a large scale of data (O'Leary, 2004, p. 99). Therefore, Quantitative research is equivalent to the "*Positivism*" or "*Scientific*" or "*Deductive*" approach (Gray, 2009, p. 22; Teegavarapu et al., 2009). In addition, it is assumed that data are measurable and repeatable; therefore, statistical techniques are a common tool to analyse data (Marczyk et al., 2010, p. 17). Moreover, Robson (2002, p. 161) suggests that at least 15 samples per variable are necessary to conduct Quantitative research.

On the other hand, Qualitative research aims to understand the contexts of phenomena. Later, data are interpreted and shaped by the researchers' own experience and backgrounds (Creswell, 2009, p. 10). It could be said that this approach helps individuals to experience the world (Given, 2008, p. xxix). It typically engages in interviews and observations without any formal measurements (Marczyk et al., 2010, p. 17), which, in principle, are known as subjective abstract concepts (Kothari, 2008, p. 77). Hence, open ended questions are common in this type of research (Hesse-Biber, 2010, p. 23). In terms of the required scale of data, this does not require a high number of data points if compared with Quantitative research (O'Leary, 2004, p. 99). In summary, Qualitative research fits into a "*Post-positivism*", "*Subjectivism*" or

"*Inductive*" approach (O'Leary, 2004, p. 99). Qualitative research has been well implemented in the social sciences (Family Health International et al., 2005, p. vi); nevertheless, there is evidence from Bender et al. (2002) of using this research approach in engineering design.

Key observations

As pointed out earlier, the constraint of a limited number of participants is an unavoidable situation in this research. So, it appears that Qualitative research is the only applicable approach. However, to address research questions two and three by developing estimation methods, it is assumed that, in each estimation method, there are strong relationships among input factors and outputs being estimated. This assumption has to be tested in order to confirm its validity. However, it is constrained with a limited number of participants, so the statistical validity will be challenged. In addition, if any given research requires both Quantitative and Qualitative methods, it falls into "Mixed methods" (Johnson and Onwuegbuzie, 2004). Furthermore, this approach has high potential to be applied in this thesis.

3.1.3 Objective viewpoint

The Objective viewpoint classifies research in a hierarchy from abstract into detailed analysis (Robson, 2002, p. 59-60). Exploratory research aims at finding out answers, whereas much is still needed to be understood about the phenomena. With a higher level of knowledge, Descriptive research assumes that previous knowledge is available in order that the portrayal of persons, events or situations can be achieved precisely. Once everything is clearly identified, Explanatory research helps to obtain relationships among the variables in the phenomena being researched. Finally, Emancipatory research is in relation to using knowledge to engage with social actions.

Key observations

Table 3-1 provides the analysis of research questions against the Objective viewpoint characteristics. Research question one is in the Descriptive research category because there are factors that are related to design rework, as analysed in section 2.9;

nonetheless, they need to be investigated in greater depth to confirm their validity in the testing and refinement phase.

Research question two makes use of Explanatory and Emancipatory research to formulate relationships among factors and the probability of design rework occurrence.

Research question three implements every element in the Objective viewpoint, because there is no literature which states exactly the precise method required to estimate design rework efforts in the testing and refinement phase. Next, the factors applied for estimation are studied. Later, confirming relationships is necessary before estimation.

Table 3-1: The analysis of research questions against Objective viewpoint characteristics

Objective viewpoint / Research questions	Exploratory	Descriptive	Explanatory	Emancipatory
What are the key drivers of the design rework occurrence?		✓		
How could the probability of the design rework occurrence in the testing and refinement phase be predicted at the early design phase?			✓	✓
How could a design team consider the knock-on effect from design issues in the testing and refinement phase at the early design phase?	✓	✓	✓	✓
How could the design team successfully identify groups of components which would incur a significant penalty in the design rework effort?				✓
How could all of the methods developed in this thesis be validated?				✓

Research question three is strongly connected with question four; therefore, it employs Emancipatory research. This is because it uses knowledge extracted from the preceding research question to develop a warning system which, in turn, is related to design rework efforts in real-world problematic situations. Furthermore, it is expected to link the potential group of components which has a high impact due to design rework efforts that may perhaps be mandatory. Finally, research question five is to validate the entire number of developed methods resulting – all of which will be linked with each company's context. Hence it is defined as Emancipatory research.

3.1.4 Research type selected

Comparing the three viewpoints, the Objective viewpoint reveals more comprehensive perspectives than the afore-mentioned strategies in terms of answering all the research questions. Therefore, the protocol design in this thesis relies only on the Objective viewpoint.

3.2 SELECTING RESEARCH STRATEGY

Selecting a research strategy is a critical process in this thesis, because it provides the guidelines to pick up the appropriate research method, as discussed in section 3.3. Robson (2002, pp. 59 and 87) recommends strategies under the Objective viewpoint as Fixed and Flexible design strategies, and the details are as follows:

3.2.1 Fixed research design

This particular strategy requires a rigid planning of the main data collection especially for Quantitative research. In principle, it seeks group properties and general tendencies through numerical data and statistical methods; therefore, a sample average is looked for, rather than individual characteristics.

3.2.2 Flexible research design

This protocol is the opposite of Fixed research design in the sense that multiple data sources are necessary. Together with data sources and participants' viewpoints, each researcher plays a major role in analysing their validity, and then relationships among variables are evolved after analysis.

3.2.3 Research strategy selected in this thesis

Each element in the Objective viewpoint is analysed with Fixed and Flexible research designs as shown in Table 3-2.

Table 3-2: Research strategies for each type of research (adapted from Robson, 2002, p. 59)

Strategies / Types of Research	Fixed design research	Flexible design research
Exploratory		✓
Descriptive	✓	✓
Explanatory	✓	✓
Emancipatory		✓

Flexible design research can cover the entire range of research questions in this thesis. In addition, Fixed design research is suitable for Quantitative research; however it is not appropriate for this particular situation. Therefore, the Flexible design research strategy is selected.

3.3 CHOOSING RESEARCH METHODS

The research method has strong linkages to data collection; therefore, the research method which requires a minimal number of participants is selected due to the research challenge, as discussed in section 1.6. The alternatives of the Flexible research design strategy are composed of Case study, Ethnographic study, Grounded theory study (Robson, 2002, p. 178). From these three methods, if a strategy can be applied to the minimum number of participants, which in turn leads to appropriation in design rework issues, it will be selected as a research method in this thesis. The characteristics of each research method are explained as follows:

3.3.1 Case study

A case study method allows the researcher to explore in depth a particular enquiry being researched (2009, p. 17). It involves a deep study of one person or a small group of people (Marczyk et al., 2010, p. 147). The aim of this method is to explore an accurate and complete description of any given case study and its real-world context (Woodside, 2010, p. 1). In addition, it acknowledges values of a single case and attempts to build a holistic understanding with a wide range of data sources such as surveys, interviews, observations, and document analysis (O'Leary, 2004, p. 116). After the comprehensive study in a single case is undertaken, findings can be generalised with cross-case comparisons (Eisenhardt, 1989; Flyvbjerg, 2006). Furthermore, there are evidences to implement this method to engineering design research (Kelly, 2003; Salter and Gann, 2003; Breslin and Buchanan, 2008). In addition, Gerring (2007, pp. 89 and 90) and Teegavarapu et al. (2009) propose detailed case selection techniques for generating or testing a hypothesis, as required in the scientific research approach.

3.3.2 Ethnographic study

This method targets understanding how a group, organisation or community exists, and experiences and formulates an intellectual conclusion of their lives and their world by capturing and interpreting observed data (Robson, 2002, p. 89). It is believed that each group's member is constructed and constrained by cultural experience (O'Leary, 2004, p. 119). The data collections in this method are from multi-methods such as histories, participant observations and in-depth interviews (Hesse-Biber, 2010, p. 135); furthermore, data collection will be conducted until a particular saturation point has been reached (Marczyk et al., 2010, p. 120). This method is also implemented in engineering design and design research, such as that of Ball and Ormerod (2000), and Downey and Luciana (2003).

3.3.3 Grounded theory study

It is perceived that this method will help to generate a theory from data (Robson, 2002, p. 90), or, alternately, the theory can be discovered from data (Walliman and Baiche, 2005, p. 259). In addition, this method is also applicable in research related to design (Friedman, 2003).

3.3.4 Research method selected for this thesis

All these methods are applicable in engineering design and design research; however, the Case study research method is more suitable due to the minimal number of participants involved (Onwuegbuzie and Collins, 2007), as shown in Table 3-3. The unit of analysis required in Case study research is different from the others, because it supports using multi-data sources as an addition to interviews.

Table 3-3: Recommended sample size recommendations for research design

Research designs	Sample size suggestion
Case Study	3-5 participants
Ethnographic Study	1 cultural group; 30-50 interviews
Grounded Theory	20-30 interviews

Each suggested sample size is just a guideline; however, it does depend on the scope of the study, nature of the topic, quality of data, and data collection methods. The wider the scope of the research topic, the many more sample sizes are required. This is combined with the nature of the topic which is defined by levels of clarity. Hence, a small sample size only is required if the research question is completely comprehensible.

The quality of data also plays a major role. If the quality of data is rich, the entire context can be achieved with a minimal number of data sources. A semi-structured interview requires many samples in the data collection, because it produces a small quantity of data per interview (Robson, 2002, p. 199).

If semi-structured interviews are assumed as the main source of data collection (worst case scenario) no matter what method is selected, the Case study research method is shown to be the superior technique over other methods due to its low number of participants required. Hence, the Case study research method is selected for this thesis.

3.3.5 Components of case study research approach

Yin (1994, pp. 20-52) discusses the components of the case study research approach as follows:

A study's questions

The questions "*how*" and "*why*" are suitable for the case study research method. This issue might be a challenge in research question one of this thesis, because it aims to find *what* the factors that cause probability of design rework occurrence are. Formulating research questions with "*what, who, where*" is more suitable with survey and archival analysis (Yin, 1994, p. 6). Therefore, instigating additional effort to study documents from each participant is necessary in this thesis.

Study propositions

This sub-section provides the procedure to set up the questions "*how*" and "*why*". In this thesis, factors causing design rework probability of occurrence and potential drivers to estimate design rework effort are taken from literature, as shown in chapter 2.

Unit of analysis

The criterion to define cases is based on the research questions. There are four types of analysis design: *single-case single-unit, single-case multi-unit, multi-case single-unit,* and *multi-case multi-unit*.

This research is classified as a *multi-case multi-unit of analysis design*. On the other hand, each design project in a participating company is considered as a single case. The purpose of this selection is to ensure generalised findings (Eisenhardt, 1989; Flyvbjerg, 2006), and this leads to analysing data using a cross-case technique (Gerring, 2007, p. 93).

Linking data to propositions

This is a part of data analysis, and there is more than one alternative to performing data analysis. As discussed earlier, statistical analysis is not appropriate in this study; hence, qualitative data analysis is the one mainly focused on.

Key observations

Collecting data from multi-data sources enhances the case study research method to answer the research question "what", which is research question one in this thesis. The multi-case multi-unit of analysis approach is selected in this thesis in order to maintain generalisation, and finally qualitative data analysis is the method used to confirm findings from the data analysis.

3.3.6 Bias in case study research approach

To avoid bias in the research is the ultimate goal of this sub-section; therefore the definition of bias must firstly be raised. Gerring (2007, p. 211) defines bias in the case study research approach as follows:

"Bias characterises a sample that is not representative of a population with respect to some inferences."

Thus, selecting only one case to be representative of a population is prone to bias; however, collecting data from multi cases to point out findings is one method to reduce this bias (Eisenhardt, 1989), as discussed in section 3.3.8.

In addition, Hancock et al. (2006, pp. 46 and 85) suggest that bias occurs in the data collection and analysis stages, both of which are due to personal preferences. Robson (2002, p. 324) states that bias in data collection, especially in observation, is from a "*selective manner*" and is composed of the following: *selective attention*, *selective memory* and *interpersonal factors*. Therefore, comprehensively recording evidences in data collection is necessary. Furthermore, strong involvement with stakeholders is another way to avoid bias.

Documentation within a target case study will lead to data collection bias, if people as well as their intention to create the records have not been carefully reviewed, whereas an open response interview technique reduces bias from the missing of important points.

Cognitive bias is one of the major sources of error in data analysis in case study based research. It is a systematic error either from thinking or reasoning; furthermore, over-confidence in the replication of a small sample amount can lead to this type of bias (Gray, 2009, p. 158). The method of triangulating findings with multi-data sources is helpful to reduce bias (Hancock et al., 2006, p. 66). Dey (1993, p. 65) suggests that keeping the researcher's mindset free from "*preconceived ideas*" helps to reduce bias from preferences. Furthermore, sharing facts from findings with colleagues in the same topic area is also helpful in disclosing any undiscovered bias from preconceived ideas (Hancock et al., 2006, p. 67).

Key observations

Bias occurs from selecting a case to be representative of a population being studied. Besides this cause, collecting and analysing data are also related to bias. Therefore, multiple case data collection is preferred in this research. Furthermore, multi-data sources are helpful to reduce bias with the applicability of triangulate findings. In addition, sharing results with the experts in the topic area is inevitable in this research in order to minimise bias from the researcher's preconceived ideas.

3.3.7 Validity of case study research approach

Case study research is extensively applied in social science methods, and it is common practice to validate findings qualitatively (Yin, 1994, p. 33). The quality of the case study research approach is based on four principles as follows:

Construct validity

This is to measure the conceptual correctness by multiple sources of evidence in the data collection phase.

Internal validity

This is an explanatory study by revealing any causal relationship during data analysis. Detailed methods in this test are executed using pattern-matching or explanation-building exercises.

External validity

A generalisation of findings is achieved with this type of test. The findings seek replication from multi-case studies.

Reliability

In the data analysis phase, it needs to be confirmed that all findings from multi-cases are repeatable. If other researchers follow this particular research procedure and conduct the same case study, the finding results should be similar. This activity aims to ensure the repeatability of phenomena, and the aim of this test is to reduce bias from researchers (Yin, 1994, p. 36).

All these measuring approaches are not only intended to verify the quality of research design, but they are also applied to the developed methods in this thesis known as the *"Validation square method"* (Pedersen et al., 2000; Olewik and Lewis, 2005). More detailed explanations are shown in section 3.7.

3.3.8 Selecting cases

This is an activity to decide on the representative of the participating companies in order to analyse data. Therefore, reviewing case selection techniques and evaluating the most suitable one is a critical task. The limitation of the participating companies is still the criterion. This task is conducted after the decision on the unit of study as "*multi-case* *multi-unit of analysis*" is confirmed; selecting cases is important because they assist in the reduction of bias. The case selection techniques are reviewed as follows:

Gerring (2007, pp. 86 to 144) proposes that, in a large number of samples within multi-cases, a random selection technique is applicable to choose the representative cases. In addition, the sample mean is inferred as a population mean. But in a small number of cases and small samples, the mean has the possibility to deviate from the population centrality by too much. Therefore, it could lead to "bias" in not selecting cases as representative. Hence, the random sampling technique is not suitable when there are small samples and a small number of cases. However, there are nine non-random selecting methods suggested for the case study research approach, as follows: *typical, diverse, extreme, deviant, influential, crucial, pathway, most-similar* and *most-different.* The explanation of each technique is as follows:

Typical case: This technique looks for cases that are representative of the population in order to achieve general understanding through hypothesis testing. It is assumed that, within cases, the ranges of data from a single dependent variable and a single independent variable are available. So, typical cases which have strong relationships are selected.

However, in reality there is more than one variable to consider relationships, so selecting a typical case is not a simple task. In addition, without a full range of data being available the selection seems to be difficult to implement.

Diverse case: Selecting cases to capture maximum variance along relevant variables is the aim of this technique. Cases are expected to show the range of independent and dependent variables. So, the relationship among variables can be determined. From researchers' perspectives, cases are categorised, e.g. colour, geography, etc. Therefore, this technique is quite similar to stratified random sampling by arranging a population into groups. Later, the samples are randomly selected (Blaxter et al., 2006, p. 63).

To use this technique, it is assumed that internally homogeneity among cases is maintained either within or through categories and researchers need to have a certain degree of confidence about the existence of relationships among variables.

Extreme case: This technique focuses on cases which have extreme value in dependent variables. It is dissimilar to the *Typical case* technique which looks for cases that are representative, or the average, of a population. In brief, the distinctive or unusual cases compared to others are selected from those subjects that are considered from the maximum variation of dependent variables to the mean of population. Therefore, the independent variables can be examined for their impact on the dependent variables. In addition, this activity can be applied to develop a comprehensive list of the independent variables which have strong relationships to the dependent variables. For example, an automotive OEM which always uses a shorter lead time than the industrial average is selected in order that the key drivers to reduce lead time can be addressed.

A researcher needs to understand the range of data before the extreme case is concentrated on. However, the *Extreme case* technique is vulnerable in choosing cases which exceed the acceptable range and become "*bias*" (stated in section 3.3.6).

Deviant case: The cases which conclude surprising results from the dependent variables are picked. Thus, the *Deviant case* technique basically searches for distinction from judgement based (relative to the general model) rather than deviation from the mean as used in the *Extreme case* technique. Later, an investigation is conducted into what are influenced by dependent variables, so a new hypothesis can be set. For example, a design team which always delivers successful products is selected to follow this selection technique.

The assumption in this technique is that the researcher needs to understand the norm of the phenomenon being studied in order to select a desired case appropriately.

Influential case: This technique aims to select cases to invalidate a theory. If the theory cannot be invalidated, then it is confirmed. Moreover, the exception from, or limitation of, the theory can be defined and this leads to verification of assumptions. In principle, influential cases are those which cannot be explained by the causal relationship within a predefined theory*.

Influential and *Deviant case* techniques seem similar to each other, but there are two main differences. Firstly, the *Influential case* technique assumes that theory for a

* For example, Galileo mentioned that every object will fall to the ground in an equal amount of time even if each of them is released from the same height. However, this theory will not be valid if a feather is dropped to earth. So, dropping a feather is selected as an influential case.

phenomenon is available (causal relationship provided), while in the *Deviant case* technique, the norm of an independent variable is available but there are neither causal relationships nor an explicit list of dependent variables. Secondly, this technique is suitable for hypothesis testing while the *Deviant case* technique is suitable for hypothesis generation.

Crucial case: The crucial case is the case that corresponds very well with the theory but it must not fit at all with any rule contrary to that being proposed. By this definition it is helpful to identify the least-likely case to comply with the theory, so it is also helpful to either confirm or refute the theory using cross-case analysis. Criteria to consider the most-likely and least-likely cases are obtained from looking at the predicted output when a theory is applied to cases. If the predicted output from the case is completely deviated, it is least-likely; otherwise most-likely.

However, the assumption for this technique is that a theory to explain the phenomenon must be available. In addition, the set of independent and dependent variables as well as their relationships have to be reasonably well defined.

Pathway Case: This technique is for elucidating the causal relationships between sets of independent and dependent variables. Isolating each relationship for a particular pair of independent and dependent variables is the aim of this technique. In principle, cause-and-effect analysis is done through this procedure; as a result, it is known as a *mechanism*.

However, it is assumed that the causal relationships between independent and dependent variables have to be well represented from cross-case analysis.

Most similar case: For the purpose of generating a hypothesis, a pair of similar cases is selected when their outputs are dissimilar. Consequently, the cross-case analysis enhances identification of the key factors resulting in differences. For hypothesis testing, this technique is useful when their outputs are similar but their inputs are different. The control variables play a major role in this technique, because the similarity is reviewed through them. However, ranges of inputs and outputs from cases have to be available.

Most-different case: This technique is the opposite of the *Most-similar technique*. A pair of the most different independent variable cases but equal dependent variables is selected. However, the assumption in this technique is analogous to the *Most-similar case* technique.

Each case-selecting technique is either suitable for hypothesis testing or generating. In analysis, each technique is determined with a set of independent and dependent variables within cases. Sample mean and variance concepts are criteria for evaluation. The summaries of case study selecting methods against their purpose are shown in Table 3-4.

Table 3-4: Comparison of case study selecting techniques (adapted from Gerring, 2007, pp. 89-90)

Methods	Hypothesis generating	Hypothesis testing	Cases required	Purpose
Typical case		✓	One or more	To represent the broader phenomena
Diverse case	✓	✓	Two or more	To cover the range of phenomena
Extreme case	✓		One or more	To probe dependent and independent variables
Deviant case	✓		One or more	To develop new explanation of dependent variables
Influential case		✓	One or more	To validate theory by trying to invalidate theory via cases
Crucial case		✓	One or more	For confirmation of or refuting the theory
Pathway case		✓	One or more	To probe causal mechanism
Most-similar case	✓	✓	Two or more	To clarify or confirm causal relationships
Most-different case	✓	✓	Two or more	

Case-selecting technique in this thesis

The Diverse case technique is employed as a case-selecting technique in this thesis for the following reasons:

- As stated earlier, design activities tend to be difficult to assess in each company. If the selection method presumably requires the range of independent or dependent variables as well as the causal relationships between them, this does not seem possible. However, the prerequisite of causal relationships among variables is not required in the *Diverse case* technique.

- Furthermore, the industrial context classifies companies into OEMs and Tiers, as stated in section 1.2, and this classification is recognised as a category. In addition, the geographical location of each company is considered as another category in this research. More categories lead to a higher chance of capturing a wide range of data. So this action is not only to reduce bias, but is also in line with the case selection technique.

3.3.9 Conceptual setting for case study approach in this thesis

The case study research method is selected for this thesis, as discussed in section 3.3.4. This subsection is for conceptually designing a research methodology to fit with the research focus. The conceptual design, from the researcher's analysis, as follows:

- *A study's questions:* Data collections are planned to achieve answers to all research questions, as stated in section 1.3. Moreover, questions that start with *"how"* or *"why"* are strictly used during the interviews.
- *Study propositions:* Questions set for the data collection phase are derived from section 2.8.3.
- *Unit of analysis: Multi-case multi-unit of analysis design* is chosen in this research in order to reduce bias, as stated in section 3.3.6. Furthermore, cases are selected based on the *Diverse case* technique.
- *Linking data to propositions:* The data analysis complies with qualitative data analysis because of an insufficient number of participants being available to perform quantitative data analysis.

3.4 COLLECTING DATA

The data collection reviewed in this section is confined to the case study research technique only. There are six sources of evidence: *documentation, archival records, interviews, direct observations, participant observation* and *physical artefacts* (Yin, 1994, p. 80).

3.4.1 Documentations

This data source comprises mainly of communication documents such as letters, agenda announcements, progress reports, newspapers, etc. which are accurate with a broad coverage and a timely range. In addition, it has a relatively low bias; however, it is not well documented in reality. Apart from newspapers, other documents are considered as internal documentation. However, and particularly within this research, the availability of documents in design are restricted from viewing by outsiders; so, any expectation of obtaining detailed company documents will be medium to low.

3.4.2 Archival Records

Both documentation and archival records are defined as a secondary information source (Gray, 2009, p. 30). The major contrast between documentation and archival records is the purpose of recording. Documentation is a means to communicate purposes, either for internal or external organisations. On the other hand archival records represent organisational outcome and organisational contexts. Materials in this classification are, for example, service records, organisation charts, budgets, geographics of the organisation, stakeholder lists, survey data, and personal records. The benefits and weaknesses of this evidence are similar to those for documentation.

3.4.3 Interviews

This is one of the most important data sources in the case study research approach. Questions used are open-ended because the benefit is to acquire opinions and events of a case, which are valuable in comprehending the case study context.

Interviews are defined roughly into Structured, Semi-structured and Unstructured interviews (Robson, 2002, p. 270; O'Leary, 2004, p. 164). Variations in interview techniques are cascaded into more detail, as shown in Table 3-5. The interview types are selected from the level of clarity in each phase of the project.

In the early phase, *Interview as informal conversation* tends to be constructive because there are many variations in the very early phase, and this tactic helps to present a clear direction in the study. Once the direction becomes more transparent, *Interview as open ended* is selected to confirm the initial findings.

Table 3-5: Variations in interview method (Hancock et al., 2006, p. 34)

Type of Interview	Interview Characteristics	Strengths	Weaknesses
Interview as fixed responses	Questions and responses options are predetermined, response options are fixed, and respondent selects appropriate response.	-Data analysis is simplified, -Responses can be compared and combined, and -A larger number of questions can be addressed in a brief space and time.	-Experience and perceptions are fitted to predetermined categories. -Often perceived as impersonal, irrelevant, and mechanical. -Meaning or richness of experience may be distorted by limiting response options.
Interview as open-ended responses	Specific wording and sequence of questions are predetermined, all participants are asked basic questions in the same order, and all questions require open ended responses.	-Comparability of responses may be strengthened, -Completeness of data for each person is enhanced -Biases are minimised, and -Analysis and organisation are facilitated.	-Flexibility is limited by relating the interview to specific individuals and circumstances. -The standardised wording of the questions may limit variation in answers.
Interview as guided conversation	Information to be addressed is specified in advance, but interviewer defines the sequence and wording of questions during the course of the interview.	-The plan increases the completeness of the data and makes data collection more systematic for each participant, -Potential gaps in process can be anticipated and addressed, and -Interviews remain conversational and situational.	-Critical topics may be inadvertently missed. -Flexibility in sequencing and wording questions may result in different responses from different participants and may reduce the comparability of responses.
Interview as informal conversation	Questions are derived from the ongoing context and are asked in the course of the interview and there are no predetermined questions, topics, or wording.	-Value and relevance of questions is heightened, -Topics are built on and emerge from observations, and -The questions can be matched to individuals and circumstances.	-Information may be different when collected from different people using different questions. -May be less systematic and comprehensive if particular questions do not arise. -Data organisation and systematic analysis may be difficult.

Later, *Interview as fixed response* tends to be used at the latest stage of the research in order to test and validate the developed methods which have evolved from the findings.

3.4.4 Direct observations

This method covers all “*site*” visit activities. Its aim is to collect behaviour and context of the cases. Observing meetings, pedestrian activities, factory work, class rooms, etc. are all accepted in this method; furthermore, it can be conducted informally. However, it is important to understand that this method enhances obtaining additional information rather than being a main source of data collection. It is considered as “*passive*”, because observers have no role in the observed activities. To increase reliability, multiple observations or an increasing number of observers are necessary. Therefore, this method is time consuming in order to fully capture a case's context.

This method has a high potential to be used in this thesis because the observers remain "*outsiders*". In addition, site visitations are more common than full involvement in design activities.

3.4.5 Participant observations

Observers have "*active*" roles in observations. Unusual phenomena are easily captured because the observers are parts of cases; therefore, an "*inside view*" is effortlessly recognised. However, this method may lead to bias due to over-emphasis on the group to which the observers belong.

This method is not suitable for this thesis because it is uncommon to allow "*outsiders*" to be part of the design team due to the enterprise's confidentiality.

3.4.6 Physical artefacts

Physical artefacts are entities either within, or outputs from, cases. For example, tools used in companies or finished parts are physical artefacts. The interpretation of data from physical artefacts can be analysed through the direct observation method. This method has greater value in order to understand the generic context than a specific phenomenon. However, this method has been used extensively in anthropology.

In this thesis, this method is treated as a part of direct observation, because the artefacts are observed and recorded during observations.

3.4.7 Planning for data collection in this thesis

The *Participant observation* technique is not suitable for this thesis because it requires strong involvement with each organisation's design activities. Participating in design activities seems difficult for a researcher who is not part of the organisational team. In summary, data collection in this research is planned as follows:

- Apart from the *Participant observation* technique, all recommended data collection techniques are applied in this thesis.

- *Direct observation* is selected because most interviews are conducted on site. However, this method cannot be completed remotely.
- All interview techniques are selected in this thesis. In the early stage, *Interview as informal conversation* and *Interview as open-ended response* are implemented, because both techniques are non-restrictive to any answers. Hence, the researcher can capture comprehensive viewpoints.
- Once interview data from the early phase are analysed, the information is applied within further interviews to confirm findings. Therefore, *Interview as fixed response* is implemented to obtain more specific answers in the method validation.

3.5 ANALYSING AND REPORT DATA

Yin (1994, p. 102) mentions that data analysis in the case study research technique has the least development compared with others. Even though statistical analysis or the quantitative method are prominent techniques for analysis, they still require a certain number of samples in order to comply with statistical requirements. Hence, the quantitative data analysis tends to be an inappropriate method in this thesis. Therefore, other techniques, such as thematic analysis, are reviewed in this section.

Qualitative data analysis is another alternative for the case study research approach (O'Leary, 2004, p. 99). Thematic analysis, categorical analysis and narrative analysis are the common techniques for analysing data in a case study research method (Hancock et al., 2006, p. 61). Each has its own uniqueness; however, each individual has common principles as follows: repetitive, ongoing review of accumulated information in order to identify recurrent patterns, themes, or categories. Nonetheless, narrative analysis emphasises a chronological sequence of themes (Dey, 1993, p. 51).

Therefore, this section is directly focused on a thematic analysis because all three methods are similar in principle.

3.5.1 Thematic analysis

Thematic analysis is normally applied in qualitative research. This analysis is a process of segmentation, categorisation and re-linking of aspects from the database using researchers' judgements. It involves a focus on repeated words or phrases, case studies or evidence of answers to the study questions. Data collection and analysis are completed simultaneously by using this method (Dawson, 2002, p. 116).

Thematic analysis is frequently preferred by researchers at a beginner's level. After the questions are asked, each new piece of information is constructed for tentative answers. Later, the responses are categorised into themes. This process is iteratively conducted until the emerging themes are well-supported by all the available information. Multi-case studies are helpful to confirm the validity of themes. Once information from all sources supports tentative answers, they are reported as findings. The theme starts to develop from several engagements, as follows (O'Leary, 2004, p. 196):

- Literature
- Researcher's experience
- Insights gathered through the process of data collection

3.5.2 Criteria to develop themes

Hancock (2006, p. 62) proposes criteria to develop themes as follows:

- Themes must reflect the purpose of the research and respond to the questions being investigated.
- Themes must evolve from a dissemination of the collected data relevant to the research questions.
- Even though themes are sometimes hierarchical and interconnected, themes represented separately of findings should be continued until researchers have confidence that there are no more new themes.
- Each theme should be specific and supported by the data collected.

3.6 KEY OBSERVATIONS OF RESEARCH METHODOLOGIES

A summary of research methodologies from sections 3.1 to 3.5 is shown in Table 3-6. All selections are acknowledged as baselines in designing the research protocol in this thesis, as described in section 3.8.

Table 3-6: Summary of research methodologies of this thesis

List of selections	Selected methods	Sections illustrated
Identify type of research	Objective viewpoint	3.1
Research strategy	Flexible	3.2
Research method	Case study	3.3
Selecting cases	Diverse case technique	3.3.8
Collecting data	Multi sources	3.4
Analysis of data	Thematic analysis	3.5

3.7 VALIDATING DEVELOPED METHODS

Sections 3.1 to 3.6 support the characteristics of design rework issues in industries. Once findings from industries are captured, they are implemented in method developments. Hence, this section is an additional method to validate the developed methods. Pedersen et al. (2000) and Olewnik and Lewis (2005) propose a means to validate research in the topic area related to design methods; however, the latter work is less comprehensive compared to the former. Therefore, the validation square method suggested by Pedersen et al. (2000) is the one focused on.

The Validation square method is developed from the Case study research approach. Assuring for "*Structural validation*" and "*Performance validation*" are the targets in this method, both of which have six requirements for validation as follows:

Structural validation

In conclusion, the structural validation confirms the logical setting of the developed method. It focuses on how to formulate the method and cases selection; hence, the detailed explanation is as follows:

Acceptance of construct's validity: This is the valid paradigm to build up confidence in the developed method with the qualified literature. Hence, exploitation of only valid literature is the best practice that needs to be followed.

Acceptance of method consistency: The method developed must be clearly identified in accordance with required information and steps in order to achieve it. Valid assumptions are also crucial at this stage.

Acceptance of the example problem(s): The selected cases must be clearly shown in relation to the problems for which the method is designed. The data available from the cases are valuable to formulate conclusions.

Performance validation

This section is to confirm the usefulness of the method either from the selected cases or the potential to apply them towards others in the organisation. There are three requirements to fufil as follows:

Acceptance of the usefulness of the method outcome with respect to the initial purpose for some chosen example problem(s): The usefulness of the method must clearly address the metrics to measure the usefulness; e.g. cost or time reduction.

Acceptance of the linkage between the achieved usefulness and the method: The result must be unique and obtained only from the developed method. In addition, it must be within the required acceptable range.

Acceptance of the method's usefulness to be applied beyond the case studies: The method's validity is confirmed by its validity, if it is transferable to other cases.

3.8 DESIGNING RESEARCH PROTOCOL OF THIS THESIS

This section aims to explain the research protocol of this thesis, as represented in Figure 3-2. It is separated into three major phases: Research strategy and focus; Main data collections, analysis & method development; while the Validation with case studies is the final phase. The detailed explanation of each phase is represented in sections 3.8.1 to 3.8.3. Section 3.8.4 then addresses the limitations of applying the case study research method in this thesis.

IDEF0 (Kim and Jang, 2002) is applied to design the research methodology in this thesis. Each box in Figure 3-2 represents an activity. Each individual arrow which points to the box on the left hand side represents input. At the same time, outputs are indicated on the right hand side. On the top of the box is illustrated the controls over the activity. The bottom of the box represents the industrial participants in that particular activity. The nomenclatures are shown at the bottom left of the figure. The two special arrows are for a quick explanation of the diagram. The research protocol of this thesis is complicated. To simplify the diagram, outputs of each activity are reduced to one line, which separates and directs to other activities as desired. The inputs are designed to receive multi sources in order that the diagram can show the traceability of inputs. Each curve represents that individual lines overlap another one.

The activities in each phase are illustrated against each chapter, as summarised in Table 3-7. There is an overlap from initial and comprehensive literature reviews in chapter 3, because this concern needs to be addressed throughout the thesis. The detailed explanations are discussed in the adjacent sections.

3.8.1 Research strategy and focus

This project has received no financial support from any industries; therefore, the focus is initiated from the researcher's interests. The researcher needs to investigate iteratively through *Initial literature reviews* and *Initial data collections & analysis* to formulate the research focus and research questions, as presented in Figure 3-10.

The preliminary question on what creates a design process delay sets the direction for the literature review. As a result, research background and industrial context (as shown in sections 1.2) becomes a beginning point of *Initial data collections & analysis.* A limited number of participants is the key challenge in this thesis. Therefore, the case study research approach is selected. As a consequence, it has control over *Initial data collections & analysis* in terms of interview questions and acquiring multiple data sources.

Interview as informal conversation is a most important interview technique – the very early stage in order to create the "*overall view*" of the topic, and questions are at first developed from the initial literature findings. Once the research focus becomes unambiguous, *Interview as open-ended responses* is used. The initial results feed back to *Decision on research focus* and *Building up research questions* activities in order to be concisely focussed. Detailed data collections are described in chapter 4.

3.8.2 Main data collections, analysis and method developments

Once *Decision on research focus* and *Building up research questions* are ready, the *Comprehensive data collections & analysis* activity is prompted to begin. Questions are prepared to answer the research questions. Moreover, initial findings are prepared to be interview questions during the data collection stage. The open-ended response technique supports the views of interview experts and additional findings are recorded. In the later stage, the guided conversation technique is implemented. In addition, the discoveries founded in the initial data collections control this activity.

The *Comprehensive data collections & analysis* and *Comprehensive literature reviews* are conducted iteratively. Each and every data collection helps to confine the search for literature. Thematic analysis is implemented to analyse interview data. On the other hand, other internal documents enhance the understanding of each company's context.

The outputs from *Comprehensive data collections & analysis* and *Comprehensive literature reviews* support all developments of this thesis. The Design Rework Probability of Occurrence Estimation (DRePOE) method is a combined development of drivers and an analogy-based estimation technique. This method aims to answer research questions one and two.

The Design Rework Effort Estimation (DREE) method fulfils research question three. It is developed from industrial practices captured in both data collection activities. In addition, the functional analysis system technique (FAST) and analogy based estimation method are applied in this method.

The Prioritise Design by Design Rework Effort Based (PriDDREB) method aims to identify groups of components which have high impacts on the design rework effort. With this capability the design team can manage to reduce design flows early. The recent development is extended from the DREE method. In addition, industrial practices found in both data collection activities are derived to be assumptions. Later, an optimisation technique is used. Hence, research question four is satisfied.

The control relationships tie all the methods together. They are developed with experts from case study one to confirm their validity in an industrial context. Detailed developments of all means are illustrated in chapters 5, 6 and 7.

3.8.3 Validation with industrial case studies

This thesis cannot be completed without validation. Therefore, testing with two additional industrial case studies is necessary to confirm the validity of all methods. All the stages are designed under the validation square method. The *Interview as fixed responses* technique is to review the acceptability level of the methods from experts. On the other hand, *Interview as open-ended responses* technique is applied to collect the experts' viewpoints on the methods. In brief, this phase completes research question five. The detailed explanations are in section 8.3.

All activities are summarised in Table 3-7. Each activity is reviewed against phases in the research protocol as well as the technique selected, as shown in columns three to eight. Factors reducing design rework and industrial practices in the product design process are developed in chapters 4 and 5. All relationships and factors are hypothesised and subsequently methods are developed with multi-data sources. All method developments are explicitly shown in chapters 5, 6 and 7. The causal relationships between dependent and independent variables are indirectly validated through the developed methods by using multi industrial case studies. All validating activities are performed with the Validation square method, as represented in chapter 9.

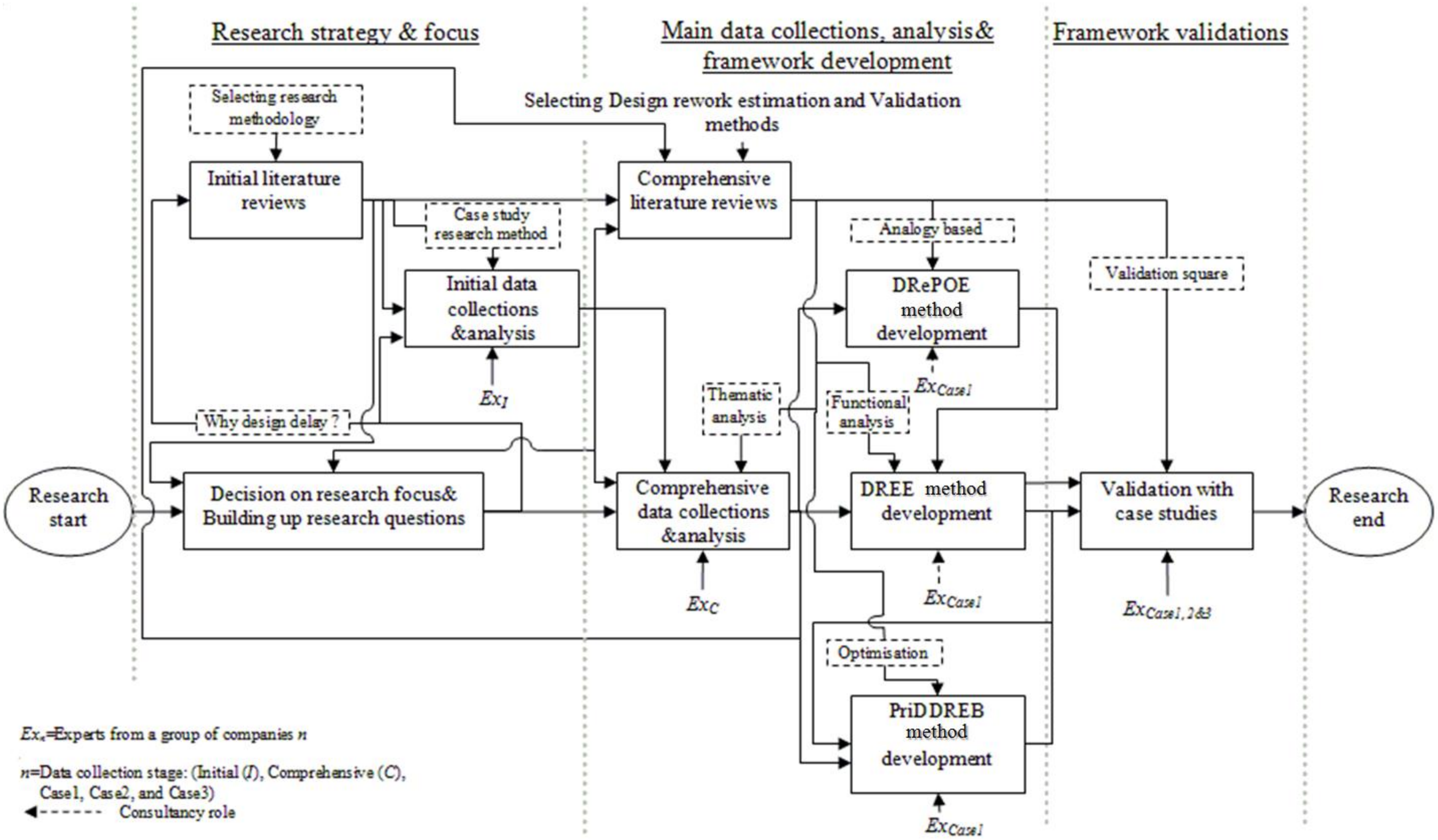


Figure 3-2: Research protocol of developing design rework estimation methods

Table 3-7: Activities in research protocol

Activities	Phases in research protocol	Selected techniques						Chapters
		Objective viewpoint	Flexible research strategy	Case study	Diverse case technique	Multi-sources	Thematic analysis	
Decision on research focus and Building up research questions	Research strategy & focus	✓	✓	✓				1
Initial literature reviews								1,2,3
Initial data collections & analysis					✓	✓	✓	1,4
Comprehensive literature reviews	Main data collections, analysis & method development							2,3
Comprehensive data collections & analysis					✓	✓	✓	5,6
DRePOE method development						✓		5
DREE method development						✓		6
PriDDREB method development						✓		7
Validation with case studies	Method validations						✓	8

CHAPTER 4
INDUSTRIAL FIELD STUDIES

The objective of this chapter is to answer research objective one by identifying industrial practices. Furthermore, factors activating design rework occurrences are synthesised from industrial interview in this chapter. This chapter is compiled of initial data collection & analysis, as shown in Figure 3.2. This is comprised of two stages which are primary and secondary data collection.

The data collection is designed to comply with the flexible design research strategy; therefore, the data collection process is not rigidly established at the start of this process. A case study research approach is applied and companies A, B, C, D and E are treated as a single case study. Data collection is conducted through the OEMs and the suppliers in the automotive industry, as shown in Table 4-1; moreover, cases are selected from the different geographic locations. Only company E is treated as multi-unit of analysis, because the data collected is from three projects in a similar product range. In addition, one of these projects performs a distinctively worst case scenario in terms of design rework effort compared with the others, while the other case is acknowledged as single unit of analysis. Collecting data from multi-data sources is applied in this activity, while the data collection by interview follows the open-ended response technique. Accessibility to other data sources relies on the willingness of each interviewee. The data collection procedure is explained in section 4.1. The primary data collection is conducted through companies A, B, and C as shown in section 4.2 to 4.5 and, then the key observations from each company are analysed together in section 4.4.

Collecting data in companies D and E is in the secondary stage, as represented in section 4.6 and 4.7 and the findings from both companies are displayed in section 4.8. The discoveries from both stages are synthesised as the research gaps, industrial practices and recommendations for further development, as shown in section 4.9. All data is analysed with the thematic analysis technique, as summarised in the rightmost column of Table 4-1. Nonetheless, the findings from the literatur identify in Table 2-8 are the additional sources for data analysis in the secondary data collection activity.

Table 4-1: Summary of data collections in each case in initial data collections and analysis

Company	Roles in industry	Locations	Stages of data collections		Data sources			Data analysis (Thematic analysis)
			Preliminary	Secondary	Interviews	Direct observations	Documentations	
A	Japanese Tier 1 supplier	Thailand	✓		✓	✓	✓	Researcher’s experience, Insights gathered through the process of data collection
B	UK Tier 1 supplier	UK	✓		✓	✓	✓	
C	Japanese Tier 1 supplier	UK		✓	✓		✓	Researcher’s experience, Insights gathered through the process of data collection, Literature
D	Thai Tier 1 supplier	Thailand		✓	✓	✓	✓	
E	UK OEM	UK		✓	✓	✓	✓	

4.1 QUESTIONNAIRE DEVELOPMENTS FOR INITIAL DATA COLLECTIONS

4.1.1 Hypothesis for initial data collections

Before setting up questions for data collection, especially for interviews, the hypothesis setting is necessary. The hypothesis is formulated from curiosity about what factors induce design rework occurrence and drive design rework effort, specifically in the testing and refinement phase. Factors captured from literature as represented in Table 2-8 are implemented to estimate the design effort of the whole design process, but they are not directly covered in the thesis's focus yet. However, they provide the direction to address the design issues in the testing and refinement phase. Therefore, the hypothesis of the initial data collection is as follows:

"*The factors from Table 2-8 can be used to explain design rework occurrence in the testing and refinement phase*."

However, asking industrial experts whether or not the factors captured from the literature relate to design rework in the testing and refinement phase would lead to bias. Hence, the questions have to be open ended in order to allow a wide rage of answers for capturing as many factors as possible. Therefore, Interview as informal conversation and open-ended response are implemented, as described in section 4.1.2.

4.1.2 Preliminary data collection stage

Questions set in this section aim to capture the generic aspect of a product design and development process. During data collection, it is necessary to search emerged issues which might induce design rework in the testing and refinement phase. All questions were reviewed and the pilot test was conducted with Company A. The questions are as follows:

- Would you please explain the product development processes used in your organisation?
- Please explain product architectural design and integration methods. Are there any software tools supporting this activity?

- Who should be involved in the PD team? How do you structure your PD team?
- Please explain the project planning methods implemented in your design project. Are there any software tools used?
- Please explain how to estimate the time and effort required for each design activity.

The questions are added into the questionnaire, as shown in Appendix A. During the data collection, especially in interviews, the researcher did not lead the sessions, but the researcher only made sure that all the questions were answered. The main focus is on question one. If any emerging issues arose, the researcher would spend more time on them. Later, all concluding points were investigated and compared with those of other companies.

4.1.3 Secondary data collection stage

After primary data collections were completed, any emerging issues were evaluated in order to refine the questions and subsequently use them in the interviews during the secondary data collection stage.

4.2 COMPANY A

Japanese automotive OEMs have had the highest market share in Thailand for more than 20 years. In Thailand, company A is an engineering design company which is a subsidiary of a Japanese automotive OEM. This company supports engineering design for the customers in Thailand, as well as in Indonesia, Malaysia, Philippines, Vietnam, Taiwan and India.

Data collection was achieved mainly by an interview process as informal conversation technique for three hours with the General Manager of purchasing in the engineering department. The questions outlined in section 4.1.2 were used during the interview in order to conduct a pilot test.

The interviewee had been employed by the company for approximately 20 years. The venue was at company A's headquarters which are in an eastern sub-district of

Bangkok. In addition, the use of camera and voice recording was not permitted during data collection, so taking notes was the only means available to record data.

4.2.1 Direct observation

Even though the data collection was performed on site, it was set in a meeting room. Therefore, performing the observation was in a limited setting. There are only two distinctions, which are the list of technical centres all over the world, and distributed locations for manufacturing and assembly sites and suppliers in Thailand. There are two assembly sites for passenger cars. One is in the south of Bangkok located approximately 40 Km. away from the head quarters'. The other is in Prachinburi province, which required a one-hour of drive north east of Bangkok.

Thus, there are cleary two conclusions. This Japanese OEM distributes design to every continent. In addition, the design centre in Thailand is not located in the same area as the manufacturing and assembly sites.

4.2.2 Documentations

The interviewee brought company A's product design and development handbook as an example during the interview; however, photocopying any part of the book was not allowed. Therefore, taking notes in a notebook was the only opportunity to record the data. The flow chart for product design and development is shown in Figure 4-1. The detailed discussion is captured from interviews as shown in section 4.2.3.

4.2.3 Interviews

The interviewee provide company A's product design and development handbook as an example during the interview; however, photocopying any section of the book was not allowed. Hence, taking any annotations from the book was the sole method of recording the data. The flow chart for product design and development is shown in Figure 4-1. The detailed discussion captured from interview is shown as follows:

Product design and development captured from company A

This technical centre has the responsibility to design and develop car parts. The interviewee had a lot of experience in car body design and development projects; while was thus used as the main focus of the interview. In Figure 4-1, Styling represents the overall appearance of the car, while Design activity confirms each part's durability. Car development takes 4 years through design and development; however, the lead time is set by management. Planning and Styling a particular car model are conducted in Japan where Thai engineers from company A have to be co-located with a Japanese team. The main database for designing a car is stored and maintained in Japan; therefore, the first two stages have to be completed in the company's motherland. Planning is the process to convert customer requirements from market surveys into specifications in order that all information is ready for Styling. A clay model is the main medium in the Planning and Styling stages. Then conceptual drawings for cars are developed upon which part drawings are released; these two drawing developments take up one year's lead time.

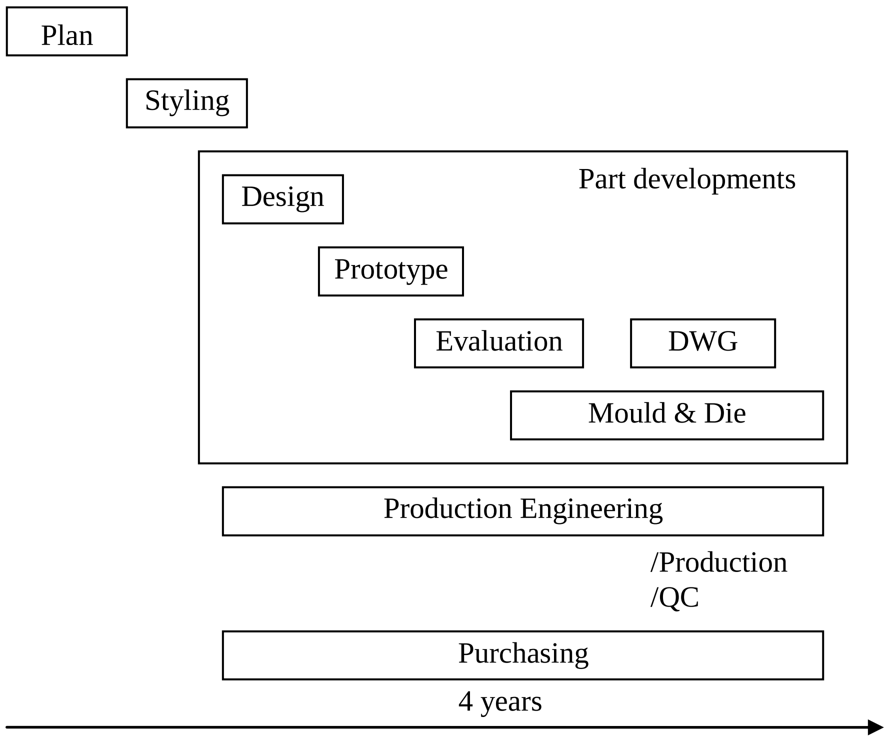


Figure 4-1: Company A's product design and development process partly captured by hand drawing

Company A's team has no full authority to design the whole vehicle but they are allowed to design parts which require less interaction with others; for example, bumpers, wheels, seats, spoilers, grilles and radiators. For these low-interaction parts, company A's team has full authority from the initial planning stage onwards. Five 1:5 clay models for each part are constructed and then the chief engineer selects one of them to be developed into a 1:1 full scale. Once styling is completed, company A's team takes the conceptual design drawings back to Thailand to develop all the necessary parts with their local suppliers.

In Thailand, there are Design Investigation Review (DIR) activities in the Prototype and Evaluation stages. The design will never be perfect at the first stage. If designs need to be revised, an Engineering Change Instruction (ECI) is released from the team. Production Engineering and Purchasing are involved in all DIR activities, as in Figure 4-1. The goal of DIR is to confirm the drawing (DWG) activity before launch to production. The DIR must carefully evaluat the designs, because technical issues from conception would cause significant amounts of correction costs when they are captured after the mold and die development stage.

Mould & Die is a vital activity while requires two to eleven years development before the first trial assembly. DWG cannot be released, unless parts are confirmed to be manufactured by Mould & Die engineers. Moreover, developing mould and die costs around £1.6 billion (exchange rate ฿50 = £1) per series.

Local suppliers are involved in designing and developing parts. Sometimes a detailed design has to be changed because suppliers have a limited capability to manufacture. However, engineers have the authority to reject local suppliers and import Japanese parts for the Thai market.

All activities are under company A's responsibility and it aims to achieve "*zero*" defects in the customer's hands. Therefore, everybody in the design team as well as parts suppliers have ownership concerning feed back errors, including design mistakes. Each activity in Figure 4-1 conducts concurrently each other. Design, Prototype, Evaluation, DWG, and Mould & Die are considered as Part Developments, and it is developed concurrently with Product Engineering and Purchasing as well as every aspect of Production and Quality Control (QC).

4.2.4 Key observations captured from company A

There are two caveats, as follows: Assembling all parts together in the manufacturing process of a car is a crucial task, because any changes have a high impact in terms of

Mould and Die correction costs. Thai engineers have no authority to design the highly integrated parts such as engine parts, because these interact with other parts within the vehicle. Bumpers, wheels, seats, spoilers, grilles and radiators are considered as "*outer*" parts of a car, and they are dependent on other internal parts; therefore, they are much easier to design.

It is interesting that design has to be confirmed before launching production of Mould & Die and changing leads to high consequence impacts of costs on correction of Mould & Die, as shown in key observations eight and nine in Table 4-2. The reason is that both of them relate to design rework in the testing and refinement phase; therefore, they require more investigation. The key observations are developed from insights gathered through the process of data collection and shown as follows:

- Previous knowledge is important for new car model design and development for Company A.
- Close coordination among the team is important for company A; therefore, a design team needs to be in Japan to work closely with its Japanese counterpart team.
- Car design and development is set by management; therefore, it can be inferred that design and development lead time is assigned to the design team.
- Concurrent Engineering (CE) is applied in the car design and development.
- Interactions among components are critical to the design. Hence, company A's team is always allowed to design the low-interaction components for every new vehicle design project.
- Design can be changed from various sources such as Prototype, Evaluate, Product Engineering, Purchasing and it initiated by the from DIR activity.
- A Supplier's expertise is advantageous to a feedback design team when design mistakes are captured.
- Before launching production of Mould & Die, part drawings have to be confirmed. Confirming part drawings assure part durability.
- Technical issue leading to changes could inevitably lead to enormous consequence impact to Mould& Die correction costs.

4.3 COMPANY B

An Interview as open-ended responses was applied in this data collection method. Taking notes was the critical means for collecting interview data. In addition, data collection was performed in Company B located in Norwich, the UK; therefore, it is an opportunity for direct observation. However, cameras along with any other imagery devices were not allowed inside the factory. This data collection was conducted with the chief engineer in the CAE department.

4.3.1 Direct observation

From observation, there are three companies in the site's location; company B, UK car OEM, and Electrical vehicle OEM. Company B focuses on specific engineering projects of a car design and development project; for example, a new power train design for the UK car OEM. In addition, there is a racing circuit to evaluate cars being developed.

There are a lot of notice-boards that revealed the successful development initiated by company B to the automotive industry, for example, implementation of fiberglass for car body and chassis, reducing overall weight with a monocoque car chassis, improving car handling by using a strut for rear suspension units. In addition, the researcher observed that there is a lot of staff working on parts modeling.

4.3.2 Documentations

The Product Change Request (PCR) form was reviewed during data collection. The researcher asked questions about the cost impact related to design rework; hence, the interviewee considered that PCR documentation would probably answer the question. However, duplication of the documents was not permitted. The PCR costing sheet reveals the costs incurred due to changes. Five categories are considered; Direct cost, Incurred cost, Tooling cost, External logistics cost and Lead time (from PCR completion). The costs which are close to the design rework effort are incurred as cost and Lead time. The Incurred costs are composed of R&D and Redundant material costs. The R&D costs are the additional charges in terms of human hours spent to resolve any changes that may be required. Logistics, In-house lead time and Supplier lead time are categorised into the Lead time upon which is counted upon PCR placement.

4.3.3 Interviews

The interviewee has confidence to answer with regards to the interaction between design and CAE activities. Nevertheless, both of them are detailed activities in the design and development process. In addition, the classification of changes is captured as represented in the adjacent sub-section.

Interaction between Design and CAE for Structural Design of Power Train Projects

The power train system is composed of an engine and its transmission systems. The aim of structural design is to assure the durability within the expected life of parts and subsystems. The Computer Aided Engineering (CAE) team has to support the power train design team. The activities between these two groups are Initial Analysis, Detailed Layout, Detailed CAE and Detailed Design. Manufacturing and supplier support the inputs to design. Before conducting Initial Analysis, design requirements are finalised between the customers and company B as well as the lead time required for design and development. Customers can be internal customers (within company B) or customers from other companies. Finally, parts CAD models are validated by detailed CAE and they are then delivered to suppliers for manufacturing. The process is shown in Figure 4-2.

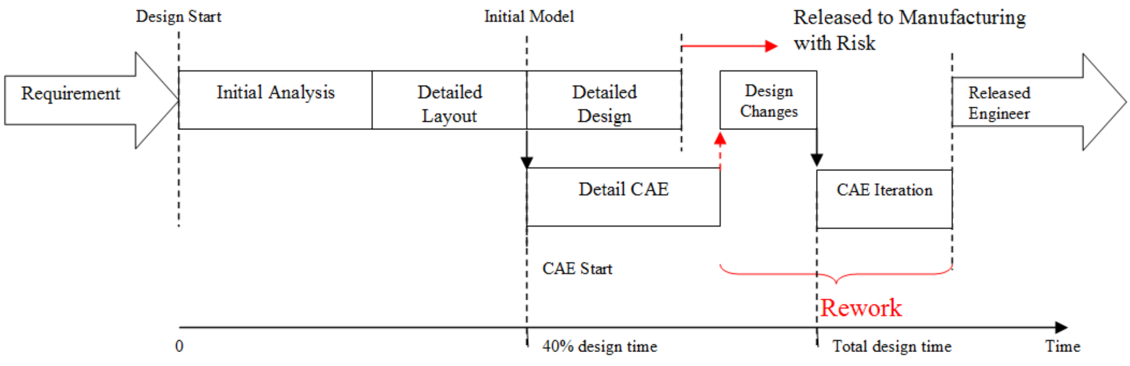


Figure 4-2: Interaction between Power train Design and CAE Activities captured by interviews

Initial Analysis: This activity is conducted by CAE and Power train teams. The purpose of this activity is to introduce analysis by specifying the draft dimensions for part designs. Historical data from previous projects initiates this activity. Furthermore, the calculated results from this activity are applied with load and boundary conditions set in the Detailed CAE. The initial analysis is composed of Performance Simulation, Base Engine Analysis, and 1D Oil & Cooling Network. Once the analysis is completed, the drafted parts dimensions are ready to be delivered to the Detailed Layout.

Detailed Layout: The dimensions from the first activity are drawn with CAD software by the design team. The integration among parts is evaluated. Furthermore, the initial models are used in the Detailed CAE activity.

Detailed CAE: The design used in Detailed CAD is called the "*first cut design*" or initial model. This design is detailed to a satisfactory level, initiating CAE analysis. The initial models are released normally at 40% of design lead time, as shown in Figure 4-2. The Detailed CAE starts when Design and CAE teams agree that any design progress will not impact the comparison of results between CAE and test results in the future. For example, structural CAE for a piston does not require a piston ring, so the details of piston ring are not required. Decision making about the details between CAD and CAE is based on experience. Detailed CAE activity is composed of Create CAE Model, Apply Load and Boundary Condition, Solving and Post Processing. Create Model and Apply Load and Boundary Condition are called pre-processing in the CAE discipline. After Post Processing, if the results show that the specific parts can not operate under the expected conditions, the suggestions will be fed back to the design team in order to be redesigned. The explicit activities are shown in Figure 4-3.

Detailed Design: This activity is concurrently evolves with the Detailed CAE. The detailed design is amined at manufacturing a prototype. The detailed CAD models can be released only if they are confirmed by CAE results. After detailed CAE, Design Changes might be required due to design error feedback from Detailed CAE. If design changes occur, CAE iterations are not avoidable. The time and effort spent for Design Changes and CAE iteration are accounted as rework time and effort. The validated CAD data is proposed and released to engineers for manufacturing approval.

Explicit Explanation of Detailed CAE Activity

Create CAE Model and Apply Loads & Boundary Conditions are considered the as pre-processing stage followed by Solving and Post Processing. The detailed explanation is as follows:

Create CAE Model: The first cut design of each part is used to create a CAE model. Each CAD model is converted into CAE model by introducing nodes, elements and material properties.

Apply Load s& Boundary Conditions: Data from historical projects, Initial Analysis, clients, and /or from testing are entered into the considered CAE model as loads (initial condition), or boundary conditions to components. Loads and boundary conditions are assigned to simulation in order to imitate components during operations.

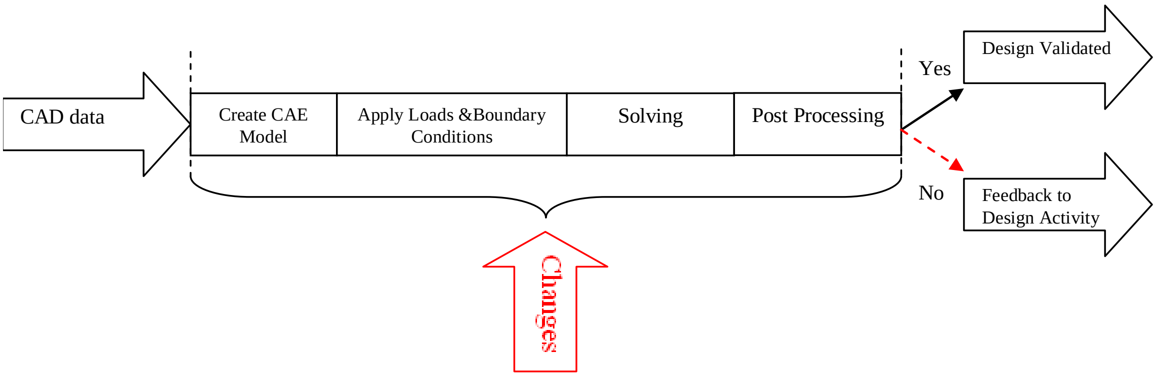


Figure 4-3: Detail CAE activity captured from interviewing with Company B

Solving: The completed CAE models are passed to a third party, the solving service provider. This third party group provides computer program solver, such as ABACUS, NASTRAN, etc. to validate the design requirements. The lead time for this process is highly dependent on the problem size (nodes, boundary conditions in the model), and computational speed.

Post Processing: CAE results are converted to interpretable formats, such as graphs and other visuals. Detailed relationships between displacement to stress, strain or thermal stress are reviewed. The purpose is to ascertain the durability of each component; furthermore the analysed results are also used to generate the FMEA analysis for parts integration purposes which is the responsibility of the integration team. This team will feed back the results to the design team to rework, if there are design issues. Then, the corrected designs are fed forward for CAE iteration to validate the new designs. When CAE iteration occurs, the whole CAE iteration process is similar to Detailed CAE activities. However; Pre Processing and Post Processing would be shorter than in the first iteration.

Classification of changes happening between design and CAE activities

The classification emerged from the interviewee. As shown in Figure 4-3, there is the evidence of change; therefore, this is the opportunity for the researcher to ask for the change categorisation protocol. Design rework effort is a consequence of design alters. Changes in different stages of design activities have diverse impacts. The explanations of impacts due to changes in each stage are as follows:

Requirement changes: It is obviously derived from customers. Sometimes they want to add more features to a system, or they require a need for a higher/lower performance, etc. This change directly impacts to the Initial Analysis. Initial designs are generated from Initial Analysis results, so changing any requirements would force the CAD to change. Furthermore, Initial Analysis also provides initial and boundary condition data to the Detailed CAE activity. If this change happens in a later stage, the impact will be enormous because the Initial Analysis has to be revisited.

Design progress: The cause of this change is from the design progress. For example, a manifold and cylinder head must be connected together. If there is a problem of a lack of space in the front bonnet, a manifold design needs to be changed. When a manifold is altered, the change impacts directly to the cylinder head. Therefore, both the cylinder head and manifold needs to be redesigned.

Feedback from downstream: Feedbacks are derived from Detailed CAE results or physical testing. If changes are requested from testing, it will be more expensive than the changes requested from Detailed CAE.

Material change: This change does not mainly impact CAD data but influences the loads and boundary conditions in CAE models. An example of this change is assigning different materials for parts. This change is directly linked to the Create CAE Model task.

4.3.4 Key observations captured from Company B

Insights gathered through the process of data collection techniques and Experience gained from the first data collection are two methodologies to analyse data. The key observations are as follows:

- Design rework is the consequence of a change occurring. From the author's point of view, *Requirement change* comes from outside the design process and from customers while others are from within the design process.
- Innovation or a new element in a new product is common in company B's working environment.
- Design lead time is negotiated between customers and the development team.
- Power Train Design and CAE team have to work together throughout the design activity
- Previous design knowledge is required for new design projects.
- Costs incurred from PCR are composed of design effort to resolve problems, testing and tooling.
- CAE is a useful tool for simulating parts under design conditions to confirm their functionality. The results from CAE analysis also have benefits for parts integration activity.
- CE is implemented during design and CAE analysis.
- Even though Design and CAE are linked from different principles of knowledge (vertical direction, Figure 2-3b.), the real design rework effort required is from the component's point of view (horizontal direction, Figure 2-3a).
- There are different types of changes for each stage in the design process.

4.4 FINDINGS FROM PRELIMINARY DATA COLLECTIONS

Key observations from company A and B are collectively displayed in Table 4-2. Then, themes are developed in column 3. From a Case Study Research Approach, a unique phenomenon is still valuable to investigate deeper. Therefore, all themes are further looked into during the secondary data collection stage. Themes developed in preliminary data collection are synthesised from a researcher's experience and insights gathered through the process of data collection techniques. To develop themes, the author clusters the collected data from both companies (columns one and two) into groups. The clustering activity is achieved through the researcher's experience and sybsequently all themes developed are numbered as shown in column three. It seems that every theme is related to a design process; however, the researcher differentiates between *context* and *content* of design activities. The context theme is defined as a working condition for the design team. The context theme cannot be manipulated by the design team, while the content theme is the facts that are manageable.

There are four themes defined as the context theme: 4, 5, 6 and 9. Design lead time is designated by from the management to the design team (theme 4). In addition, it is revealed that both companies work under the CE approach while they are designing a product (theme 5). Furthermore, it is a fact that changes will/may occur from various causes (theme 6). In addition, the reactive actions to resolve design failures are design rework effort and correcting tooling costs (theme 9). From the researcher's point of view, themes 4, 5, 6 and 9 are considered as *industrial practices* in a product design. Therefore, a design team has no control over them. therefore, these themes are defined as *context* in design and in the development process. For other themes, they are defined as contents of events in design activities. In the content themes, a design team is capable of manipulating them. For example in theme 3, a design team can increase the level of coordination in the current project. Another example in theme 2 is that the design team members can manage themselves to collect knowledge from any previous projects to reuse them in a new product design. The context and content themes are a preliminary summary at this stage; however, they have to be confirmed for generalisation with other cases in the secondary data collection stage. The last important point from preliminary data collection is the mismatch with the terminology "design rework". This terminology comes directly from literature; however, it is more common to refer to change in industry. Nevertheless, the preliminary understanding at this stage shows that design rework is the consequence of changes. Therefore, there are three tasks that need to be clarified further in secondary data collections as follows:

- Comprehensively identify context theme,
- Comprehensively identify content theme,
- Clarify the differences between design changes and design rework.

Table 4-2: Key observations from primary data collection and themes developed

Key observations from companies		Themes developed
Company A	Company B	
Interactions among components are critical to the designs. Hence, company A's team is always allowed to design the low interaction components for every new vehicle design project.	Innovation or new elements in a new product is common in Company B's working environment.	(1) Component integration towards a final product is difficult. If new design has more components, the integration will be more challenging.
Previous knowledge is important to a new car model design and development for company A.	Previous design knowledge is required for a new design project.	(2) Previous knowledge is necessary for starting new projects.
Close coordination among the team is important for company A; therefore, a design team needs to be in Japan to work closely with its Japanese counterpart team.	Power Train Design and CAE team have to work together throughout the design activity	(3) Coordination among team members is necessary for new design project.
Car design and development is set by management; therefore, it is infered that design and development lead time is assigned to the design team.	Design lead time is negotiated between customers, and the development team.	(4) Design lead time is arranged by management.
CE is applied in the car design and development.	CE is implemented during design and CAE analysis.	(5) CE approach is common in design process.
Design can be changed from various sources, such as from Prototype, Evaluate, Product Engineering, and Purchasing.	There are different types of changes. Requirement change comes from outside design process due to customers while others are from within design process.	(6) Changes are from various causes.
Supplier's expertise is advantageous to a feedback design team when design mistakes are captured.		(7) Suppliers have influences to design and development activities.
Before releasing designs to Mould & Die production, part drawings have to be confirmed. Confirming part drawings is aimed at assuring their durability.	-CAE is a useful tool to simulate parts under design conditions to confirm their functionalities. The results from CAE analysis also helpful for a part integration activity. -Even though Design and CAE are linked from the different principles of knowledge (vertical direction, Figure 2-3b.), but the real design rework effort required is from component's point of view (horizontal direction, Figure 2-3a).	(8) Parts need to be verified and validated before launch for production. CAE should be a high potential tool to assist design in horizontal direction.
Technical issues leading to changes could inevitably lead to enormous impacts on Mould & Die correction costs.	Costs incurred from PCR are composed of design effort to resolve problems, testing and tooling.	(9) Consequence from technical issues leading to changes could cost design rework effort and correcting costs on production tools (Mould & Die)

4.5 FINDINGS FROM SECONDARY DATA COLLECTIONS

The secondary data collection activity was conducted with companies C, D and E and the results are shown in Appendix B. All themes developed from primary data collections are used to analyse key observations from companies in the secondary data collection stage, as shown in Table 4-3. The purpose of this action is to confirm the generic phenomena among the participating companies in the primary and secondary data collection stages, while the additional themes are still open, as represented in Table 4-4 in order to explore more themes to explain the nature of design rework. Nonetheless all themes have to be confirmed in the comprehensive data collections phase, as outlined in chapter 5.

The principles of theme developments are maintained in the secondary data collection stage. From Table 4-4, themes 10, 12 and 13 are content themes because a design team can manage them during the design phase. Theme 14 is a context theme because it is a fact derived and identified from implementing the direct method to capture the relationships among components.

Table 4-5 is the summary of answers captured from all companies that participated in the primary data collections. The original theme 9 gives the information about the actions to resolve changes and their consequences which are design rework effort and production tool costs; however, company C and company E reveal the additional information on design rework effort from components or sub-system interactions. Thus, theme 9 has been modified into subcategories in order to cover all aspects as represented.

Themes 10 to 14 are the evolution from secondary data collection; however, the researcher considers them to be crucial to the success of design and develop product, especially theme 10. However, they must be validated further more in the forthcoming stages.

Content themes are compared with the factors from Table 2-6 in order to identify causes of design rework, as illustrated in section 4.6.1. Context themes are used to develop methods to estimate design rework as represented in chapters 5, 6 and 7.

Table 4-3: Key observations from secondary data collections allocated to theme developed from primary data collection

Themes developed from Primary data collections	Key observations from companies		
	Company C	Company D	Company E
(1) Component integration towards a final product is difficult. If a new design has more components, the integration will be more challenging.	Designers have to make sure that every body part is integrated to perform the vehicle's required functions.	In detailed design, every seat component is designed iteratively in order to achieve the design.	APQP and CPPD teams have to meet on a weekly basis and make sure that every sub-system can be integrated together to achieve engine design.
(2) Previous knowledge is necessary for starting new projects.	-Vehicle body architecture is evolved from previous design, so designers have the starting point to design new project. -Lesson learnt, such as Engineering Manual and Engineering Standard, is helpful to design new vehicles.	Designing new products always begins with previous design to ensure that design will comply with safety requirements, and it also reduces testing costs.	Previous knowledge is helpful to generate FMEA in the early design phase.
(3) Coordination among team members is necessary for new design project.	-Designing a new vehicle body required a group of people from different disciplines working together throughout the project. -IT technology supports coordination is very helpful, only if designers use it.	Qualified staff members and equipment capability are criteria to negotiate with OEMs.	More coordination through meeting potentially helps to reduce design rework in Design V&V.
(4) Design lead time is arranged by management.	-Design effort or manpower is driven by budget. -SOP is relatively unchanged. If changes occur, special activity such as increase resources is needed to maintain SOP.	Design lead time is reach through from negotiation with Company D management and OEMs.	Design and development lead time is set due to legislation milestone in Company E.
(5) CE approach is common in design process.	CE is implemented either in vertical or horizontal point of view.	Components in seat are concurrently designed.	CE principle is implemented either in horizontal and vertical direction in Company E.
(6) Changes are from various causes.	There are three types of changes realise from interviewee; process driven changes, physical testing driven changes, over-written changes from management.	In seat itself, design change happens from progressively design, feedback from testing. But there are a lot of changes requested from OEM due to changing the connecting point between seat and car floor.	Design rework in V&V occurs due to design failures.
(7) Suppliers have influences relating to design and development activities.	Suppliers have a vital role to feedback the potential concerns to the design team.	(Company D is Tier 1 supplier)	Supplier should have enough expertise to design and eliminate any problems from the assigned product.

Table 4-3: Continued

Themes developed from Primary data collections	Key observations from companies		
	Company C	Company D	Company E
(8) Parts need to be verified and validated before launch for production. CAE should be a high-potential tool to assist design in horizontal direction.	CAD and CAE are very important for car body analysis.	(Company D fully uses CAD technology but not CAE.)	Exploitation of CAE Software is potentially a key to reduce design rework in Design V&V phase.
(9) Consequence from changes could be design rework effort and correcting costs on production tools (Mould & Die) (It refers to reactively solve the issues.)	-Considering design rework required are done reactively after event take place. -Knock-on effect from design change from one part to others is not desirable.	Reactions to failures are evaluated from the difficulty to resolve the problems, alternatives to solve problems, economic aspects; furthermore, they have to be assessed with requested performances.	-Resolution is necessary if there are issues found in Design V&V phase. -Company E has to re-analyse not only ball bearing but also impeller and gear because both of them create tangential force to damage ball bearing. -There are no standard procedures to estimate design rework effort.

Table 4-4: Key observations from secondary data collections and additional themes developed

Key observations from companies			Themes developed from Primary data collections
Company C	Company D	Company E	
Workload is the barrier preventing designer from updating their design.		-Company E increases workload to team and works closely with supplier to finish the second project as quick as possible to replace supplier in the first project, and the results are good even though schedule is so tight.	(10) Workloads or time constraints will have influence on design rework.
FMEA is a capable tool to capture design failures in the testing phase and it has been used since the design begins.	FMEA analysis is available since product design start.	-FMEA begins in the early design phase. -FMEA considers failure modes which might happen in the field. It does not tell the amount of design rework effort to resolve problems.	(11) FMEA is a useful tool to evaluate problems happening when products are used in useful life.
New vehicle design project starts from clearly defining what customer wants.	Specification is either clearly given from OEMs or developed by company D team.	The level of specification clarity potentially decreases design rework in Design V&V phase.	(12) Clarity of specifications is vey important in design especially, reducing design rework as found in company E's case.
The related components and design sequence to deliver new specifications are from design team experience.	OEM treat seat as dependent system to car floor panel on which seat design have to rely.	Water pump performances depend on engine requirements and the supplier has to achieve them.	(13) Method to mange dependency in among components, sub-systems during product design is important.
	It is very time consuming to implement direct method to capture component relationships by using DSM.	It was very difficult for the cooling team leader to capture components' relationship into DSM by the direct method.	(14) It seems that the direct method for getting relationships among components is not suitable from a practical point of view.

Table 4-5: Summary on themes developed from primary and secondary data collections

Themes \ Companies	A	B	C	D	E
(1) Component integration towards a final product is difficult. If a new design has more components, the integration will be more challenging.	✓	✓	✓	✓	✓
(2) Previous knowledge is necessary for starting new projects.	✓	✓	✓	✓	✓
(3) Coordination among team members is necessary for new design project.	✓	✓	✓	✓	✓
(4) Design lead time is arranged by management.	✓	✓	✓	✓	✓
(5) CE approach is common in design process.	✓	✓	✓	✓	✓
(6) Changes are from various causes.	✓	✓	✓	✓	✓
(7) Suppliers have influences to design and development activities.	✓		✓		✓
(8) Parts need to be verified and validated before launch for production. CAE should be a high potential tool to assist design in horizontal direction.	✓	✓	✓		✓
(9) The reaction characteristics to changes are as follows:					
-Correcting costs on production tools e.g. Mould & Die (Vertical direction)	✓	✓			
-Design effort on related components (Horizontal direction)		✓	✓		✓
-No standard procedure to estimate design rework effort in the testing and refinement phase.					✓
-The evaluation is done reactively.			✓		✓
(10) Workloads or time constraints will have influence on design rework.			✓		✓
(11) FMEA is a useful tool to evaluate problems occurring when products are used in useful life.			✓	✓	✓
(12) Clarity of specifications is very important in design, especially reducing design rework as found in company E's case.			✓	✓	✓
(13) Method to manage dependency among components, sub-systems during product design is important.			✓	✓	✓
(14) It seems that direct method for getting relationships among component is not suitable from a practical point of view.				✓	✓

Noted: Themes 4, 5, 6, 9, 13 and 14 are context theme otherwise they are content theme.

4.6 KEY OBSERVATIONS FROM INITIAL DATA COLLECTIONS

Each company has its own design and development process which is deviates from the generic design process shown in Figure 1-1. However, the common element between the design process from literature and industries is that the design has to be validated before releasing it to SOP. Thus, the generic design process from the literature is still used to communicate with industries in comprehensive data collections (chapter 5) because the focus in this thesis is on the testing and refinement phase. Section 4.6.1 is to develop design rework drivers while section 4.6.2 is to identify research gaps, industrial practices and recommendations for method developments.

4.6.1 Developing design rework drivers from content themes

There are two stages to develop design rework drivers. First of all, content themes have to be linked with design rework factors that have been captured from Table 2-6. All factors are analysed based on the researcher's experience in order to arrange the suitable correlated themes to an appropriate factor. Later, the allocated themes are improved to become design rework drivers. The detailed explanations are as follows:

Linking design rework factors and content themes

From the hypothesis as stated earlier in this chapter, design rework issues in the testing and refinement phase are the consequences of the factors embedded in the design process. Content themes are summarised from industrial good practices. It is mentioned that factors from literature (Table 2-6) explain design rework inherent in design but not to explain the phenomena specifically in testing and the refinement phase. So, the challenge at this stage is to extend the knowledge of design rework factors to explain the behaviours in the focus phase.

To resolve this challenge, the researcher used the experts' experience to link content themes to the factors, as revealed in Table 4-6. In principle, the factors captured from literature explain how design rework could happen and its consequences, while the industrial good practices aim to confine and reduce design rework. Therefore, the researcher bonded the factors and content themes together.

It is stated earlier that the design team can manipulate content themes. The last column shows the influence type when the themes are manipulated. For example, in theme 1, if the new design has more components, the Project complexity in terms of integration is increased so as to necessitate design rework. Therefore, theme 1 has a positive proportional relationship to design rework occurrence. Similar principle is applied to other themes. There are four themes considered as the approaches to reduce the design rework occurrence from Project complexity.

Information exchange and its sub-categories are considered as context in product design and development, so it is not considered in Table 4-5. However, the most highly-correlated theme to this category is theme 6.

Theme 7 relates to suppliers; however, it is an additional point compared with literature. There is a conflict in theme 10. Company C mentioned that time constraints restricts team members from updating changes and therefore design rework occurs due to using obsolete information. But the time constraint to complete the second project in company E enables the design team to complete a well-manufactured and high-quality water pump. Nevertheless, it would be valuable to investigate further with other cases as recommended from the *Case study research* approach (Eisenhardt and Graebner, 2007).

Table 4-6: Analysis of design rework factors and content themes developed from initial data analysis

Design rework factors (Taken from Table 2-6)		Content themes	Relationship to design rework
Project complexity (Integration)		(1) Component integration towards a final product is difficult. If a new design has more components, the integration will be more challenging.	+
		(2) Previous knowledge is necessary to start new projects.	-
		(8) Parts need to be verified and validated before launch for production. CAE should be a high potential tool to assist design in horizontal direction.	-
		(11) FMEA is a useful tool to evaluate problems occurring when products are used in useful life.	-
Dependency		(13) Method to manage dependency among components, sub-systems during product design is important.	-
Information exchange	Upstream change	This is considered as context theme.	
	Faults found by downstream		
	Amount of overlapping tasks		
Pre-communication		(3) Coordination among team members is necessary for new design project.	-
		(12) Clarity of specifications is very important in design, especially reducing design rework as found in company E's case.	-
Crashing		(10) Workloads or time constraints will have influence on design rework.	- (Company E), + (Company C)
n/a		(7) Suppliers have influence relating to design and development activities.	-

Developing design rework drivers

Once the content themes are analysed against the factors captured in Table 2-8 as represented in the previous sub-section, all themes are used for developing the design rework drivers. The design rework drivers are synthesised from content themes as represented in Table 4-7. Each theme is summarised by the researcher's experience; however, all drivers are again validated during comprehensive data collections in chapter 5.

Column three of Table 4-7 reveals the design rework drivers synthesised by the researcher, while column three and four classify how themes describe design rework phenomena. The researcher divides themes based on how they induce the probability of occurrence or effort required.

FMEA is a brainstorming activity. Moreover, previous knowledge is important to achieve this; so it is assigned as a part of the two drivers, Lessons Learnt and Coordination across Team Members. The summary for each driver is explained as follows:

Novelty Level: In a new product design, there are always new requirements which lead to new challenges in terms of integrating components together. For example, a new car that is required to use less fuel; therefore, it has to be lighter, combined with higher combustion efficiency, less drag, etc. Even though the whole concept of the car is similar, the new requirements drive the existing design to achieve these new requirements. This driver has a positive proportional relationship to the design rework probability of occurrences.

Exploitations of CAE Software: This method is to analyse or simulate products or parts under operational phenomena by using mathematics and the laws of physics. The purpose of CAE is to optimise designs to achieve the required performance and reliability. This driver helps to reduce the probability of design rework occurrence because issues can be captured early with the enhancement of CAE software before signing off designs to prototype production. For example, the transient torsion load interactions within an engine water pump from company E was very difficult to understand and to capture by a traditional analysis method. Therefore, there were a lot of water pump failures because of torsion activities leading to fatigue. The unknown transient axial forces due to torsion activities lead to a selection of improper bearings in the first project; however, the problem has been eliminated since company E implemented in-house CAE software to simulate torsion activities.

Lessons Learnt: This driver infers to experience of success and failure from the designed products, hence, it's an accumulation of previous knowledge and experience. Design engineers can retrieve the previous knowledge to use as guidelines, if the product being designed has a certain degree of likelihood. For example, company C has a lesson learnt book. It provides recommended curvatures for car metal body design, and this recommendation helps the designer to select the best possible design solution with optimised styling, crash-worthiness and manufacturability. Therefore, without lessons learnt, design rework would be considered as a high probability.

Interaction of Subsystems/Components: This represents the sequence of designing components or components within a product due to dependency. The sequencing is very important to reduce the effort required due to design rework. For example, company D's engineer starts to design a seat from a cushion rather than start from the back of the seat, because starting from a cushion requires less effort to resolve design rework problems than initiating from the back. This driver represents the effort required for design rework due to interactions. Design structure matrix (DSM) will be used to represent the interaction among subsystems/components. Critical interaction among subsystems/components will be identified by the required effort to resolve design issues.

Coordination across Team Members: It indicates the level of coordination across team members in terms of frequency and contents. The content of the meeting should identify the critical requirements that need to be achieved. For example, company E spent less meeting and discussion time between the engine development team and the water pump development team in the conceptual stage in the first project. Therefore, there were an awful lot of meetings in the detailing, verification and validation phase (the testing and refinement phase) in order to resolve design rework problems. Moreover, all information relevant to the torsion activities, such as rotational speed from the engine under design and off-design point which are the key critical components to bearing selection that need to be clearly communicated to the water pump development team. Therefore, the probability of design rework occurrence also depends on the frequency for communications and content of this driver.

Clarity of specifications: This driver refers to the clarity level on specifications. For example, company C explicitly identifies the axial force due to torsion activities in the specification document of the second benchmark project. It was not clearly documented in the earlier benchmark, so there were a lot of water pump failures. Hence, the design rework probability of occurrence has a negative relationship with this driver.

Constraints to deliver project on time: This driver represents the negative relationship of design rework occurrence for company E. This company decided to shift from the first supplier to the second supplier as soon as possible, because the company's schedule to deliver the product was at risk of cost and time overrun. From this constraint, it pushed the team members to work with greater care. Therefore, it influences the design rework probability.

However, this factor increases the probability of design rework occurrence for company C, because it prevents the design team from updating the design. Thus, design rework occurs because of using obsolete data. This conflict is therefore closely investigated in the next stage (chapter 5).

Table 4-7: Synthesis of design rework drivers.

Content themes	Developed drivers	Probability	Effort required
(1) Component integration towards a final product is difficult. If a new design has more components, the integration will be more challenging.	Novelty Level	✓	
(2) Previous knowledge is necessary to start new projects. (11) FMEA is a useful tool to evaluate problems occurring when product are used in useful life.	Lesson Learnt	✓	
(8) Parts need to be verified and validated before launch for production. CAE should be a high potential tool to assist design in horizontal direction.	Exploitation of CAE Software	✓	
(13) Method to manage dependency among components, sub-systems during product design is important.	Interactions of Subsystems/ Components		✓
(3) Coordination among team members is necessary for new design project. (11) FMEA is a useful tool to evaluate problems occurring when products are used in useful life.	Coordination across Team Members	✓	
(12) Clarity of specifications is very important in design, especially reducing design rework as found in company E's case.	Clarity of Specifications	✓	
(10) Workloads or time constraints will have influence on design rework.	Constraint to Deliver Project on Time	✓	
(7) Suppliers have influences to design and development activities.	Supplier Expertises	✓	

Design rework drivers for probability of occurrence apart from *Novelty Level* have a conversely proportional relationship, because, for example, the clearer specifications will lead to the lower probability due to ambiguity should be minimal.

The researcher does not put more effort on this driver because it is obvious in reality but it can be used in a method to estimate design rework probability of occurrences as shown in chapter 5. *Interaction of subsystems/components* is used to develop a method to estimate design rework effort as discussed in chapter 6. In addition, *Interaction of subsystems/components* is a driver influencing the effort required; because the effort required is based on types of design rework occurred. For example, if the design rework takes place due to complex interaction of forces among components in an engine, it will require a lot of time to analyse. But if it occurs due to use of incorrect material to design a water seal, it will be easier to select another water seal material to solve the problem.

4.6.2 Research gap analysis, industrial practices and recommendations for method development

The purpose of this section is to compare the findings from the literature against context themes in order to identify gaps between them. The analysis results are used to develop industrial practices on design activities and later they are used to develop a method to estimate design rework in chapters 5, 6 and 7. The literature findings are from Section 2.9.

The research gaps are identified from the disagreement among context themes and findings from literature. For example, the major contrast between literature and reality from themes is in obtaining the design lead time or design effort (theme four). The aim captured from each literature is to achieve accuracy in the estimation of design lead time or effort, while the findings from industrial field studies show both are assigned or provided either from management or from industrial contexts, e.g. legislation or market, in an industrial environment. In addition, it is the challenge to develop a method to estimate the probability of design rework occurrence which is clearly provided in literature. Another contrast is the method to capture component relationships with DSM. The researcher had already tested the direct method to obtain component relationships with company D and company E, but it was found very difficult in real applications.

Another analytical principle to identify gaps is looking for the mutual agreement which is lacking among context themes and the findings from literature. For instance, themes 13, 14 and the literature agree on the lack of procedures to obtain the relationships among components. If the context themes and findings from literature concur on the existing facts, they are considered as industrial practice. For example, both literature and industries mutually consent on considering in the CE in the design process. In addition, there is evidence that the industries take CE into account for a horizontal direction, as mentioned in theme eight. The next agreement is that there is only one literature source which compensates design rework by increasing resources. Lastly, both the literature and industrial findings have no standard procedure to estimate design rework effort. Finding seven from the literature focuses on the knowledge and experience; however, it is considered as a content theme. Hence, it is not considered in this table. The closest theme to this finding is theme two.

Table 4-8: Comparison between findings from literature and themes

Findings from literature (Section 2.9)	Themes
1. All the literature looks at design rework as embedded in product design lead time or effort and they try to achieve accuracy of estimation. 2. Most the literature is simulation and optimisation based, and it is developed either for accurate lead time estimation or for managing resources and overlapping to achieving target lead time. The probability of upstream changes or evolutionary are assumed as given for simulation purposes, but there are no clear links to real-life applications.	(Context theme 4) Design lead time is assigned by management.
3. Concurrent Engineering approach is a basis for all literature in this section.	(5) CE approach is common in design process.
4. Increasing resources to compensate design rework is another issue which is only Roemer and Ahmadi (2004) look at; hence, further investigation into this area would be highly beneficial for contribution to knowledge.	(6) Changes are from various causes. (9) The characteristic reaction from changes are as follows: -Correcting costs on production tools, e.g. Mould & Die (Vertical direction)
5. Only Loch and Terwiesch (1998) and Smith and Eppinger (1997) estimate design effort and rework in horizontal direction.	-Design effort on related components (Horizontal direction).
6. All literature does not directly estimate design rework in the testing and refinement phase.	-No standard procedure to estimate design rework effort in the testing and refinement phase. -The evaluation is done reactively.
7. Only Loch and Terwiesch (1998) and Mitchell and Nualt (2007) consider the effect of knowledge and the experience of development team; therefore, there should be more investigation in this direction.	(2) Previous knowledge is necessary to start new projects.
8. Numeric relationship is a good way to identify dependency among design task. However, only Smith and Eppinger (1997) use this approach for estimating lead time, but there are no such clear guidelines to obtain relationships.	(13) Method to manage dependency in among components, sub-systems during product design is important. (14) It seems that direct method for finding relationships among components is not suitable from a practical point of view.

Note: The highlighted cells are research gaps otherwise they are industrial practices.

From the analysis above, the research gaps, industrial practices are represented in Table 4-9. The author proposes the actions against research gaps and recommendations for further developments. The research gaps are to support the developed methods, while the industrial practices are to develop assumptions of the methods as shown in chapter 5, 6 and 7 consecutively.

Table 4-9: Research gaps, industrial practices and recommendation for further developments

Research gaps	Industrial practices	Recommendations for further developments
	The accuracy to estimate design lead time and effort is not generic in industries because they are set or given by markets or legislation.	In order to get along with the industrial contexts, the method developed should not try to achieve accuracy in estimation.
	CE is common practice either in vertical or horizontal directions.	The developed method has to be able to be implemented in CE environment.
There is not much literature that proposes methods to estimate design rework effort to resolve problems in the testing and refinement phase; furthermore, there are no such procedures in industries.		The developed method would have the capability to estimate design rework effort in testing and refinement or Design V&V phase, as shown in chapter 5
There is not much literature that considers design effort and rework in horizontal direction.		The method developed is for estimation of design rework in a horizontal direction, as shown in chapter 5.
Resolving issues found in the testing and refinement phase are done reactively.		The method developed has capability to assess design rework proactively, as discussed in chapter 6 and 7.
There is not much literature that enhances the effect of knowledge on design rework estimation.	A new design project starts from previous design or knowledge.	The effect of knowledge on design rework is studied in-depth in chapter 5 and 6.
Literature uses a direct method to capture relationships, but it is difficult when implemented with industries.		The indirect method is developed to capture relationships among sub-systems or components, as discussed in chapter 6.

4.6.3 Differentiation between design change and design rework, and scope analysis

This section emerged during the primary and secondary data collections in this chapter. The consequence from design changes is effort spent to redesign; hence this section aims to clearly define the difference between design change and design rework.

Theme six is the development of key observations focusing on change issues from each company and they are evaluated to compare with design rework definition in Table 4-10; the design changes can be classified into three major groups, as follows:

Evolutionary changes: It is based on the progressive changes due to design evolution. The person who is responsible for the design decides to make changes. Based on design rework definition, this type of change is effective in making design converge; therefore, it is not design rework.

Feedback changes: This type of change is based on design failures which are an evaluation from testing or reviewing. For example, in car bonnet design, radiator engineers found that air passing through the radiator grille does not achieve the requirements to remove heat; so the fault is fed back to the grille designer. Another example, the testing engineer reports that the car body doesn't satisfy the crash test requirements; hence, the car body designer has to rework the body design. For this reason, the change happens from others rather than the designer responsible for this task. From design rework definition; this type of change is design rework, because it violates the design-right-first-time principle.

Over-written changes: There types of changes are directly outside the design team. For example, a car body design has to be changed even though it passed requirements due to a management request. In addition, company D has to change the connecting point between the seat and the vehicle's floor due to an OEM request. Another source is adjustments due to requirement changes from market influences. Therefore, designers have no control over them because they are originated from outside the design team and are difficult to predict. This change has benefited the overall organisation to launch the product, but from a designer's point of view it is unnecessary and repetitive work; so it could be arranged into a design rework category.

This thesis focuses on design rework in testing and refinement. Design has to be finished before testing; hence, evolutionary change is out of the scope. In terms of prediction of design rework probability of occurrence, Over-written changes is from an outside design team which is stochastic in nature. Even though it is a challenge, it is somewhat disconnected from the characteristic of the design team's performance; so it is considered as out of the scope. Whilst, the Feedback change in the testing and refinement phase is rather a consequence from the design team's output, so it is considered as in scope. For estimation of design rework effort, both Feedback change and Over-written changes is possible to cover with a similar principle to predict them; however, the assumption before making changes is that the functional structure must be maintained. The scope analysis for this thesis is in Table 4-11. The detailed development for design rework probability and effort required is in chapters 5 and 6.

Table 4-10: Detailed analysis on change issues against design rework definition

Company					Design rework definition
A	B	C	D	E	
Design can be changed from various sources, such as from Prototype, Evaluate, Product Engineering, and Purchasing.	There are different types of changes:	There are three types of changes realize from interviewee:	In seat itself, design change occurs due to		Design rework is unnecessary repettitive design tasks which occurred due to relationships among tasks
	-within design process.	-process driven changes,	-progressive design		
		-physical-testing-driven changes	-feedback from testing	Design rework in V&V is happened due to design failures.	
	-*Requirement change* comes from outside design process due to customers	-over-written changes from management.	-There are a lot of changes requested on connecting point between seat and car floor from OEM.		

Table 4-11: Scope analysis in design rework research from design change point of view

Causes of design rework	Design rework probability of occurrence	Design rework effort required
Feedback changes	In scope (Chapter 5)	In scope (Chapter 6)
Over-written changes	Out of scope	In scope* (Chapter 6)

*Functional structure is reserved.

4.7 KEY OBSERVATIONS FROM DEVELOPING DESIGN REWORK DRIVERS

- Objective one is not fully completed, because the developed design rework drivers need to be validated with those of other companies. Nonetheless, the validation is completed in chapter 5.

- The design rework drivers in Table 4-6 and Table 4-7 are developed from content themes by comparing them with factors from Table 2-6. Even though they are captured from literature, they are not directly focused in the testing and refinement phase. Hence, this concern is the main challenge in chapter 5.
- The research gaps and industrial practices are captured in this chapter as shown in section 4.6.2 and they steer the research direction as explained in chapters 5, 6 and 7.
- The design rework problem is a common issue in industries, because it has been proven by data collections though companies from across geographic locations and cultures.
- The differences between design rework and changes are explicitly confirmed by data from industrial field studies. However, the intersection between them is feedback changes.

4.8 CHAPTER SUMMARY

The factors in Table 2-8 are considered to be able to explain the design rework characteristics in the testing and refinement phase. Therefore, all activities in this chapter are meant to verify this hypothesis by applying the Case Study Research approach. The main outcome in this chapter is the design rework drivers. However, this mission still does not accomplish its goals because the developed drivers are not fully validated with those of other companies. Nonetheless, identifying the research gaps, industrial practices and recommendations for further developments, as represented in Table 4-9, are claimed as successes in this chapter.

In order to avoid bias, the questions developed in the primary data collection are designed to collect all generic phenomena from each company. Then, thematic analysis is used to synthesis themes from data of companies A and B. There are nine themes from primary data collections and they are used to analyse the secondary data collections.

There are three companies in the secondary data collection stage; moreover, four additional themes are developed during this protocol. All themes are classified as either content or context themes. The content themes are examined against the factors in Table

2-8, and then there are seven design rework drivers. However, there is a conflict in Constraints to deliver a project on time. Therefore it needs to be closely investigated again as shown in chapter 5.

Finally, the context themes are analysed with the literature findings to obtain research gaps and confirm the industrial practices. The gaps are to support the needs/requirements of the method development in chapters 5, 6 and 7, while the method assumptions are developed from industrial practices.

From all activities completed in this chapter, it is reasonable to state that "*The factors from Table 2-8 can be used to explain design rework occurrences in the testing and refinement phase*."

CHAPTER 5
THE DEVELOPMENT OF DESIGN REWORK PROBABILITY OF OCCURRENCE ESTIMATION METHOD

This chapter is a part of a comprehensive data collection activity as represented in Figure 3-2. The aim of this chapter is to answer research objectives one and two by consecutively validating design rework drivers captured from chapter 4 and developing the method to estimate the design rework probability of occurrence. Fundamentally, both research objectives are related to the evaluation of design rework issues by the principle of risk assessment, as represented in Eq. 2-3. Therefore, the probability and impact have to be estimated. This chapter is to develop the method to estimate design probability while chapter 6 is to estimate impacts. All activities in this chapter have been summarised in Table 5-1. The research objectives are firstly raised and then the proposed method is proposed. The challenges represent the concerns to complete the objectives; however, the details are recommended to resolve them.

The first part of this chapter aims to validate the design rework drivers as initially developed and shown in Table 4-7. Furthermore, this activity has been established in order to achieve research objective one. The key challenge to completing this objective is that all drivers developed earlier are not directly focused on the testing and refinement phase. Hence, the need to validate them with several cases from other organisations is inevitable. In addition, multi-data sources are the key to success for this activity. All drivers are validated apart from Novelty Level and Interaction of Subsystems/Components, due to the discussion in section 4.6.1. *The Interviews as guided conversation* technique is implemented in most validation activities as well as email communications; however, any emerging points related to design rework are allowed. Researcher experience is implemented to group the emerged themes during data analysis. Moreover, the sub-drivers are captured and revalidated as explained in section 5.1. Later, the Design Rework Probability of Occurrence Estimation (DRePOE) method is developed by the analogy-based estimation method as proposed in order to reach research objective two. The Analytical Hierarchy Process (AHP) is applied because it is suitable towards comparing subjective entities such as design rework drivers. The method is tested with the automotive water pump case study from company E, and the result is validated by two experts.

Table 5-1: The summary of the developments in chapter 5

Research objectives	Proposed method/methods	
To identify the key drivers for the probability of occurrence of design rework in the testing and refinement phase.	Validate drivers developed from Table 4-7 with Diverse Case Technique	
To develop an estimation method for the design rework probability of occurrence at the early design phase.	DRePOE method	
Challenges	Proposed methods	Sections
Drivers from Table 4-7 are not confirmed to explain design rework in the testing and refinement phase.	Multi-data sources	5.1
The probability of design rework occurrences need to assess in the early design phase.	Analytical hierarchy process (AHP)	5.3

5.1 VALIDATION DESIGN REWORK DRIVERS

5.1.1 Hypothesis for design rework driver validation

The design rework drivers are extensively developed from product design and development factors from Table 4-7. However, they do not directly explain the design rework phenomena in the testing and the refinement phase. Therefore, this activity is to confirm their validity. Consequently, the hypothesis for validation is as follows:

"There are relationships among the captured design rework drivers from Table 4-7 and design rework probability of occurrence in the testing and refinement phase."

5.1.2 Developing questions and selecting participants in validation

The pilot test was conducted with experts from different companies. Each design rework driver was validated with two questions, as shown below.

- Are all of these drivers valid in terms of reducing design rework in the testing and refinement phase?
- Are there anymore factors that should be considered?

The participating companies were selected diversely in terms of geographies, cultures, as well as extended from enterprise concept, OEMs and suppliers. In addition, there were aerospace experts from the UK and the USA cooperating in validation in order to maintain generalisation and enhance the validation results; however, all experts have involved only in mechanical design systems. There were two methods to collect data: interviews and email communications. The first three validations were pilot tests while the others were further validations. Once the individual interviewee answered all questions, each interview result was documented by means of a digital recorder and these conclusions/results were fully transcribed for analysis. The summary for the participating companies is in Table 5-2. The interviews with automotive companies from the USA and Thailand were completed over telephone, while the expert from company H was interviewed in a School of Engineering, at Cranfield University. The details for pilot test and further validations are explained in section 5.1.3.

Table 5-2: Summary of participants in design rework drivers' validation

Job Titles	Companies	Companies' detailed	Years of Experience	Data collection methods	Stages
Independent Consultant	Company F	Aerospace consultancy	23	Face to face interviews	Pilot validation
Product Planner and Program Management	Company G	USA automotive OEM in Thailand	5	Emails	Pilot validation
Coordination Director	Company H	USA aerospace OEM	46	Face to face interviews	Pilot validation
Design Engineer	Company I	French Tier 1 automotive supplier	2.5	Emails	Further validation
Stress Engineer	Company J	UK Tier 1 aerospace supplier	2	Interviews over telephone	Further validation
Product Engineer	Company K	USA Tier 1 automotive supplier (suspension)	3.5	Interviews over telephone	Further validation
Team Leader	Company A	Japanese Tier 1 supplier, in Thailand	5	Interviews over telephone	Further validation
Senior Engineer (Car body)	Company A	Japanese Tier 1 supplier, in Thailand	5	Interviews over telephone	Further validation
Senior Engineer (Upper Body)	Company A	Japanese Tier 1 supplier, in Thailand	5	Interviews over telephone	Further validation
Senior Engineer (Hand Brake)	Company A	Japanese Tier 1 supplier, in Thailand	5	Interviews over telephone	Further validation

5.1.3 Design rework driver validation results

The validations were conducted in two stages: the pilot and the further validations. All drivers are extended from the drivers which are not specific for the testing and the refinement phase; therefore company F, G, and H are for pilot test. The pilot summaries are in the last column of Table 5-3, so, they are analysed to develop the further validation results, as shown in Table 5-4.

Results from pilot validation

The good practices and key concerns related to each driver from each individual company are interesting; therefore any recommended actions to resolve design problems were the first priority to search for during analysis. In general, all participants did agree on the driver's validity. However, most experts did articulate their opinion extensively in each driver. The pilot study results are in Table 5-3. The summaries from different drivers are clustered by double lines. Column one fills with the drivers taken from Table 4-7, and columns two to four are confirmed by the interview results from each company. Considering column-wise, the pilot summaries are developed with a thematic analysis technique, and the synthesis results are shown in column five.

For Exploitation of CAE Software, the majority of the respondents realises it as a useful device in design activity; however, the participant from company H suggests that the user must aware its limitations as well as the fundamental physics of the apparatus. So, there are two concerns for this driver, as shown in column five.

There are two points from Coordination across Team Members: Obtaining the right people as soon as possible and a process to inform the decision making.

For Clarity of specifications, expert from company H proposes that specifications should be negotiable or changeable if they could cause the delay problems, as highlighted in Table 5-3. However, it is strongly related to the Constraint to Deliver a Project on Time frim the researcher's point of view, so it is summarised in the other category. Besides, this expert supports that any timing delay issues must be informed to all related people in the team to make decisions. For example, company H's customer (the US air force) changed the specifications after the analysis revealed that the developing a new radar would take too long to develop. Nonetheless, there is the disagreement on the driver "Constraint to Deliver Project on Time". But the researcher continues using this driver heading in the further validation stage in order to confirm the disagreement.

Table 5-3: Design rework drivers validation results from pilot confirmation stage

Drivers	Companies			Pilot summaries
	F	G	H	
Exploitation of CAE Software	It helps to iterate the design more with lower cost than using prototypes solely. However, it is not intelligent; engineers must understand the inputs of the programs. If not, it is very much like "rubbish in rubbish out."	CAE analysis is not real important unless the part designed effects the overall system's mechanical structure. Most of the parts are added on parts or simple designs don't have to do CAE to save cost.	-It is not a major issue, and the reason is the following. If we just use the CAE to calculate for aerodynamics forces on an airplane which is just look like the previous one but it just needs to be more efficient. But going into new area of composite structure in a much greater way that it has never been done before. It is better to be careful that CAE is used with validity to the size of structure and the importance of it. The biggest problem for CAE is people using it outside the range of the original design without knowing it. -Sometime people use CAE without the fundamental in physics of it. When the software is pulled from the shelf, it is better to know what the limitations are.	-Be careful to use CAE for the new area which has never been design before. -Fundamental knowledge of physics on product being design helps to understand CAE limitation, and increase more confidence on CAE results.
Coordination across Team Members	-Getting the right people to the right team. -Coordination needs to come together with expertise of the team. If we put the right people at the early stage everything will be ok.	If a process to capture deliverables and decision making are good, coordination of team members will automatically follow the system.	-It is very important to get as many as possible of people who eventually involve in the product at the initial design stages. -There are no limits to how early to bring people from different discipline to help you out. However, you need a starting point. It's unusual to start to design a part with 20 people, once you have a starting point, it's better to bring people as soon as possible.	-Getting the right people who relate to product being design as soon as possible. -A process to inform progress and decision making helps team to be better coordinated.
Lessons Learnt	This heading is related to experience, how well to document the lessons learned, and retrieve ability. Ex., warranty is part of lessons learnt, because, aerospace OEMs need to understand the warranty history to sell the contract.	-In automotive business, more than half of the parts are carried over from previous model or across platform, so lessons learnt can help new designs. -Expertise of development team members is important if lesson learnt and knowledge database system is not good.	Lessons learnt are the combination of two things, experience from the past and a combination of new people coming with new ideas. Ex., you are hoping the new person will come with the new idea to evaluate two or three CAE approaches to a particular problem.	It is a method to document experience of team members working in the project. The lessons learnt prompts companies to step forward.

Table 5-3: continued

Drivers	Companies			Pilot summaries
	F	G	H	
Supplier Expertises	Supplier can help to select shelf solutions rather than spending time and cost to develop new parts.	Normally supplier has better knowledge on each part than the design team	Supplier expertise is needed because you don't have the area of expertise.	Supplier is needed in the area of which company has less experience.
Clarity of Specifications	Specifications are objectives to complete, so they must be clear from start, and they should be stable especially in the late stage.	I think this is importance especially when project timing get closer to launch	Specification should come clear upfront of the development. But it need to have an option to mutually change the specifications, if some parts of the work seem not possible or takes too long.	-Specifications should be clear and stable. -Specifications could be changed, if some parts takes to long or seems not possible
Constraint to Deliver Project on Time	Definitely, there are always a delivery date. Products need to be out on the shelf or out for the customer plan. There will be higher non conformant parts (not meet the quality) from the tight project time than the project with less time constraint, because you do thing on rush.	If everything is under control the time constraint should not be the problems.	-Time should not be a constraint, but there should be an agreement to work together. If time is coming into the consideration, team should decide whether too late to the project or remove a specification and let the job done. We have a very good customer (US air force). The US air force agreed to change to use the infra-red detector as sole equipment for the advance military aircraft rather than continue developing radar system which takes to long to complete. -If designing an airplane requires a lot longer than it would. The smart thing is to get your customer and your boss in the company further up the line keep them informed, so that we can make decision early.	Commitment to solve problems about timing issue is importance. Any issues harmful to the delivery date should be informed to everybody in order to make decision earlier.

Table 5-4: Design rework drivers validation results from further confirmation stage

Pilot summaries	Companies							Sub-drivers
	I	J	K	A (Interviewee 1)	A (Interviewee 2)	A(Interviewee 3)	A (Interviewee 4)	
-Be careful to use CAE for the new area which has never been design before. -Fundamental knowledge of physics on product being design helps to understand CAE limitation, and increase more confidence on CAE results.	It must not be forgotten that it is only a tool and they can't prevent from errors made by the user. Testing and prototyping are methods which can be used to complete the virtual study made with CAE software.	-It is very difficult to get similar CAE results from two engineers because of the knowledge to set boundary condition, how to simplify 3D models before put them into the program. Fundamental knowledge on strength of material is another necessary knowledge to set boundary conditions. -The principle knowledge behind the CAE tools is also important. CAE for structure analysis is based on finite element method. There is a parameter called "epsilon" to verify the simulation model.	-Data base to benchmark simulation results from CAE is important; otherwise the simulation results are questionable. The data base is the best practice from previous project of the company. -One key successful for CAE is knowledge of users on preprocessing; meshing, assigning boundary conditions. -The knowledge to simplify problems being simulated is also necessary; otherwise it is not practical to put the model to CAE software.	-This company uses the benchmark CAE from previous design as guideline for new design. Therefore, previous designs helps not only reduce analysis time but also helps to give direction to iterate design more in critical area. -To achieve CAE analysis, knowledgeable engineer is getting involved to interpret the CAE results from understanding products from physical point of view.	-The CAE results have to be compared with tested results from previous body designs otherwise the engineers have no confidence to make prototype. If the most similar benchmark is used, it would be good enough to provide trend for new design not true deflection values. -User should understand that CAE is just a tool. If there is no knowledge in product being design, trial and error by CAE will have no direction. -Fundamental knowledge of strength of material is importance for putting boundary conditions or analyse results.	-Historical projects are used to evaluate results of CAE. They are documented, and judged by staffs who involved in testing. -Physical knowledge related to object being analysed is necessary to set boundary condition.	-Engineers use CAE as a guideline and then wait for testing results to validate design. -The principle knowledge e.g. strength of material is importance in order that boundary condition e.g. force acting on parts are properly assigned. -Knowledge on the limitation of software is also importance for capturing the precise stress in parts is achieved by refining mesh.	-Benchmark CAE results -Fundamental knowledge of product being designed. -Fundamental knowledge of mathemetics behind CAE tools
-Getting the right people who relate to product being design as soon as possible. -A process to inform progress and decision making helps team to be better coordinated	-It is necessary to ensure that each system has clearly defined limits and set the information that has to be shared by the right team members. -It can be achieved by being very careful in sharing the right pieces information at the needed time, and prevent misunderstanding.	-This company is selected as a part of team by aircraft OEMs. -Stress engineer works closely with aircraft OEM. There are checklists to provide guidelines for analysing the design. If there are problems in the design, stress engineer will make a report to aircraft OEM to inform issues	-In each project, there are product engineers taken responsibility in technical issue, while program managers take responsibility for financial and time of the projects. -There are always problems of failure in the verification phase. One of the root causes is simplifying prototypes by manufacturing engineers without notice to product engineers.	-For development team members, there are three teams for CAE analysis, body crash analysis, noise and vibration and component strength. -If there are mistakes, it this necessary to share the problems found to everybody in team. -Sharing knowledge and information to team is crucial. This company has transparency to get into knowledge to engage with problems and distribute to every team member.	-In conceptual design, team evaluates which part requires new design and then assign work load to the appropriated design team members. -Then, everybody can communicate each other during design. -Informal communication is used, if changes are not impact to the other neighborhood parts. But, if impact requires huge amount of changes, the formal meeting is requested. The line manager (e.g. car body and headlamp) for each impacted part will find solution together. If the decision still could not be made, Chief engineer will make decision about changes. Finally every decision has to be documented.	-Philosophy of working as a team is awareness of work being done by other colleagues. So, getting right stakeholders in the team is necessary. -Sharing information facilitates the achievement of this point. There are many ways to share information. If changes are not impacted on major specification, informal communication for change could be made. Regular meeting to inform changes will be set up; they are impacted to a lot of team members.	-There are a design manager, a senior engineer and engineers in a team; however, hand break team also need to talk to the other team e.g. console team or cushion team. There is a department which facilitate and monitor the whole project in overall. -There is a principle called "ORENSO" which compose of three best of practices as follows: -Every progress needs to be informal informed to the steak holders. -Put progress into a formal report. -Each problem, which is not sure how to solve, needs to be consulted by a person who has experience.	-Sufficient number of qualified team members. -Procedure to inform update to design team members -Procedure to make decision on conflict design issues.

Table 5-4: continued

Pilot summaries	Companies							Sub-drivers
	I	J	K	A (Interviewee 1)	A (Interviewee 2)	A(Interviewee 3)	A (Interviewee 4)	
It is a method to document experience of team members working in the project.	The technical background and the experience of the team members are linked to the quality of the database available for the team about previous projects. It allows not making the same mistake several times. Performance and quality of the product can be estimated quickly.	There are no lesson learnt systems in company; however, trick to analyse design is given from the supervisor. Therefore, lessons learnt are considered as experience of each individual engineer.	There is a discipline problem for new product engineers. The new comers tend not to use the lessons learnt within company. No one takes responsibility to assure that every engineer needs to go through the company's lesson leant systems.	-Team has to develop process or flow manual then it becomes to be a standardisation of working process for team in the future. -Company A has strong culture which inherently forces every one to follow rule or standard in everybody's daily working.	-There are check sheets to give guidelines for design.	-There are lessons learnt document stored in company A's IT system ready to use. -It is a tradition to go back to start working by lessons learnt.	-A new model of hand break starts from previous model in order to reduce development cost. So, it is necessary to seek for the most similar previous design. -There are guidelines to design such as recommendations of the weakness points of a component and the guidelines to solve them.	-Availability of lessons learnt -Discipline to implement lessons learnt for new design projects.
Supplier is needed in the area of which company has less experience.	*This company is a supplier.*	*This company is a supplier.*	The quantitative evaluation system to select supplier expertise is necessary in company K's context.	Supplier must follow Company A's standard	-Internal management of supplier impacts a lot on company A. The internal management problems could harm the delivery date.	-One project, she asked for change supplier in the middle of the project. The supplier has capability in terms of knowledge and experience to work with but there are machine's limitations.	- The criteria to evaluate supplier are capacity and capability to manufacture, ability to design. Engineers know very well about hand break, so they can judge whether suppliers are qualified or not. Supplier could be changed, if suppliers perform badly during development.	-Supplier's technical expertise -Supplier's internal management
Specifications should be clear and stable.	Specifications must be expressed clearly as early as possible during the design phase. It concerns main functions, technical specifications, reliability and prices.	Aircraft OEM gives drawing and load cases to the company to analyse stress. Therefore, the specifications are clear at the beginning.	Specifications are considered as objectives to achieve. Specifications make OEMs and suppliers understand each others	There are three phases in detail design. Design will be changed not more than 2 times before Certify Vehicle (CV) or start of production.	Chief engineer will deliver conceptual specifications to various departments.	-Specifications are given from vehicle project. The vehicle project converts customer requirements to conceptual specifications and then development teams to develop engineering specifications. -Chang request from vehicle project is common, because of market environment. This situation gives engineers hard time.	-Conceptual specifications will be given by vehicle project team. The conceptual specifications are developed from marketing requirements. Engineers have responsibility to find detail engineering solutions. -Specifications of styling parts tend to be changed more often than parts which have no aesthetic functions. For example, interior parts have more often to change than suspension part.	Clarity of specifications
Commitment to solve problems about timing issue is importance. Any issues harmful to the delivery date should be informed to everybody in order to make decision earlier.	Time constraint puts additional pressure to the design team. Design rework can induce delays in the delivery, so their impact on the project schedule must be evaluated carefully.	There is a standard time sheet to negotiate with aircraft OEMs; however, if there are some changes and they require more analysis, the company will discuss with OEMs to charge for more hour.	-From experience, a project with very tight schedule is hardly to finish smoothly. -If there is a problem with time frame, it is always opened to discuss with OEMs especially American. Time constraint is negotiable; however, the impact is cost of the project will be increased.	Even though hours to be charged are set by customers and management of company A, the team leader has authority to verify the estimation results.	-There are 3 phases in detail design. -If there are problems, it is common to negotiate with line manager about time to deliver. But it will delay the completion of neighbour hood part.	-Working hours for each project are given from the line manager to engineers in operational level. -If there are problems about time line, it is common to open issues and inform the steak holder to be aware.	-If engineer feels that work loads are too much to finish on time, it is opened to inform the direct management to ask for reallocate the others to help.	Open Communication to Inform Design Time Issues.

Results from further validations

Later, the pilot summaries are presented in column one of Table 5-4, column one. The questions for interviews in this stage are similar to the previous stage. Again, the pilot's summary results were not asked directly during interviews in order to avoid bias. All participants accepted the validity of the drivers in Table 4-7. To analyse the interview results, the answers from each participant are represented against each pilot summary, and they are in columns two to eight. Column nine composes of the sub-drivers synthesised with the thematic analysis technique.

All sub-drivers are developed from each company's good practices to reduce the probability of design rework occurrences. The sub-drivers are summarised as follows:

Exploitation of CAE Software: The best practices in these drivers are the availability of Benchmark CAE results, Fundamental knowledge of product being designed, and Fundamental knowledge of mathematics behind CAE tools.

Coordination across Team Members: The good coordination is achieved by Sufficient number of qualified team members, Procedure to inform update to design team members, and Procedure to make decision on conflict design issues.

Lessons Learnt: The Lessons Learnt cannot be achieved if there are no Availability of lessons learnt, and Discipline to implement lessons learnt in new design projects.

Supplier Expertises: The supplier expertise is evaluated by OEMs into two categories: Supplier's technical expertise, and a Supplier's internal management.

Constraint to Deliver Project on Time has been conflicted since chapter 4 whether it helps to reduce design rework occurrence or not. From the participating companies shown in this chapter, it is found that the constraint itself will increase the design rework occurrence. But, if the design team keep the issues transparency and let the involved people informed, this action will reduce the design rework occurrence. Therefore, this driver is renamed as "*Open Communication to Inform Design Time Issues*".

5.2 CONCEPTUAL SETTING FOR THE DESIGN REWORK PROBABILITY OF OCCURRENCE ESTIMATION (DRePOE) METHOD

The method shown in this chapter is the final version after it was iteratively developed with the experts from company E. The conceptual setting for this method is as follows:

5.2.1 Concept of the DRePOE method

The method is conceptualised with Analytical Hierarchy Process (AHP) technique. Eq. 5-1 is the additional development from Bashir (2001). The original equation is added with the Novelty Level; hence, there are two groups of drivers. The first group composes of the drivers to reduce design rework occurrence, as developed in section 5.1, while the Novelty Level is the driver which is increasing design rework occurrence, as explained in section 5.2.2. Each driver weighted average is derived with the AHP.

$$P_{es} = NL \frac{1}{n_B} \sum_{i=1}^{n_B} \frac{w_i}{w_{es}} P_i \qquad (5\text{-}1)$$

where P_{es} is the probability of design rework being estimated, P_i is the probability of design rework from benchmark product *i*, n_B is the number of benchmark products, w_i is the weighted average of the drivers to reduce design rework for benchmark product *i*, w_{es} is the weighted average score of the drivers to reduce design rework for the product being estimated (new product), *NL* is the estimated Novelty Level for the new product.

The Novelty Level is obtained with AHP by comparing the new product and benchmark products, so, it weighted average is calculated with Eq. 5-2.

$$NL = \frac{1}{n_B} \sum_{i=1}^{n_B} \frac{NL_{es}}{NL_i} \qquad (5\text{-}2)$$

where *NL* is the estimated Novelty Level for the new product, n_B is the amount of benchmark products, NL_{es} is the Novelty Level score from the product being estimated (New product), NL_i is the Novelty Level score from the benchmark product *i*.

w_i / w_{es} is the assessment of the likeliness of the design rework happening by comparing with the weighted average scores from each benchmark *i* and the new product. Once each ratio is obtained, the average can be achieved by dividing with the total number of the benchmark product (n_B). Similar principle is pertained to the estimation of the Novelty Level, as represented in Eq.5-2, but the ratio NL_{es} / NL_i is different in terms of the nominal compared with the ratio w_i / w_{es}. The main reason is because the Novelty Level is a linearly proportion to the probability of design rework occurrence while it is not for the drivers to reduce design rework occurrence. Therefore, *NL* infers as the average Novelty Level of the new product compared with every benchmark product.

5.2.2 The assumptions of DRePOE method

The DRePOE method is working under four assumptions as shown below.

- Probability of design rework occurrence is directly proportional to the Novelty Level while it is inversely proportional to the drivers to reduce design rework.
- Design rework probability of occurrence is not specific for a particular component; but it gives the overall likeliness of the whole product being design.
- CAD itself, regardless of linkages to other analysis modules is assumed as a good practice implemented in every company, each of which has relatively no difference in CAD expertise.
- The benchmark and the new products have to be in the similar product range.

This method is developed with the analogy based technique. The design rework probability of occurrence turns out due to the Novelty Level in a new design product, which is driven from new challenges otherwise there would be no design rework. However, the probability of design rework should be reduced if the design team conducts the design activities by complying with good practices realised as the drivers and sub-drivers developed in section 5.1. Assumption two, the product being design could be either systems or sub-systems but the estimation of design rework probability of occurrence is calculated for the overall product rather than for a particular component. In the next assumption, the CAD expertise itself does not significantly vary among companies because it is a well established technology. Last assumption, the comparison needs to be within a similar product range because of the AHP's requirements.

5.2.3 The experts involved in the DRePOE method development

This method was iteratively developed along with two experts from the automotive water pump case supported by company E. Two experts involved in developing this method have experience with the automotive water pump for 30 and two years consecutively.The senior expert has been working as CPPD Oil & Cooling, while the other is a Product Management Graduate.

5.3 THE PROCEDURE FOR DRePOE METHOD

The DRePOE method was iteratively elaborated with two experts as mentioned in section 5.2 and the final version of the method was initially tested with automotive water pump from company E as represent in section 5.3.1 to 5.3.5. The detailed steps to estimate design rework probability of occurrence are shown in Figure 5-1. This protocol is designed for the design team to implement with the new product being designed. This method is developed under an analogy based estimation system because it can be implemented in the early design phase and it is suitable when there are insufficient samples to develop parametric based estimation methods as discussed in section 2.6.

The major contributions in this method are the development of drivers to reduce design rework occurrence and Eq. 5-1. The detailed explanation of DRePOE method with the example of water pump product from company E is represented in section 5.3.1 to 5.3.5. The automotive water pump is a sub-system in an engine, which prevents engine overheat because it pumps coolant throughout the engine jacket in order to remove the heat excess. The engine capacity increases, the water pump must be replaced with the higher flowrate water pump to remove heat surplus.

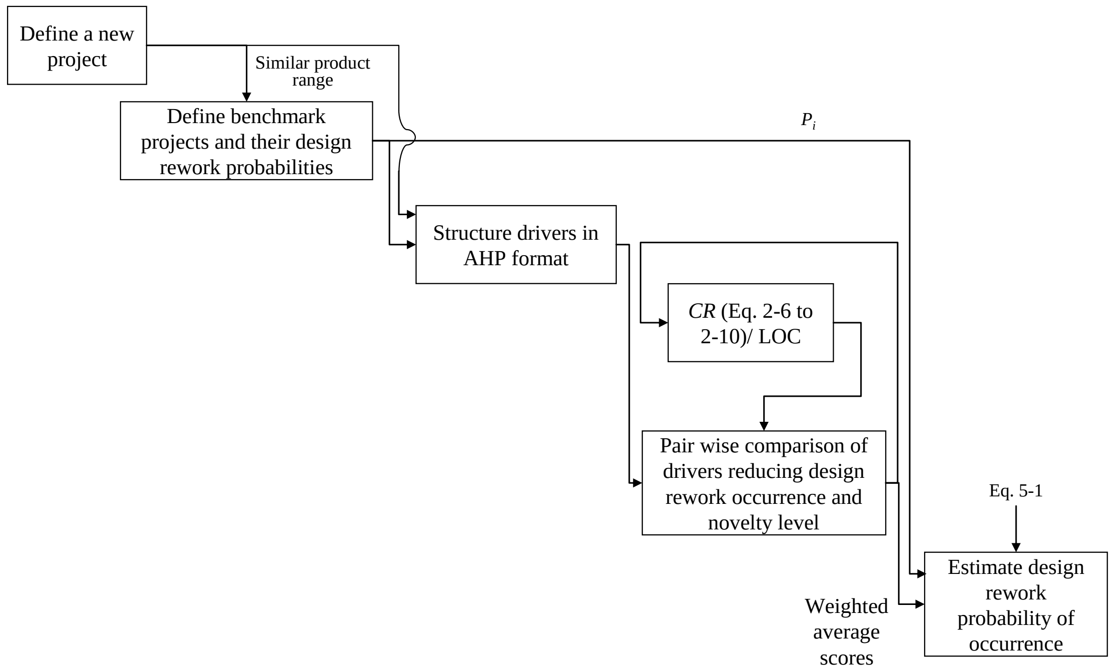


Figure 5-1: The PROCEDURE for the DRePOE method

5.3.1 Define a new product

From Figure 5-1, the first task is to define a new product. This method allows estimating design rework in the testing and refinement phase; moreover, this assessment can be performed at the very early design phase because of the capability of the analogy based estimation method. The new product is developed into the hierarchy structure as discussed in section 5.3.3. The engine version is classified as Tier defined by American legislation. During the method development, a Tier 4 engine has been developed. Therefore, the new product in this case is the automotive water pump for the Tier 4 engine.

5.3.2 Define benchmark products and their design rework probabilities

Benchmark products

The benchmark products must be within the similar product range compared with the new product due to the requirement of analogy based estimation method. The higher number of benchmark products will provide the higher transparency to the design team members to evaluate their previous designs. Benchmark 1 is the automotive water pump developed in parallel with a Tier 3 engine, while benchmark 2 is a stand alone project to replace benchmark 1 due to the massive design problems reported in the testing and refinement phase.

Design rework probabilities

The historically design rework probability of occurrences for each benchmark is the data required from both benchmark products. The guideline to calculate design rework probability of occurrence in the testing and refinement phase is by Eq. 5-3.

$$P_i = \frac{The \quad amount \quad of \quad design \quad issues \quad found \quad in \quad Design \quad testing \quad phase}{Total \quad amount \quad of \; product \quad tested} \tag{5-3}$$

where P_i is the probability of the design rework occurrence for product i. If there is no such a data from previous products, the likeliness of probability should be identified from experts involved in the previous product design activity such as Benchmark 2.

The design issues found in the testing and refinement phase are realised after the root cause analysis is performed; therefore, only the root cause from design issues are counted for the nominal part of Eq. 5-3. Each failure in the testing and refinement phase is recognised only once per one event. One failure issue leads to one root cause; therefore, it is mutually exclusive from others. For example, in Failure Mode Analysis (FMA) document from benchmark 1 from company E. It records the failures from a ball bearing, an impeller and a water seal and none of them are from the same water pump. There are 23 out of 180 water pumps that failed due to design issues (Appendix C).

Table 5-5: The probabilities of design rework occurrences from the previous developmemts

Products	Probabilities of design rework occurrences	Sources
Benchmark 1	$(23 \div 180) \times 100 \approx 13\%$	FMA document
Benchmark 2	$\approx 3\%$	Experts' judgement

5.3.3 Structure drivers in AHP format

Rationales to select the AHP technique for developing method

The full discussion of techniques in the analogy based estimation is in section 2.6.3; however, the reason to select the AHP technique is as follows:

- It can provide the true measurement for each entity being compared, because the relative orgin of measuring among them is assign after the scoring activity completes. Hence, the qualitative drivers can be evaluated mathematically.
- It can incorporate multi-critia into estimation easily; therefore, the drivers and sub-drivers are fully weighted up.

Structure drivers for reducing design rework occurrence

It is necessary to structure the drivers and their choices being compared in hierarchy as shown in Figure 5-2. Design Rework Occurrence is the aim which is located at the top level. The drivers as well as the drivers in levels two and three of the structure are factors from industrial good practices to reduce the Design Rework Occurrence (the goal). Products being compared: new and benchmark products are in the structure's lowest level. The probability of design rework occurrence is estimated for the new product while the benchmarks are previously designed products. There are no limited number of benchmark products; however, there are two in this example; therefore Figure 5-2 is tailored for this example, and then the pair-wise comparison is implemented.

Structure products under the Novelty Level

In general, the Novelty Level increases when the engine development moves to the next Tier level due to heat rejection. The improving in combustion efficiency required the higher Tier lead to greater heat generated in the piston; therefore, substantially heat excess needs to be removed by the coolant. As a result, designing the new automotive water pump is inevitable. Changing the impeller material from cast iron to plastic due to weight saving is the product novelty captured from interviews. But reducing torsional activity in the ball bearing provided by this method is a benefit from this changing but it is prone to impeller fatigue ptoblem. To structure factors in AHP format has to be applied to compare the Novelty Level for each product, as exemplified in Figure 5-3.

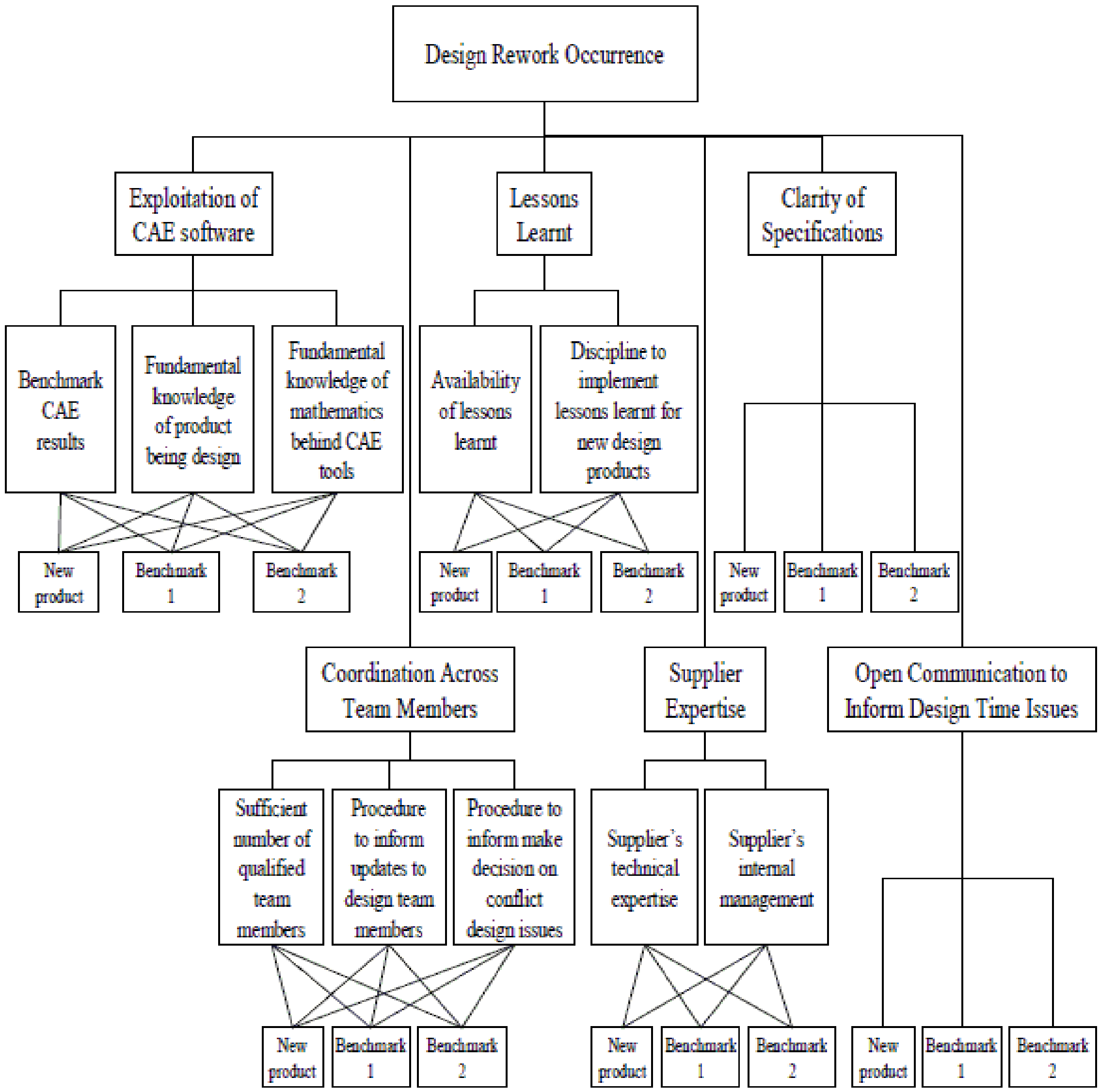


Figure 5-2: The structure of drivers for reducing design rework occurrence and products

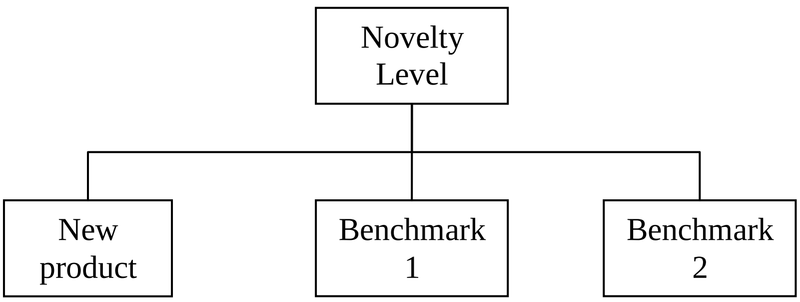


Figure 5-3: The structure of products for comparing the Novelty Level

5.3.4 Pair-wise comparisons of drivers for reducing design rework occurrence and novel level

The example of full pair-wise comparison for Exploitation of CAE Software driver and its sub-drivers

The full pair-wise comparison is a matrix which composes of less than four elements being compared in this thesis. It is a square matrix which all items are identical in row and column headings. The elements from the same hierarchy in Figure 5-2 are formed to be the matrix; furthermore, the matrix must be set from the entities under the similar direct upper entity. For example, Table 5-6 develops from the sub-drivers under the Exploitation of CAE Software driver. These three sub-drivers are in level three of the structure, as shown in Figure 5-2; however, there are many more sub-drivers in level three, but there are three sub-drivers in the pre-mentioned driver.

There are two parts of the matrix, the upper and the lower diagonal. The scoring requires performing the upper diagonal only; because each cell in the lower diagonal is reciprocal of the upper diagonal. For instance, all scores are achieved in the upper diagonal of Table 5-6, while the lower diagonal part is their reciprocation. Row five shows the column-wise total which is the requirement of the weighted average method as described by Eq. 2-5. The weighted average results are in column five and the total weighted average must be equal to one as requested by the AHP principle.

The Consistency Ratio (*CR*) employs as the quality of scoring results. If *CR* exceeds 20%, it means the scoring closes to random scoring, so the scores in the matrix need to be revisited. *CR* can be calculated with Eq. 2-6 to Eq. 2.10, as located in row six of Table 5-6.

Table 5-6: Pair-wise comparison matrix for sub-drivers under Exploitation of CAE Software

Exploitation of CAE Software	Benchmark CAE results	Fundamental knowledge of product being design	Fundamental knowledge of mathematics behind CAE tools	Weighted average scores
Benchmark CAE results	1	$\frac{1}{7}$	1	0.12
Fundamental knowledge of product being design	7	1	5	0.75
Fundamental knowledge of mathematics behind CAE tools	1	$\frac{1}{5}$	1	0.13
Total	9	$1\frac{12}{35}$	7	1
CR	1.09%			

Each *CR* is calculated immediately after the scoring finished because the pair-wise comparison is applied into the computer spread sheet program (EXCEL). So, this approach helps to quickly response against the scoring results, if the *CR* reveals inconsistent. Furthermore, it enhances the user friendliness of the approach.

The example of the spread sheet is Figure 5-4. There are two judgments in the spread sheet. The first one is making decision of which elements have the stronger strength and later the rating has to be scored. For example Figure 5-4a first choice, Benchmark CAE results has less influence to the Exploitation of CAE Software compared with the Fundamental knowledge of product being design. Later, the scoring on strength is performed in the next stage, Figure 5-4b. If a couple of drivers have equal strength, tick equal in the first stage then scoring for the strength is unnecessary. The *CR* is in the bottom of Figure 5-4b as well as the recommendation whether the scoring is good or not.

Similar principle is implemented throughout the AHP structure and all results for the case study one are shown in Appendix D.

Drivers	Please answer in pair	Drivers	Yes	No	Equal
Benchmark CAE results	has greater influence to Exploitation of CAE software than	Fundamental knowledge of product being design	☐	☑	☐
Fundamental knowledge of product being design	has greater influence to Exploitation of CAE software than	Fundamental knowledge of mathematical behind CAE tools	☑	☐	☐
Fundamental knowledge of mathematical behind CAE	has greater influence to Exploitation of CAE software than	Benchmark CAE results	☐	☐	☑

(a)

A	Please answer one A has greater impact than B									B	Status
	Equal		Moderate		Strong		Very Strong		Extreme		
Fundamental knowledge of product being design	Please score	☐	☐	☐	☐	☐	☑	☐	☐	Benchmark CAE results	Correct
Fundamental knowledge of product being design	Please score	☐	☐	☐	☑	☐	☐	☐	☐	Fundamental knowledge of mathematical behind CAE tools	Correct
Fundamental knowledge of mathematical behind CAE tools	TRUE	☐	☐	☐	☐	☐	☐	☐	☐	Benchmark CAE results	Correct

Consistency Ratio (CR)	1.09 %
Reccommendation	Good scoring

Target CR	Value
Good scoring	CR<=10 %
Acceptable scoring	10<CR<=20 %

(b)

Figure 5-4: The example of spread sheet for comparing for sub-drivers under Exploitation of CAE Software driver (a) Decision on the higher strength factor (b) Scoring the strength

The full pair-wise comparison for Novelty Level among products

Analogous principle is applied throughout the hierarchy, as shown in Figure 5-3, and the results are in Table 5-7. It is demonstrated that the new product has the greatest weighted average score. Hence, the new product should have the most challenges compared with previous products otherwise there is no product evolution any more.

Table 5-7: Pair-wise comparison matrix for products under Novelty Level drivers

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores for Novelty Level
New product	1	3	2	0.55 (NL_{es})
Benchmark 1	$\frac{1}{3}$	1	1	0.21 (NL_1)
Benchmark 2	$\frac{1}{2}$	1	1	0.24 (NL_2)
Total	$1\frac{5}{6}$	5	4	1
CR	1.58%			

From Table 5-8, the Novelty Level for the new product is calculated with Eq. 5-2 and an example of estimation is in column four. The weighted average scores in this table are taken from column five of Table 5-7 while the NL_{es}/NL_i and NL are obtained from Eq. 5-2.

Table 5-8: The estimation for the Novelty Level for the new product for automotive water pump

Products	Weighted average scores	NL_{es}/NL_i	Estimated Novelty Level for the new product (NL)
New product	0.55 (NL_{es})	Being estimated	2.44
Benchmark 1	0.21 (NL_1)	2.60 (NL_{es}/NL_1)	
Benchmark 2	0.24 (NL_2)	2.28 (NL_{es}/NL_2)	

The example of incomplete pair-wise comparison for drivers reducing design rework occurrence

During the development of the method with the first case study, the full comparison had been implemented throughout case; but there was a request from a sponsor company to reduce the scoring effort. After selecting the suitable incomplete pair-wise comparison technique, the chain wise paired comparison was implemented. Therefore, the mentioned technique is implemented and the scoring results are shown in Table 5-9.

Table 5-9: The example of chain wise paired comparison results for drivers reduced design rework occurrence

Drivers	w_1	W_2	w_3	w_4	w_5	W_6
Exploitation of CAE Software (w_1)		1				
Coordination across Team Members (w_2)			$\frac{1}{3}$			
Lessons Learnt (w_3)				3		
Supplier Expertises (w_4)					$\frac{1}{3}$	
Clarity of Specifications (w_5)						5
Open Communication to Inform Design Time Issues (w_6)	1					

There are *n* comparisons required, so there are six assessments shown in Table 5-9. The example of the algorithm for estimating the weighted average is illustrated in Table 5-10a as complied with a procedure in Table 2-6. Column six is the estimated weighted average scores while the bottom cell is the total and it is always equal to one. The chain wise Paired comparison is also assign into the EXCEL spread sheet. The *LOC* is monitored instead of *CR* while its recommended *LOC* value is provided and the example of the spread sheet is Figure 5-5.

The scoring method is similar to the full pair-wise comparison example as shown in Figure 5-5a; however, there are only six comparisons required instead of 15 judgments compared with the full scoring (calculated with Eq. 2-11). Another major different is that *CR* is replaced by *LOC* as represented in the bottom of Figure 5-5b. In addition, the recommendation for scoring results is clearly displayed there.

The estimated results from the drivers to reduce design rework occurrence taken from column five of Table 5-10a are summarised in Table 5-10b and they are to estimate the probability of design rework occurrence as demonstrated in section 5.3.5. Clarity of Specification has the highest strength to reduce design rework occurrence because it provides the direction for the design team.

Drivers	Please answer in pair	Drivers	Yes	No	Equal
Exploitation of CAE Software	has more effectiveness to reduce the design rework probability of occurrence than	Coordination across team members	☐	☐	☑
Coordination across team members	has more effectiveness to reduce the design rework probability of occurrence than	Lessons learnt	☐	☑	☐
Lessons learnt	has more effectiveness to reduce the design rework probability of occurrence than	Supplier expertises	☑	☐	☐
Supplier expertises	has more effectiveness to reduce the design rework probability of occurrence than	Clarity of Specifications	☐	☑	☐
Clarity of Specifications	has more effectiveness to reduce the design rework probability of occurrence than	Open communication to inform design time issues	☑	☐	☐
Open communication to inform design time issues	has more effectiveness to reduce the design rework probability of occurrence than	Exploitation of CAE Software	☐	☐	☑

(a)

A	Please answer one A has more effectiveness to reduce probability of design rework occurrence than B									B	Status
	Equal		Moderate		Strong		Very Strong		Extreme		
Exploitation of CAE Software	TRUE	☐	☐	☐	☐	☐	☐	☐	☐	Coordination across team members	Correct
Lessons learnt	Please score	☐	☑	☐	☐	☐	☐	☐	☐	Coordination across team members	Correct
Lessons learnt	Please score	☐	☑	☐	☐	☐	☐	☐	☐	Supplier expertises	Correct
Clarity of Specifications	Please score	☐	☑	☐	☐	☐	☐	☐	☐	Supplier expertises	Correct
Clarity of Specifications	Please score	☐	☐	☐	☑	☐	☐	☐	☐	Open communication to inform design time issues	Correct
Open communication to inform design time issues	TRUE	☐	☐	☐	☐	☐	☐	☐	☐	Exploitation of CAE Software	Correct

Level of consistency (LOC)	91.84 %
Recommendation	Good scoring
Target LOC>=	88.9 %

(b)

Figure 5-5: The example of the spread sheet for chain wise paired comparison method (a) Decision on the higher strength factor (b) Scoring the strength

Table 5-10: The estimating weighted average algorithm of the drivers for reducing design rework occurrence from automotive water pump case (a) Calculation algorithm (b) Results summary

(a)

i	R_i	D_i	$\tilde{R}_i = D_i \Big/ \sqrt[n]{\prod_{i=1}^{n} D_i}$	M_i	w_i^*
1	$R_1 = w_1 / w_2$	$D_1 = R_1 = 1$	$\tilde{R}_1 = 0.9184$	$M_1 = \prod_{i=1}^{6} \tilde{R}_i = 1.0889$	$w_1^* = M_1 / M = 0.08$
2	$R_2 = w_2 / w_3$	$D_2 = R_2 = 1/3$	$\tilde{R}_2 = 0.3061$	$M_2 = \prod_{i=2}^{6} \tilde{R}_i = 1.1856$	$w_2^* = M_2 / M = 0.09$
3	$R_3 = w_3 / w_4$	$D_3 = R_3 = 3$	$\tilde{R}_3 = 2.7552$	$M_3 = \prod_{i=3}^{6} \tilde{R}_i = 3.8730$	$w_3^* = M_3 / M = 0.29$
4	$R_4 = w_4 / w_5$	$D_4 = R_4 = 1/3$	$\tilde{R}_4 = 0.3061$	$M_4 = \prod_{i=4}^{6} \tilde{R}_i = 1.4057$	$w_4^* = M_4 / M = 0.11$
5	$R_5 = w_5 / w_6$	$D_5 = R_5 = 5$	$\tilde{R}_5 = 4.5919$	$M_5 = 4.5919$	$w_5^* = M_5 / M = 0.35$
6	$R_6 = w_6 / w_1$	$D_6 = R_6 = 1$	$\tilde{R}_6 = 0.9184$	$M_6 = 1$	$w_6^* = M_6 / M = 0.08$
Aggregation for each column		$\prod_{i=1}^{n} D_i = 1.6667$	$\prod_{i=1}^{6} \tilde{R}_i = 1$	$M = \sum_{i=1}^{6} M_i = 13.1451$	$\sum_{i=1}^{6} w_i^* = 1$
LOC		91.84%			

(b)

Drivers for reducing design rework occurrence	Weighted average
Exploitation of CAE Software	0.08 (w_1^*)
Coordination across Team Members	0.09 (w_2^*)
Lessons Learnt	0.29 (w_3^*)
Supplier expertise	0.11 (w_4^*)
Clarity of specifications	0.35 (w_5^*)
Open Communication to Inform Design Time Issues	0.08 (w_6^*)
Total	1.00

5.3.5 Estimate design rework probability of occurrence

There are two sub-stages before performing estimation; getting total weighted average and estimation as follows:

Obtain total weighted average

The total weighted averages are calculated only for the drivers to reduce design rework occurrence in this thesis; however, the procedure to achieve them is generic. The value reveals the product that is prone to have design rework occurrence. However, there are many drivers and sub-drivers as represented in Figure 5-2; moreover, AHP allows users to consider each product at one aspect at a time. Therefore, it is necessary to combine all effects together by beginning at the level above the alternative level.

For instance, there are three sub-drivers under the Exploitation of CAE Software driver, so the weighted average score from the individual sub-driver of each product can be combined as a matrix, as shown in Table 5-11. The new product has the strongest score against each sub-driver compared with the benchmarks. Nevertheless, each sub-driver has a different strength to the Exploitation of CAE Software driver which is each column heading, as extracted from column five of Table 5-6. However, the scores cannot identify of which the product has the most significant strength on the driver unless Eq. 5-4 is applied.

Table 5-11: Combining the alternative weighted average scores from sub-drivers under Exploitation of CAE Software driver.

Sub-drivers / Products	Benchmark CAE results (0.12)	Fundamental knowledge of product being design (0.75)	Fundamental knowledge of mathematics behind CAE tools (0.13)
New product	0.70	0.64	0.67
Benchmark 1	0.06	0.06	0.09
Benchmark 2	0.24	0.30	0.24
Total	1.00	1.00	1.00
CR	18.67%	9.13%	0.61%

$$w_T = A_D \times D \tag{5-4}$$

where w_T is the total weighted average vector for alternative products, D is the weighted average vector for alternative products considered in sub-drivers or drivers (e.g. column five of Table 5-6), A_D is the sub-driver or driver weighted average matrix (e.g. Table 5-11).

After the weighted average scores from Table 5-11 and column five of Table 5-6 are calculated with Eq. 5-4, the results are in column two of Table 5-12. This principle is necessary to carry out to other drivers as well as sub-drivers as shown in column three to seven of Table 5-12. Furthermore, the numeric values in each column which can easily be provided to the design team to evaluate internal drivers against products. For example, the Lesson Learnt is continuously improving from benchmark 1 until the new product based on the increasing of weighted average.

Each driver in the column heading has individual strength to reduce design rework occurrence, and each numeric value is obtained from Table 5-10b. Once the result matrix from Table 5-12 (A_D) is calculated with Eq. 5-4 and the weighted average vector from Table 5-10b (D), the likeliness of strength for the design rework probability of occurrence in each product can be evaluated numerically with Table 5-13 (w_T).

The new product has the most considerable weighted average score compared with both benchmark products. This scenario means the probability of design rework occurrence in the New product should be the lowest because all drivers shown in Figure 5-2 are inversely proportional to the probability of design rework occurrence; but this inference is incomplete unless it includes the effect from the Novelty Level.

Table 5-12: The weighted average score of products against drivers for reducing design rework occurrence

Products	Weighted average scores					
	Exploitation of CAE Software (0.08)	Coordination across Team Members (0.09)	Lessons Learnt (0.29)	Supplier Expertise (0.11)	Clarity of Specifications (0.35)	Open Communication to Inform Design Time Issues (0.08)
New product	0.65	0.62	0.65	0.60	0.43	0.66
Benchmark 1	0.06	0.07	0.06	0.06	0.14	0.16
Benchmark 2	0.29	0.31	0.29	0.34	0.43	0.18
Total	1.00	1.00	1.00	1.00	1.00	1.00

Table 5-13: The total weighted average scores for design rework occurrence of each product in automotive water pump case

Products	Total weighted average scores
New product	0.57 (w_{es})
Benchmark 1	0.09 (w_1)
Benchmark 2	0.34 (w_2)
Total	1.00

When the Novelty Level scores from column five of Table 5-7 are taken into consideration, the new product has the trivial Novelty Level score. Therefore, the new product should have the highest design problems risk, however, the estimation with incorperate still incomplete unless all drivers are considered in the next sub-section.

Perform estimation

The data required to estimate design rework probability of occurrence of the new product is summarised in Table 5-14. The numeric value in columns two to four are from Table 5-5, Table 5-8 and Table 5-13 consecutively, while the design rework probability of occurrence is estimated by Eq. 5-1. Even though the new product is less probable for design rework occurrence (as the score represented shown in column four) but it has the Novelty Level on an average of more than two times compared with the benchmark products (as shown in column three). Therefore, the probability of design rework occurrence is around 4.88% which is more than benchmark 2 but less than benchmark 1. It is interpreted that the issues in the testing and refinement phase would result in the design issues of roughly 4.88% of the total product supplied in the mentioned phase.

Table 5-14: The estimating design rework probability of occurrence for automotive water pump

Products	Actual probability of design rework occurrence	Estimated Novelty Level for the new product (*LN*)	Total weighted average scores for each product	w_i/w_{es}	Estimated design rework probability of occurrence for the New product
New product	Being estimated	2.44	0.57 (w_{es})		$\approx$ 4.88%
Benchmark 1	13%		0.09 (w_1)	0.17	
Benchmark 2	3%		0.34 (w_2)	0.60	

5.4 KEY OBSERVATIONS FROM DRIVERS VALIDATION AND DRePOE METHOD DEVELOPMENT

- The selected design rework drivers from Table 4-7 are initially accepted by experts that they are capable to reduce design rework occurrence in the testing and refinement phase. In addition, all drivers deliver the guidelines during validation which leads to the development of the sub-drivers.

- In terms of validating drivers to reduce design rework, selecting cases by Diverse Case technique is very propitious in strengthening initial findings from chapter 4. In addition, this technique allows the participants from different geographies, cultures, and industries to acknowledge the appropriate concrete drivers and sub-drivers. For instance, the interview results from the automotive sector are supported by findings from the aerospace sector.
- The Case study research method is suitable to apply in this chapter because it enables wide range of data sources to understand the industrial contexts.
- Thematic analysis provides the flexibility to analyse data because it endorses the researcher to use their experience to group the varieties of responses from the qualitative questions into themes. Without this technique, all drivers and sub-drivers cannot be achieved
- AHP is very useful method in developing the DRePOE method; however, the full comparison is an exhausted work to complete and impractical in real life situation as noticed by the experts from company E. So, the chain wise paired comparison is implemented and it is accepted as a realistic approach for company E's context.
- The real challenge in this chapter is to archive the data required for the DRePOE method because they are no such a system to collect in each company. However, this challenge is solved by replacing the missing document especially the probability of design rework occurrence of each benchmarh by expert's judgements. For instance, there was no FMA document for the benchmark 2 product; however, there was only the progress presentation. Therefore, the design rework probability was deducted from the report and confirmed with the experts involved in the project. On the other hand, the Benchmark 1 product has a lot of failures; so, the FMA document is available. Thus, the successfully implementation of this method is triggered the requirement for improving data archiving system.
- This method visualises the probability occurrence of the design rework issues in the testing and refinement phase. In principle, this method provides the % likeliness of design issues happening. There are several root causes on issues

transpired during the mentioned phase, e.g. design, quality. However, the attempt to classify the comprehensive list of issues is not the focus in this thesis.

- The design rework probability of occurrence limits for the overall product level, but it is not specific for a particular component.
- The limitation of this method is it requires at least one benchmark for comparison.

5.5 CHAPTER SUMMARY

This chapter completes objectives one and two. It has presented the development of the DRePOE method by starting with the validation of design rework drivers developed in chapter 4. In addition, there are sub-drivers captured during validation activities. All drivers and sub-drivers are acknowledged as a generic list for the mechanical design project.

Later, the AHP is implemented in the development of the estimation part of the DRePOE method. The traditional approach in comparing elements in AHP is replaced with the Chainwise paired comparison in order to reduce the comparison endeavors. The concept of the method and the estimation result are accepted by the experts in company E; so the hypothesis set in section 5.1.1 has initially been accepted by the participants. However, the drivers as well as sub-drivers, method assumptions and the detailed process in the method have to be validated again with two industrial case studies as represented in chapter 8. Therefore, three industrial cases are used to validate this method.

It is mentioned in earlier in this chapter that the probability and impact of design rework is the target to achieve due to a risk assessment principle. However, the probability estimated is not for a specific component but for the overall occurrence. If the design team members have the ability to review the effort required to resolve the issues, it will be very helpful for them; therefore, this challenge is overcome in chapter 6.

CHAPTER 6
THE DEVELOPMENT OF DESIGN REWORK EFFORT ESTIMATION METHOD

The aim of this chapter is to achieve research objective three which is to develop the method to estimate the design rework effort in the testing and refinement phase with taking into consideration knock-on effects. In addition, this estimation has to be performed at the early design phase. Moreover, the development in this chapter helps to interpret the design rework probability of occurrence estimated by the DRePOE method as developed in chapter 5.

After the likelihood of design rework occurrence has been obtained with the DRePOE method, the impact in terms of design rework effort required is estimated from the Design Rework Effort Estimation (DREE) method which will be developed in this chapter. The DREE method is developed to estimate the design rework effort in a worst-case scenario, which is defined as follows:

"*The worst case of design rework effort occurs when the design rework effort is more than expectation due to knock-on effects.*"

When an issue from one component forces the designers to consider another component, this is the worst-case scenario. The knock-on effect is undesirable, as supported by key observations from companies B and C. Hence, the output from this method shows the amount of design rework effort that would occur on other components. The concept of the DREE method is initiated from the recommendations as shown in Table 4-9, while some research gaps in this table become to be challenges in this chapter, as outlined in Table 6-1.

There are two novelties to overcome in challenges one and three by combining the Function Analysis System Technique (FAST), DSM, AHP and matrix algebra to obtain the "*direct*" relationships among components. Relationships are considered by a design team. It is understood that components must work together to achieve the designed functions. Challenge two relates to the method to capture design rework issues proactively; hence, the failure modes addressed in Failure Mode and Effect Analysis (FMEA) are modified by using a zigzag technique. FMEA is a good practice in industries and it is utilised to identify any potential failure modes; moreover it is continuously developed in various design projects from the earliest stage. Nonetheless, it is claimed as a novel improvement in this thesis by applying the zigzag technique to capture components' failure relationships, because this technique is modified from Axiomatic Design (AD). The failure relationships are "*not expected*" to happen in the service phase; therefore, it is preferable to find out and resolve them as early as possible. The knock-on effect among components is visualised by using the Work Transfer Matrix (WTM) method. In addition, this method is applicable in a CE environment. The methods to prevail over all challenges are summarised in Table 6-1.

Table 6-1: The summary of the developments in chapter 6

Research objective	Proposed method/methods	
To develop a methodology to estimate the design rework effort with consideration of the knock-on effect at the early design phase.	DREE method	
Challenges	Proposed methods	Sections
Literature uses direct method to capture relationships but it is difficult when implement with industries.	FAST, DSM, AHP, Matrix algebra	6.2.1, 6.2.2, 6.2.3, 6.2.5
Resolving issues found in the testing and refinement phase are reactively made.	FMEA, zigzag technique	6.2.5
There is not much literature that considers design effort and rework in horizontal direction.	DSM, WTM	6.2.4, 6.2.5

6.1 CONCEPTUAL SETTING OF THE DESIGN REWORK EFFORT ESTIMATION (DREE) METHOD

This section represents the initiative concept in developing DREE method by beginning with the hypothesis of the method. Later, the assumptions of the method are assigned in order to define the limitations of the method. Once both hypothesis and assumptions are defined, the detailed development of the DREE method can be found in section 6.2.

6.1.1 Hypothesis for developing DREE method

The hypothesis is inferred from the 'Industrial practices', as stated Table 4-9, which explains: "*The design starts from previous design or knowledge*". So, the design team should understand and extend the functionality of previous products to develop the new version for new products. Therefore, the product function should be available in the early design stage. From this point, the hypothesis is set as follows:

"*The design rework effort to resolve the problems can be assessed in the early design phase with product functions.*"

6.1.2 The assumptions of DREE method

The industrial practices from Table 4-9 are applied to develop assumptions in this method as follows:

- Total design effort and lead time are from negotiation in the early design phase. Therefore, the dead line for the start of production (SOP) is fixed.
- All components within a product are designed in a concurrent environment.
- The new design is further developed from previous products. Therefore, the product functional structure is available in the early phase of product design.

Assumption two is very importance because it is the criteria needed to develop the estimation method. Assumption one identifies the allocated design effort, as shown in section 0, while the last assumption supports the concept of the availability of product function in the early design phase as explained in section 6.2.1.

6.1.3 The experts involved in the method development

Two experts involved in this method were the same duo from chapter 5; however both of which are revisited as follows: Two experts from the automotive water pump case given by company E both of whom have experience with the automotive water pump for 30 and two years consecutively. The expert who has more has been working as CPPD Oil & Cooling, while the other is a Product Management Graduate.

6.2 THE PROCEDURE FOR THE DREE METHOD

The method was iteratively developed with the automotive water pump case from company E. However, the procedure shown in this thesis is the final version. Two experts involve in developing DRePOE method also participate in building up this method. The indirect method to acquire the relationships among components is implemented; and the major development in it is the method to combine the Functional Analysis System Technique (FAST) and the Analytical Hierarchy Process (AHP) concurrently for ascertaining the strength of the relationships, as listed in section 6.2.1 to 6.2.5. In the early trial, the researcher attempted to employ the direct method by asking the experts to signify the relationships among the automotive water pump components. It was found as a difficult task to complete. Hence, indirect method is the alternative to accomplish relationships.

FAST is the method considered purely on functions; however, it is claimed as an innovation to link FAST with the physical components as discussed in section 6.2.2. Later, the bottom most functions in FAST that links to components are assigned with the relationship strengths by the AHP technique. Once the numerical strengths are defined, the matrix is manipulated by the matrix algebra to attain the component-component relationship matrix. Therefore, this is claimed as novelty two.

Novelty three is the modification of the zigzagging technique from Axiomatic Design principle in order to capture the indirect relationships among components based on failure relationships as explained in section 6.2.5. Finally, the Work Transfer Matrix (WTM) method is applied to estimate design rework effort with taking the knock-on effects into consideration (Smith and Eppinger, 1997b). The WTM is fundamentally used to estimate the overall design lead time which includes the knock-on effect. However, its concept is not new, but this is the first application to estimate design rework. Therefore, the preparation needed before estimation is result in the supplementary improvement. All stages are disclosed in section 6.2.1 to 6.2.6.

Figure 6-1 depicts the process to estimate design rework effort with the DREE method. There are five stages, as listed in each box.

There are four types of inputs in the method. Product drawing is necessary in order to develop a function-component relationship matrix. In addition, the schematic or sketch drawing is more reasonable to be available in the very early design phase rather than the manufacturing drawing, because all dimensions and tolerances have obviously not been decided yet.

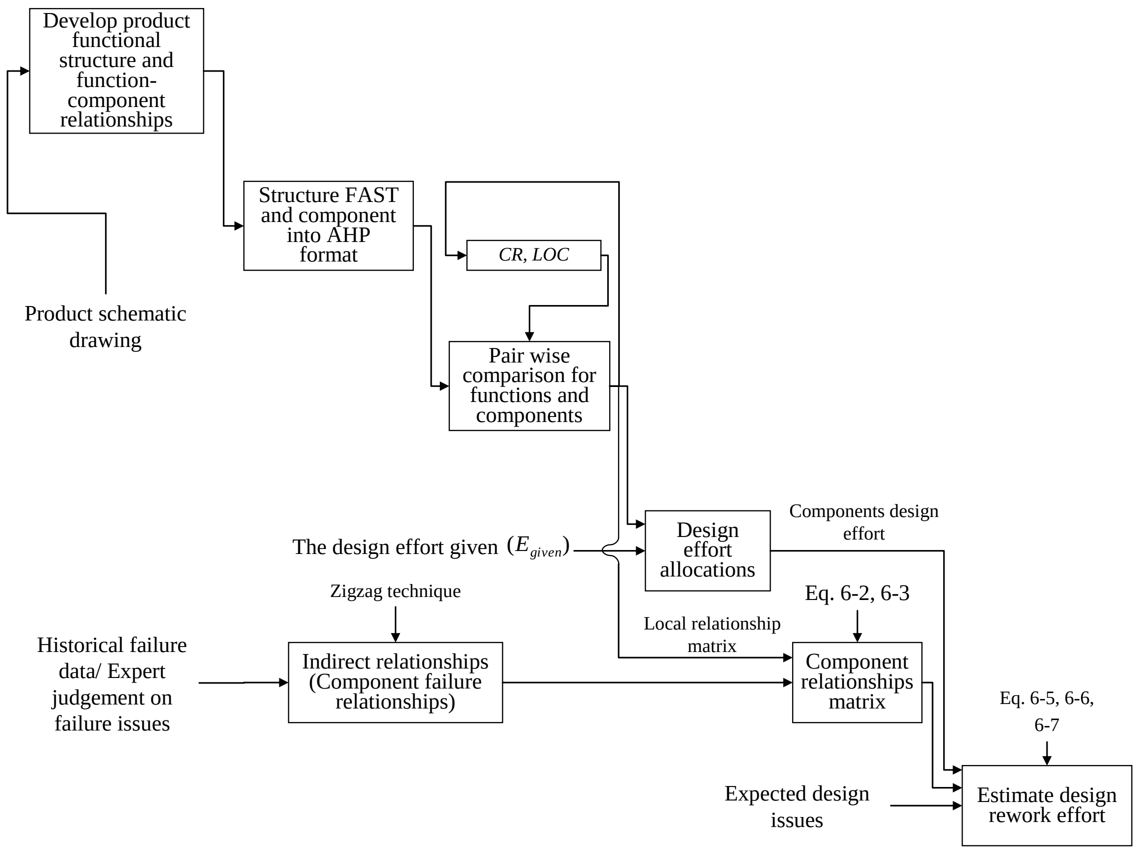


Figure 6-1: The procedure for the DREE method

The subsequent input is design effort provided which is normally assigned because it has been found in industrial practices that design lead time and effort are always set by managements. In addition, the design lead time and effort are interchangeable. To generate component relationship matrix, the component failure relationships are necessary and they are obtained by the root causes analysis of historical failure records or from experts' judgements. The final input required is the expected design issues from which are of those components that the design team still do not assure from the design issues. The main feedback in the method is reviewing the consistency of scoring (*CR*, *LOC*) after the pair-wise comparisons are applied.

In summary the required resources to perform the DREE method are summarised as follows:

- The product schematic drawing is must be provided in order to develop product functional structure.

- The experts who have experience in the product being design are needed to develop FAST and scoring the relationship strength. Moreover, they must provide their judgement in failure relationship development, as well as to critic on the quality of estimation.

A failure relationship list must be completed from either FMEA document or other failure records, otherwise design issues must be derived from expert's opinion.

6.2.1 Develop product functional structure and function-component relationships

This stage is the first step to analyse relationships among components indirectly. There are two sub-stages to be developed which are product functional structure and function-component relationships.

Rationales to select FAST to develop method

There are several techniques to structure product functions as discussed in section 2.3; however, the Functional Analysis System Technique (FAST) (Bytheway, 2007) is selected based on the reasons as follows:

- The method is well known and recognised in Value engineering.
- It makes the functional decomposition generic process to every product.
- There is an opportunity to improve the method by connecting functions with components as shown in the sub-section before section 6.2.2.
- The functional structure completed with FAST has the potential to be combined with AHP technique as explained in section 6.2.2.

Develop product functional structure

This exercise is completed with the feedbacks from the experts in terms of verification the product functional structure. It is initially derived from the schematic drawing of the previous products (Figure 6-2), as stated in assumption one. Delivering coolant to the engine is the ultimate requirement of which it is satisfied by an impeller type water pump. In FAST technique, there are two types of functions, basic and support functions.

Basic function is the function in which without it there is no need to perform other functions; therefore, Deliver-coolant function is the top level basic function. Beginning with the basic function, the functional structure can be decomposed into a lower level. Support functions sustain other functions to perform successively or reliable.

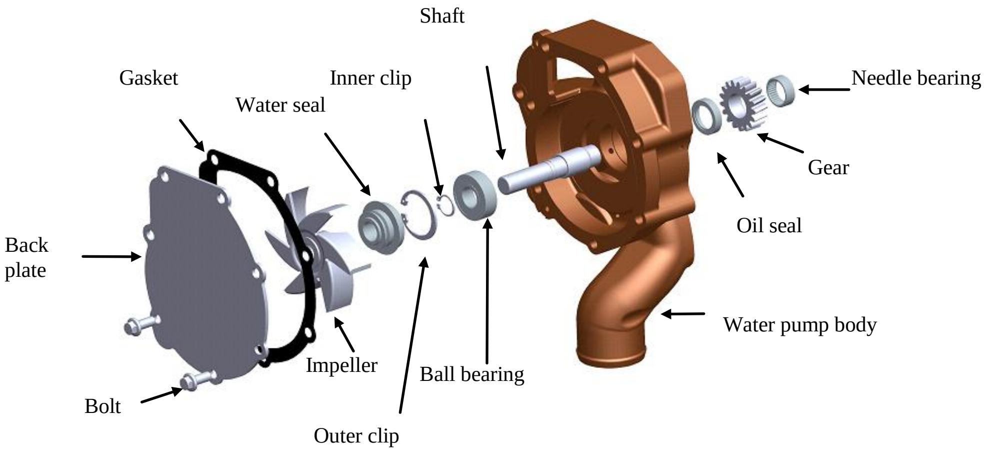


Figure 6-2: Schematic drawing of the automotive water pump

Each function is named by a verb-noun combination. Guidelines for verb and noun are obtained from Table 2-2 and Table 2-3. FAST for the automotive water pump is shown in Figure 6-3. The functional structure is developed from left hand side and expanded to the right hand side. The left most function is a basic function previously mentioned. A function on the right hand side explains how to achieve the adjacent left hand side function. Therefore, reading from left to right is explaining how to achieve the function on the left hand side, while reading from right to left is providing the reason of existing for functions on the right hand side. For example, the Contain-coolant function could be satisfied by achieving the Prevent-coolant and the Store-coolant functions. The Accelerate-coolant function exists because it helps the Increase-velocity function to accomplish. Reading from top to the bottom shows the sequence of functions. From Figure 6-3, the solid line represents the primary linkage of basic functions, while the dash line exposes support functions. One common guideline is that the functional decomposition must be maintained from the left to the right hand-side until it cannot be perfomed, and then stopped. For instance, there are five functions required to achieve the Deliver-coolant function. These five functions are ranked based on the chronological circumstances on how the product operates to achieve the adjacent left hand side function. A water pump needs to input coolant (Input-coolant) and keep it in a confined cavity of the water pump (Contain-coolant). Later, the energy is transferred to the coolant by increasing velocity (Increase-velocity), and then the velocity is decreased in order to convert the velocity head into pressure head (Decrease-velocity). Finally, the coolant is delivered to the engine (Output-coolant). This principle is applied to the lower level functions until FAST's completion. This exercise is carried with the automotive water pump experts. Subsequently, the function-component relationship matrix is completed as represented in Table 6-2.

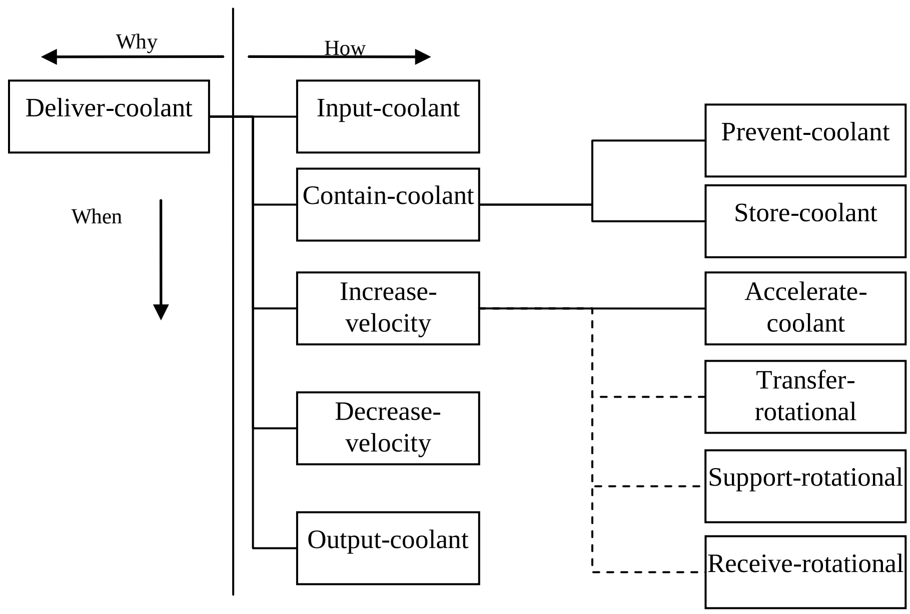


Figure 6-3: FAST for an automotive water pump from company E

Develop function-component relationships

Once FAST is completed, it is converted into a matrix format against components as revealed in Table 6-2. All components in the column heading are ordered by using experts' knowledge in terms of the sequence in designing the water pump. In this case, the experts had to answer which components would work to achieve a considered function.

For instance, the Accelerate-coolant function is achieved by the Impeller and Water pump body as signified by × in Table 6-2. The capital alphabets A-I represent groups of components to achieve the considered function as explained in section 6.2.3.

6.2.2 Structure FAST and components into AHP format

The pair-wise comparison applied in chapter 5 is also implemented in this method. Therefore, structuring FAST and components in AHP format is necessary. Considering Figure 6-3, if the FAST is rotated by clockwise direction upto 90 degree, the structure is similar to an AHP structure as represented in Figure 6-4.

In addition, the boxes embedded with capital letters in the bottom level are the representative for components groups of which they work for a particular function as signified in Table 6-2. For instance, the Support-rotational function has 'F' in bracket, and there are the water pump body, ball bearing, needle bearing and inner clip working in unison to achieve the"support-rotational" function. Once the AHP structure is completed, it is ready to perform pair-wise comparison.

Table 6-2: Function-component relationship matrix for the automotive water pump case

Sub-functions		Components												
Level 1	Level 2	Gear	Impeller	Water pump body	Ball bearing	Needle bearing	Shaft	Water seal	Oil seal	Outer clip	Inner clip	Gasket	Back plate	Bolt
Input-coolant (A)				×										
Contain-coolant	Prevent-coolant (B)			×				×	×	×		×	×	×
	Store-coolant (C)			×								×	×	×
Increase-velocity	Accelerate-coolant (D)		×	×										
	Transfer-rotational (E)						×							
	Support-rotational (F)			×	×	×					×			
	Receive-rotational (G)	×												
Decrease-velocity (H)				×										
Output-coolant (I)				×										

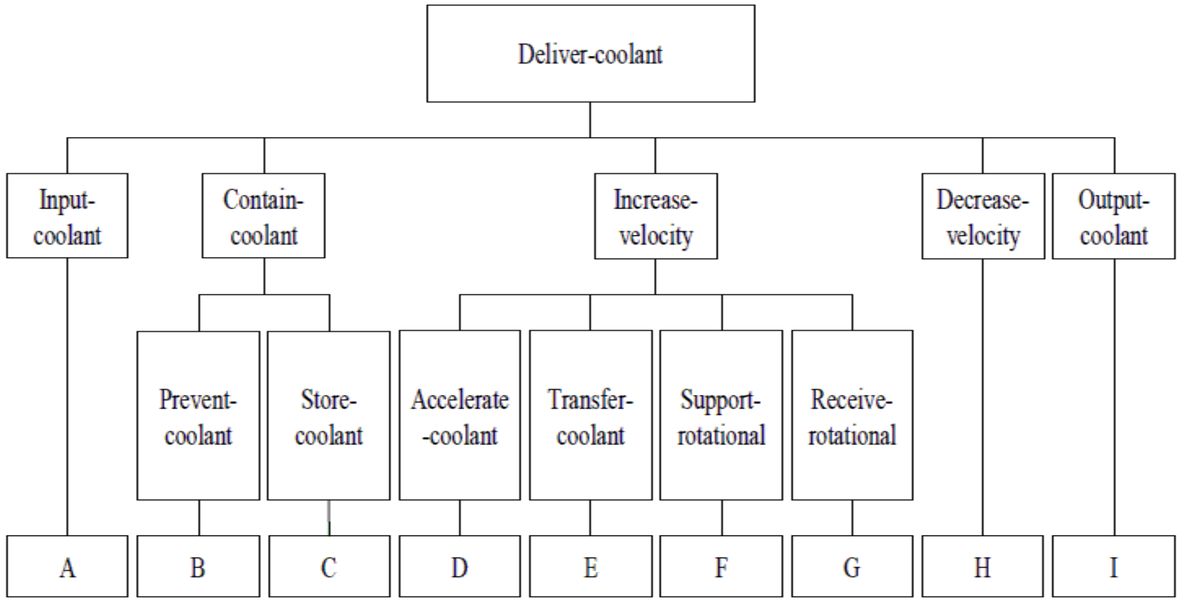


Figure 6-4: The AHP structure for FAST and components supported water pump functions

6.2.3 Pair-wise comparisons for functions and components

Rationales to select AHP technique for comparisons

This is the crucial step to combine FAST and AHP together; furthermore, it is claimed as novelty development in this thesis, because each function in FAST is subjective. So, only AHP is suitable to measure them.

The procedure to obtain function and component relationship strengths

The comparisons are asked of which function/component takes more effort to design in order to complete the above level function, as shown in the example of the spread sheet, Figure 6-5. This is the example from sub-function under the Increase-velocity function, and there are in total four sub-functions under this function. In the spread sheet, the fist question to be judged is of which function arrogates more effort and then the level of strength has to be decided.

The intention of this activity is to define the level of effort absorbed for a particular function or component. In addition, the scores define as the strengths of relationships. During the development, the full pair-wise comparison had been applied; however, the chain wise paired comparison was implemented in later cases. All comparison results are in Appendix E. There are two types of relationships; local and global relationships. The results from comparisons are in Table 6-3.

Local relationships

The local relationships are signified with the in-italic numeric in Table 6-3. They are considered on an immediate upper function. For example, the Contain coolant function is achieved by considering the Prevent-coolant and the Store coolant functions both of which recieve the design effort for 0.8333(83.33%) and 0.1667(16.67%). Hence, the aggregate scores of local relationships are always equal to 1. Comparable principle is applied to allocate design effort on components. For instance, the Water pump body, Ball bearing, Needle bearing, and Inner clip are contributed design effort to obtained Support-rotational for 0.4205(42.05%), 0.2966(29.66%), 0.2293(22.93%), and 0.0536(5.36%). The local relationships are developed to be a component relationship matrix, as explained in section 6.2.5.

Global relationships

The global relationships appear as the italic values in Table 6-3. The measurement of spending effort to achieve the Deliver-coolant function is represented by this type of relationship. A global relationship score for a particular function/component is calculated by Eq. 6-1. However, all sub-functions in level 1 are under the basic function, so both global and local scores for them are equal.

$$Gs_i^j = Gs^{j-1} \times Ls_i^j \quad (6\text{-}1)$$

where Gs^{j-1} is the global relationship score for the adjacent upper function, Ls_i^j is the local relationship score for the considered function, Gs_i^j is the global relationship score for a considered function/component.

For example, Prevent-coolant is the function under the Contain-coolant function; therefore the global relationships score is 0.0942(0.1131×0.8333), and it is interpreted that the design effort spent on the Prevent-coolant function equals to 9.42% of total effort. Eq. 6-1 is also capable to calculate global relationships in component level. For instance, the global relationship score for the Accelerate-coolant function is 0.1692; so the scores for the Impeller is 0.0846(0.1692×0.5000). The cumulative global relationship scores gathered from component level are equal to one; therefore, the global relationship scores for components represent the percentage of the design effort in comparison to the total design effort of the considered product. Hence, the global relationships are to allocate components' design effort as represented in section 0.

Functions	Please answer in pair	Functions	Yes	No	Equal
Accelerate-coolant	spends more effort than	Transfer-rotational	☑	☐	☐
Accelerate-coolant	spends more effort than	Support-rotational	☐	☑	☐
Accelerate-coolant	spends more effort than	Receive-rotational	☑	☐	☐
Transfer-rotational	spends more effort than	Support-rotational	☐	☑	☐
Transfer-rotational	spends more effort than	Receive-rotational	☐	☐	☑
Support-rotational	spends more effort than	Receive-rotational	☑	☐	☐

a)

A	Please answer one									B	Status
	A spends more effort than B										
	Equal		Moderate		Strong		Very Strong		Extreme		
Accelerate-coolant	Please score	☐	☑	☐	☐	☐	☐	☐	☐	Transfer-rotational	Correct
Support-rotational	Please score	☐	☑	☐	☐	☐	☐	☐	☐	Accelerate-coolant	Correct
Accelerate-coolant	Please score	☐	☑	☐	☐	☐	☐	☐	☐	Receive-rotational	Correct
Support-rotational	Please score	☐	☑	☐	☐	☐	☐	☐	☐	Transfer-rotational	Correct
Transfer-rotational	TRUE	☐	☐	☐	☐	☐	☐	☐	☐	Receive-rotational	Correct
Support-rotational	Please score	☐	☑	☐	☐	☐	☐	☐	☐	Receive-rotational	Correct

b)

Figure 6-5: The example of spread sheet for pair-wise comparisons for sub-functions under Increase velocity function a) Decision on the higher strength factor b) Scoring the strength

Table 6-3: Function-component relationship matrix with relationship strengths for the automotive water pump

Basic function	Sub-functions		Weighted average for each component												
	Level 1	Level 2	Gear	Impeller	Water pump body	Ball bearing	Needle bearing	Shaft	Water seal	Oil seal	Outer clip	Inner clip	Gasket	Back plate	Bolt
Deliver – coolant 1	Input-coolant 0.0801				1, *0.0801*										
	Contain-coolant 0.1131	Prevent-coolant 0.8333, *0.0942*			0.1448, *0.0136*				0.2755, *0.0260*	0.1373, *0.0129*	0.0545, *0.0051*		0.1739, *0.0164*	0.1713, *0.0161*	0.0427, *0.0040*
		Store-coolant 0.1667, *0.0188*			0.3205, *0.0060*								0.3205, *0.0060*	0.2848, *0.0054*	0.0741, *0.0014*
	Increase-velocity 0.5985	Accelerate-coolant 0.2827, *0.1692*		0.5000, *0.0846*	0.5000, *0.0846*										
		Transfer-rotational 0.1220, *0.0730*						1, *0.0730*							
		Support-rotational 0.4732, *0.2832*			0.4205, 0.1191	0.2966, 0.0840	0.2293, 0.0649					0.0536, 0.0152			
		Receive-rotational 0.1220, *0.0730*	1, *0.0730*												
	Decrease-velocity 0.0989				1, *0.0989*										
	Output-coolant 0.1095				1, *0.1095*										

6.2.4 Design effort allocations

In practices, the automotive water pump is designed and developed in parallel with the engine. If it is considered as a stand alone project, it is expected to spend one year by two engineers working full time. This time period assigned to the design project is presumably provided from the management as stated in Table 4-9 (the top cell of column three). Once the working standard in the UK has been applied, the design effort for the automotive water pump in terms of hours is summarised in Table 6-4.

Table 6-4: The total design effort given for automotive water pump given from company E

Items	Quantities	Units
Provided lead time	1	Year
Staff required	2	Engineers
Working hours	8	hours/day
Working days	5	Days/week
Working weeks (except holiday)	46	weeks/year
Total design effort given (E_{given})	$2 \times 8 \times 5 \times 46 = 3{,}680$	Hours

The aim to design a water pump is to achieve the Deliver-coolant function which is equal to one unit, as shown in column one of Table 6-3. From AHP principle, the aggregation of the scores is equal to one so as to the global relationship scores from the component levels. Therefore, the design effort allocation for each component is completed by multiplying E_{given} to the components' global relationship scores from Table 6-3 and the results are in Table 6-5. It is possible that a component can work for more than one function. Therefore, designing a component is related to what function the experts are thinking of. As a result, the design effort for each component is collectively displayed in the bottom row of this table. All allocated design effort are approximately exhibited; hence they are all visualised as integer. The water pump body requires the naximum design effort from six functions (1,884 hours).

Table 6-5: The allocated design effort matrix from the given design effort (E_{given}) for automotive water pump

Basic function	Sub-functions		Weighted average in components												
	Level 1	Level 2	Gear	Impeller	Water pump body	Ball bearing	Needle bearing	Shaft	Water seal	Oil seal	Outer clip	Inner clip	Gasket	Back plate	Bolt
Deliver – coolant (3,680)	Input-coolant				295										
	Contain-coolant	Prevent-coolant			50				96	48	19		60	59	15
		Store-coolant			22								22	20	5
	Increase-velocity	Accelerate-coolant		311	311										
		Transfer-rotational						269							
		Support-rotational			438	309	239					56			
		Receive-rotational	269												
	Decrease-velocity				364										
	Output-coolant				403										
Sum			269	311	1884	309	239	269	96	48	19	56	83	79	20

Note: Hour is the unit applied in this table

6.2.5 Component relationship matrix

This section is to develop a component relationship matrix. There are two types of relationships; direct and indirect relationships. There are two novelties in this sub-section. This thesis proposes the indirect method to acquire the component-component relationship matrix by modifying the function-component relationship matrix from section 6.2.3. Another novelty is applying Failure Mode and Effects Analysis (FMEA) in order to identify indirect relationships.

The direct relationships only show the components which work together to deliver a particular function; while the indirect relationship is not for this particular purpose. The indirect relationships in this thesis are defined as failure relationships. The detailed discussion for these two types of relationships is as follows:

Rationales to select techniques to develop component direct and indirect relationships

Direct relationships: Function-component relationship matrix is converted to be the component-component relationship matrix by matrix multiplication (Tumer and Stone, 2003) as represented in Eq. 6-2. This approach is realised as indirect method and the rationale to select this approach is as follows:

- The indirect approach is easier than the direct method. The researcher experienced this statement during developing the component-component relationship matrix by the direct approach. The automotive water pump experts were in the difficult situation to assign the component relationships.
- There is the opportunity to develop the indirect approach. The existing literature signifies function-component relationships by binary, while this thesis proposes AHP to provide the strength of relationships which is more meaningful.
- The acquired matrix always in a square matrix and it meets the requirements for the WTM method as revealed in section 6.2.6.

Indirect relationships: It is claimed that this is the first endeavour to develop failure relationships among component by applying the “zigzag” technique from the Axiomatic Design method. The rationales to select this method are as follows:

- The researcher observes that the automotive water pump project has the design rework issues on ball bearing due to torsional activity which is the axial force interaction among components. In addition, the relationships in this class are signified in the direct relationship matrix. Hence, this finding supports the need to develop the method to capture indirect relationships due to failures.

- There is a research gap in terms of identifying failure relationship among components which is not addressed in literature, as discussed in section 2.5.1. The zigzag technique is to develop components hierarchy in design activity; however, it is quite resembled to what the researcher looking for. Hence, this technique is selected to capture failure relationships.

Develop component direct relationships

The relationships are evaluated from components which deliver a particular function. The components that have numeric values in the same row of Table 6-3 are directly related together. For instance, the Water pump body and Impeller work together to complete Accelerate-coolant function. However, a particular component can work for other functions, so Table 6-3 is not sufficient enough to indentify the direct relationships among components. Hence, the direct relationships are developed from the matrix manipulation as represented by Eq. 6-2 (Adapted from Tumer and Stone, 2003).

$$M_{direct} = FC_L{}^T \times FC_L \qquad (6\text{-}2)$$

where FC_L is function-component relationship matrix of local relationships, $FC_L{}^T$ is transpose of FC_L matrix, M_{direct} is a component-component relationship matrix.

The scores in FC_L show the local relationships as shown in Table 6-3. The result for M_{direct} is shown in Table 6-6 as non-highlighted cells, while others are indirect relationships. The greater numeric value means the stronger relationships.Table 6-6: Component-component relationship matrix for automotive water pump given from company E

Table 6-6 transpires the component-component relationship matrix to convert into a DSM obtained by Eq. 6-2. The numeric values in the diagonal are taken out of the matrix because each of them shows the strength of a relationship to itself which has no meaning.

Table 6-7: Component-component relationship matrix for automotive water pump given from company E

Components	Gear	Impeller	Water pump body	Ball bearing	Needle bearing	Shaft	Water seal	Oil seal	Outer clip	Inner clip	Gasket	Back plate	Bolt
Gear		0.0833		0.0833		0.0833							
Impeller	0.0833		0.2500	0.0833		0.0833	0.0833						
Water pump body		0.2500		0.1247	0.0964		0.0399	0.0199	0.0079	0.0225	0.1279	0.1161	0.0299
Ball bearing	0.0833	0.0833	0.1247		0.0680					0.0159			
Needle bearing			0.0964	0.0680						0.0123			
Shaft	0.0833	0.0833											
Water seal		0.0833	0.0399					0.0378	0.0150		0.0479	0.0472	0.0118
Oil seal			0.0199				0.0378		0.0075		0.0239	0.0235	0.0059
Outer clip			0.0079				0.0150	0.0075			0.0095	0.0093	0.0023
Inner clip			0.0225	0.0159	0.0123								
Gasket			0.1279				0.0479	0.0239	0.0095			0.1211	0.0312
Back plate			0.1161				0.0472	0.0235	0.0093		0.1211		0.0284
Bolt			0.0299				0.0118	0.0059	0.0023		0.0312	0.0284	

The interpretation for each value in component-component relationships is very important. For instance, the water pump body and the impeller have equal local relationship score to achieve the "Accelerate-coolant" function; so both components have strength of relationship 0.25. The reason is that if Water pump body has to undertake a reworking of 100% in the worst case scenario which results in a 50% of the Accelerate-coolant function that has to be reworked. This change known as a "knock-on effect" to the impeller that has strength to deliver to the function of 50% As a results, impeller has to be reworked of 0.25 (0.5×0.5), if the water pump body is faced with the worst case design issues. Hence, 0.25 becomes to be the strength of relationship between both components. Accordingly, the strengths for each pair of relationships are relied on how both components have the relationship scores to the considered function. This activity is a radical development to build up component-

component relationship matrix in this thesis. Moreover, this is the novelty method to obtain DSM indirectly for a product being design.

Develop component indirect relationships

The indirect relationships among components are developed from failure relationships which are the extended from the Failure Mode and Effects Analysis (FMEA). The failure relationship is defined as follows:

"The failure mode that occurs from the interaction among components is defined as failure relationship."

The interaction is strictly limited for mechanical load interactions in this thesis, because the case studies provided in this thesis are all mechanical components.

Moreover, the proposed method from this section is an additional development from Stone R.B. (2000). The highlighted cells in Table 6-6 are indirect relationships because they are not working together to achieve any functions. Indirect relationships are derived from a root cause analysis for each failure mode.

All indirect relationships have to be placed into the component-component relationship matrix; however, there are two sub-stages to achieve this activity; Apply zigzag technique to capture failure relationships and Assign relationships into DSM matrix.

Apply zigzag technique to capture failure relationships: The supplementary development to analyse failure modes is by modifying the "zigzag" technique from Axiomatic design method. Originally, this method is to design a product, while it is proposed to be a tool to capture all components contributing to failures in this thesis. The mechanical failure modes are focused because its failure taxonomy is well developed (Collins et al. 1976). The failure taxonomy used in this thesis is in Appendix F.

A component failure is considered as in-optimal mechanical loads from interactions among them. Analogous to the zigzag technique, the physical entities and failure modes are separated; therefore, the components and failure root causes are developed in hierarchy. There are three guidelines to apply the zigzag technique as follows:

- Always separates between failure modes and physical artefacts.
- Three separated groups must be analysed sequentially; functions, failure modes and components related to failures. It is strictly considering one function at a time and then the potential failure mode is evaluated. The failure modes can be taken either from experts' opinions or historical data. It is possible to reveal more than one failure mode; however, thinking about one failure mode at a time is required. Moreover, the other failure mode can be evaluated again at a later stage.
- Once a failure mode is captured, a component which leads to the issue has to be identified. This activity is considered as "zig" (Moving to the right). If there are many physical entities, list them all but consider one component and revisit the other.
- When the potential failed component is captured, the failure mode for that particular component must be classified and this activity is "zag" (Moving to the left). The guideline to capture potential failure modes can be derived from failure taxonomy developed from Collins et al. (1976). In addition, failure modes can be captured from experts.
- The failure mode identified from previous "zag" is possible to derive from various causes, e.g. assembly, manufacturing, functionality. If the failure is interacted among components, it is found that the loads acting on the failed component are from others. Therefore, looking at the components transferring the mechanical loads is important. All components transferring mechanical loads must be recorded. It is noticed that all components captured is performed with the "zig" activity. This is the second time for "zig". In this stage, the hierarchy of related components are structured.
- If the component hierarchy structure is completed, cease the process to capture the hierarchy structure. If it has not been satisfied, step two to five can be reviewed.

The zigzag method to capture the root causes of failure modes is exampled in Table 6-7; however, all failure modes shown are from historical records. In addition, the analysis shown in the table is derived from guidelines provided above and the result is validated with the experts. These three issues are from Failure Modes Analysis (FMA) document which is historically recorded in company E as shown in Appendix C. The challenge is the failure mode and its root causes are always mixed between component and its failure abstraction. For example, the serious issue in the testing and refinement phase was the ball bearing fatigue and the main source is from an intermittence movement generated from the gear and the impeller. This analysis is previously defined by experienced engineers. Therefore, the zigzag method is proposed to clearly differentiate component and failure modes; as a result, the failure relationships among components can be achieved.

The prototype to capture root causes of the water pump failure by the zigzag method is closely developed with the experts in the water pump design, as mentioned in section 6.1.3. The zigzag exercise was conducted by the coordination with two experts in the automotive water pump, as mentioned in section 6.1.3. The examples to identify the root cause by zigzag method are shown against the functions as follows:

<u>Prevent-coolant</u>: From Appendix C, the issue on the water seal is wear. This component is located next to the impeller. The water seal is not rotate while the impeller is moving. The hydrodynamics effect generated from the coolant prevents the direct contact between the mentioned components. However, the effect is weak when the pump is about to turn; there is high probability to have the direct contact between the concerned components. If the improper material is selected for the water seal, wear problem is inevitable. From Table 6-7, the failure mode captured from the FMA document is wear. Once the zigzag technique is applied, the analysis must begin with function. The function for the water seal is the Prevent-coolant function, and then the failure mode for this function is rephrased as "*Fail to seal against cooling leakage*". Then, the arrow is the representative of the "zig" which is searching for the direct component related to this failure mode (water seal). Once the component is identified, the characteristics of failure must be addressed by the "zag"; therefore, 'Wear' is written down. The analysis still does not finished because the component causes the failure is still covered; so another "zig" is applied to identify the impeller. Later, the reason supports that the impeller leads to wear; thereby, the "cyclic movements" is raised.

Accelerate-coolant: There are two failure issues found in this function. For the first failure mode, the water pump fails to pump the coolant because it cannot hold its position. This failure mode emerged at the very early design process. The impeller cannot hold its position on because of surface fatigue at its cavity which is to assembly the shaft and impeller together. The surface fatigue occurs because of the tangential movement transmitted from the gear, and it is designed with the helical shape of which provides the strong tangential force. When the diesel engine begins to move, the automotive water pump is intermittency driven by the gear train. However, the solution for this failure is relatively effortless because the tolerance is the only modification.

The second failure mode is fatigue at the Impeller blades. Again the gear is the major source of intermittence movement. Once the zigzag technique is applied in analysis, the results from both failure modes are illustrated in Table 6-7.

Support-rotational: The ball bearing was the serious issue in benchmark 1 as stated earlier. Not only the gear transmits the torsional load to the ball bearing but also the impeller. The trust induces from the impeller movement; moreover, this force is acting in tangential direction. Therefore, the analysis on this issue is critical for company E in order to select the optimised the ball bearing.

Assign relationships into DSM matrix: The hierarchy of components contributed to failures are put into the DSM. The guidelines to transfer the failure relationships captured into matrix are as follows:

- If there is a relationship between a pair of components between the adjacent levels, signify 1 in the co-joint cell symmetrically.
- The relationship is not considered among the components in the same level.
- If there are other relationships between components from other failure modes, the numeric value in the cell can be increased equally to the repetitive amount.
- If the relationship is similar to the direct relationship, there is no need to signify it into the matrix, because the relationship has already been captured based on functions.

Table 6-8: The analysis for the automotive water pump's component failure relationships

Functions (Obtained from FAST)	Detailed analysis for failure modes	Components related to failures
Prevent-coolant	Fail to seal against coolant leakage Surface fatigue/Wear Cyclic movements	zig Water seal zag Impeller
Accelerate-coolant	Fail to pump coolant at all Fail to maintain position Tangential movement Intermittences/cyclic movements	Impeller Shaft Gear
	Fail to pump coolant at all Mechanical fatigue Intermittences/cyclic movements	Impeller Gear
Support-rotational	Cannot turn at all Mechanical fatigue Torsional activity	Ball bearing Gear Impeller

The example of the DSM for the indirect relationships captured from the failure modes is shown in Table 6-8. Consider the Accelerate-coolant function in Table 6-7, the impeller is connected with the gear only one time because guideline one allows to signify the relationship between the adjacent levels only. For the Support-rotational function, the relationship between the gear and impeller is not considered at this stage, as complied with guideline two, as stated earlier.

Table 6-9: Component-component relationships due to failures for automotive water pump

Components	Gear	Impeller	Ball bearing	Shaft	Water seal
Gear		1, *0.0833*	1, *0.0833*	1, *0.0833*	
Impeller	1, *0.0833*		1, *0.0833*	1, *0.0833*	1, *0.0833*
Ball bearing	1, *0.0833*	1, *0.0833*			
Shaft	1, *0.0833*	1, *0.0833*			
Water seal		1, *0.0833*			

From zigzag analysis in Table 6-7, there are no repetitive relationships between any pair of components; therefore, all of them are considered as one, as shown in Table 6-8. The Italic numbers shown in Table 6-8 are normalised values for the indirect relationships by Eq. 6-3. The indirect relationships represent as interdependent; because they are interacted to each other.

$$R_{ij}^{k} = r_{ij} / \sum_{i=1}^{n} \sum_{j=1}^{n} r_{ij} \qquad (6\text{-}3)$$

where r_{ij} is the numeric value for each cell, R_{ij}^{k} is the normalised value for group *k* at location (*i, j*), *n* is matrix size

All indirect relationships are signified with the value "1" at the beginning. This means the worst case scenario, because all components contribute to a particular failure modes are equally important. It would be possible that the relationships would be more than one; therefore, the normalisation is necessary due to the requirement of Work Transfer Matrix (WTM) (Smith and Eppinger, 1997). This method requires the square matrix; furthermore, each relationship shown in the matrix does not exceed one. Once the indirect relationships are completed, they are put into the component-component relationship matrix as shown in Table 6-6.

6.2.6 Estimate design rework effort

Rationales to select WTM to estimate design rework effort

The design rework effort estimation is from a worst case scenario because the DREE method allows collecting all possible design rework effort from the related components. The worst case scenario occurs when there are many more effort undertaken than expected. The circumstance is eminently when design rework from one component is knocked-on to others. Nonetheless, the DREE can cover this challenge by implementing the WTM. This method requires the component-component relationship and an initial evaluation on design rework effort. However, the allocated design effort in Table 6-5 are considered all internal knock-on effects, so it is necessary to calculate the ideal design effort.

The application of WTM on the design rework effort estimation is considered as contribution in this section. Originally, this method is to prioritise design by considering a knock-on effect. The principle of WTM is a combination of matrix multiplication and a limits theorem. However, this thesis applies a method to estimate design rework effort. The input for estimation is the initial assessments of design rework effort required. In terms of explanation, the principle of WTM is explained first and then the ideal design effort and initial evaluation on design rework effort are discussed. The rationales to select this method are as follows:

- From industrial practice in Table 4-9, the design activity is concurrently derived which is fit to the WTM's assumption.
- The WTM method can model the knock-on effect very well.
- The WTM method is suitable to model interdependent design task which is similar to relationships among components.
- There are two opportunities of developments in the WTM. The previous approach to develop components relationships for the WTM is the direct method that is difficult to achieve, as discussed in section 6.2.5. This is the first endeavour to estimate design rework in the testing and refinement phase.

Apply WTM to estimate design rework effort

The WTM method is initially summarised with Eq. 6-4. $\mathrm{M}_{component}$ is the component-component relationship matrix which is developed in section 6.2.5. The u_t and the u_{t+1} are input and output effort vectors both of which have size $n \times 1$, while n is the number of components. A particular element in the vector is a representative of each component's design effort.

The multiplication in Eq. 6-4 refers to iteration during design; therefore, the design effort input vector (u_t) would lead to an additional effort which is the output vector (u_{t+1}). Each element in the output vector provides the additional effort from a knock-on effect. However, there are many more iterations during design until the design converged. So, Eq. 6-5 covers all iterations.

$$u_{t+1} = \mathrm{M}_{component} \times u_t \quad (6\text{-}4)$$

$$U = S(1-\Lambda_{component})^{-1} S^{-1} u_0 \qquad (6\text{-}5)$$

where U is the total iterative design effort vector due to knock-on effect, u_0 is initial input vector, S and $\Lambda_{component}$ are Eigen vector matrix and Eigen value for matrix $\mathrm{M}_{component}$ consecutively.

Both outputs from Eq. 6-4 and Eq. 6-5 are in a vector format because they are from the multiplication of matrix and vector. If the output from Eq. 6-4 is recalculated with the same equation until each element in the final u_{t+1} approach zero. If all vectors are aggregated, the result will reach to U . Eq. 6-5 is developt from contraining Eq. 6-4 with the limit theorem. Therefore, U is interpreted the additional design effort due to the knock-on effect. In-depth explanation can review Smith and Eppinger (1997).

The additional developments of WTM in this thesis are Eq. 6-6 and Eq. 6-7. Eq. 6-6 is to calculate Ef_{tot} in which it is the total design effort from all components.

$$Ef_{tot} = \sum_{k=1}^{n} U^k \qquad (6\text{-}6)$$

where U^k is each design effort in U vector.

From Eq. 6-4 to Eq. 6-6, the critical challenge is how to develop the vector u_0 as well as the method to assign design effort into the vector. Both challenges are explained in the sub-sequence sections.

Limitations of WTM method: The WTM method is useful when the $\mathrm{M}_{component}$ is invertible. However, there are only two situations when $\mathrm{M}_{component}$ can not be inverted (singularity matrix) which are as follows:

- There is one row of $\mathrm{M}_{component}$ filled with zero.
- In $\mathrm{M}_{component}$, there is a pair of row, e.g. *X*, *Y*; and *Y* = *nX*. *n* is real number.

Situation one cannot happen, because $\mathrm{M}_{component}$ is from the multiplication from FC_L (Eq. 6-2) and there are none rows or columns in FC_L filled with zero. For situation two, it might occur when there are at least two functions which have a similar group of components in FC_L. However, this is less likely to happen because each low level functions in FC_L has unique characteristics; as a result, each of them has a low chance to have the same group of components. Hence, $\mathrm{M}_{component}$ is assumed that it has a minimal possibility to be a singularity matrix.

Calculate the ideal design effort

It is stated earlier that the design effort expressed in Table 6-5 are iteratively considered. At this stage, it is necessary to find the ideal design effort for each component, which is very important to develop input vector u_0. The essential element for this step is to prevent an over estimation from an extreme scenario which is defined as follows

"The extreme scenario is the situation when the whole design has to be revisited all over again after the the testing and refinement phase."

This event occurs when every component has to be re-designed from scratch due to failures captured in the testing and refinement phase; however, this is the ideal situation. It means u_0 will be filled with the transpose of the bottom most row of Table 6-5; and definitely the Ef_{tot} for extreme scenario $(Ef_{extreme})$. The result will mathematically exceed the total design effort given (Ef_{given}) e.g. 3,680 hour (from Table 6-4). This extreme case is not valid in reality, because the design rework effort should be not more than Ef_{given}. The ideal design effort is calculated with Eq. 6-7.

$$E_{ideal} = \left({Ef_{given}} \big/ {Ef_{extreme}} \right) \times E_{FC} \tag{6-7}$$

where E_{FC} is the allocated design effort matrix from the design effort given (Table 6-5), E_{ideal} is the ideal design effort matrix.

The $Ef_{extreme}$ is derived with Eq. 6-6, as shown in column three the bottom cell of Table 6-9b. Eq. 6-4 is implemented in this calculation, therefore, the $S(1-\Lambda)^{-1}S^{-1}$ and u_0 in the extreme case are required, as listed in Table 6-9a and b. The Eigen vector and Eigen value of $\mathrm{M}_{component}$ are shown in Appendix F. From Table 6-9b, it is shown that

$Ef_{extreme}$ is more than Ef_{given}, as explained earlier. The $Ef_{given}/Ef_{extreme}$ is 0.4992 and it is necessitated in Eq. 6-7.

Table 6-10: Calculating $Ef_{extreme}$ for automotive water pump a) Matrix for $S(1-\Lambda)^{-1}S^{-1}$ of $\mathrm{M}_{component}$ b) u_0 and U vector for extreme case

(a)

1.0259	0.1140	0.0446	0.1014	0.0112	0.0950	0.0120	0.0017	0.0007	0.0028	0.0072	1.0259	0.1140
0.1140	1.1195	0.3199	0.1456	0.0409	0.1028	0.1117	0.0131	0.0053	0.0100	0.0531	0.1140	1.1195
0.0446	0.3199	1.1629	0.1844	0.1251	0.0304	0.0912	0.0349	0.0141	0.0307	0.1753	0.0446	0.3199
0.1014	0.1456	0.1844	1.0500	0.0895	0.0206	0.0224	0.0059	0.0024	0.0219	0.0282	0.1014	0.1456
0.0112	0.0409	0.1251	0.0895	1.0183	0.0043	0.0104	0.0038	0.0015	0.0167	0.0189	0.0112	0.0409
0.0950	0.1028	0.0304	0.0206	0.0043	1.0165	0.0103	0.0012	0.0005	0.0011	0.0050	0.0950	0.1028
0.0120	0.1117	0.0912	0.0224	0.0104	0.0103	1.0218	0.0440	0.0178	0.0025	0.0708	0.0120	0.1117
0.0017	0.0131	0.0349	0.0059	0.0038	0.0012	0.0440	1.0041	0.0091	0.0009	0.0351	0.0017	0.0131
0.0007	0.0053	0.0141	0.0024	0.0015	0.0005	0.0178	0.0091	1.0007	0.0004	0.0142	0.0007	0.0053
0.0028	0.0100	0.0307	0.0219	0.0167	0.0011	0.0025	0.0009	0.0004	1.0012	0.0046	0.0028	0.0100
0.0072	0.0531	0.1753	0.0282	0.0189	0.0050	0.0708	0.0351	0.0142	0.0046	1.0466	0.0072	0.0531
0.0067	0.0496	0.1628	0.0263	0.0175	0.0047	0.0691	0.0344	0.0139	0.0043	0.1526	0.0067	0.0496
0.0019	0.0140	0.0462	0.0075	0.0050	0.0013	0.0192	0.0095	0.0038	0.0012	0.0433	0.0019	0.0140

(b)

Components	Design rework effort vector for extreme case (hours)		$Ef_{given}/Ef_{extreme}$	Ideal design effort for each component (hours)
	u_0	U		
Gear	269	457	0.4992	134
Impeller	311	1085		155
Water pump body	1883	2438		940
Ball bearing	309	780		154
Needle bearing	239	529		119
Shaft	269	397		134
Water seal	96	334		48
Oil seal	48	131		24
Outer clip	19	53		9
Inner clip	56	130		28
Gasket	83	471		41
Back plate	79	442		40
Bolt	20	125		10
Total	3,680 (Ef_{given})	7,372 ($Ef_{extreme}$)		1,836 (Ef_{ideal})

Column five of Table 6-9 reveals the ideal design effort for each component; this column is the multiplication product of $Ef_{given}/Ef_{extreme}$ with column two of Table 6-9b. The total ideal design effort for all components (Ef_{ideal}) is approximately equal to 1,836 hours which is significantly lower than Ef_{given} (3,680 hours). So, the E_{ideal} is provided in Table 6-10. E_{ideal} is defined as the matrix of an ideal design effort for each component without internal iteration. If the design team members are highly skilled in avoiding any internal iteration, each component's design effort would be equal to each element in E_{ideal}. In real-life situation, design is an iterative process, so the real design effort is always more than the ideal effort. The E_{ideal} is directly developed to be input vector in the estimation, as shown in the sub-sequence section.

Table 6-11: E_{ideal} **for the automotive water pump**

Basic function	Sub-functions		Weighted average in components												
	Level 1	Level 2	Gear	Impeller	Water pump body	Ball bearing	Needle bearing	Shaft	Water seal	Oil seal	Outer clip	Inner clip	Gasket	Back plate	Bolt
Deliver – coolant (1,836)	Input-coolant	n/a			147										
	Contain-coolant	Prevent-coolant			25				48	24	9		30	30	7
		Store-coolant			11								11	10	3
	Increase-velocity	Accelerate-coolant		155	155										
		Transfer-rotational						134							
		Support-rotational			219	154	119					28			
		Receive-rotational	134												
	Decrease-velocity	n/a			182										
	Output-coolant	n/a			201										
Total			134	155	940	154	119	134	48	24	9	28	41	40	10

Note: Hour is the unit applied in this table

Estimate design rework effort from the expected design issues

There are two sub-stages in this sub-section: obtaining input vector u_0 and calculation by Eq. 6-5. The detailed procedures to estimate design rework effort are as follows:

Develop input vector u_0 by using expected design issues: The expected design issues are from the components considered that have the high possibility to be reworked. They can be from various sources as follows:

- They are from the components which the design team members have less confidence in terms of achieving the design requirements. Moreover, these issues can be realised as either from historical data or from the team's judgements. If they are complied from historical data, it means the design team is still not sure how to resolve the problems in the new design.

- The issues captured from FMEA analysis. The failure modes should be selected from which the design team has less assurance to proactively prevent the problems e.g. issues from high detection scores.

In this case study, the expected design issues are from the FMA document which is historically recorded. However, the first failure mode from the Accelerate-coolant function was not considered because it was an effort less task for the expert to solve the problem. The benefit of using historical data is that it is relatively easy to validate not only a method's logic but also the estimated result. After the expected design issues have been captured, the sub-procedures to develop input vector are as follows:

- Identify of which function the considered component belongs to.
- Signify the percentage of design effort for each component from its original effort to deliver a particular function.

It is important to identify the function which the failed component belongs to, because a particular component can deliver to more than one function. The percentage signified on each component will be calculated each numeric value in the input vector u_0 by multiplying with the ideal design effort of the considered component, as shown in E_{ideal}. Figure 6-6 shows the example of these sub-procedures in EXCEL.

The input vector u_0 is obtained automatically after signifying the percentage due to the power of EXCEL spread sheet. It is assumed that all design issues are solved concurrently after the testing; therefore the DREE method allows a combination of more than one issues in estimating design rework effort at a time.

Failure Modes	Components	Functions								
		Input-coolant	Contain-coolant		Increase-velocity				Decrease-velocity	Output-coolant
			Prevent-coolant	Store-coolant	Accelerate-coolant	Transfer-rotational	Support-rotational	Receive-Rotational		
	Gear									
Fatique	Impeller				10					
	Water pump body									
Fail due to torsional activity	Ball bearing						30			
	Needle bearing									
	Shaft									
Leak from improper material	Water seal		60							
	Oil seal									

Section 1 / Section1.1 / Section1.2 / Section 2 / Section2.2 / Section 2.3 / Section 2.4 / Indrect / **Issues** / Allocation

Figure 6-6: The example of spread sheet to develop the input vector u_0

From Figure 6-6, the failure modes are assigned against components and functions. There are three issues related to design: Fatigue, Failure due to torsional activity and Leak due to improper material selection, all of which are from the FMA document. In addition, all failures are from the impeller (10%); the ball bearing (30%) and the water seal (60%) consecutively. The percentage is considered from designing the component to achieve the particular function. For example, the impeller is to achieve the Accelerate-coolant function, so that 10% is the percentage to complete the mentioned function. Once the related functions are identified as well as the judgment on design rework effort, the input vector u_0 is completed, as shown in Table 6-11.

Table 6-12: The input vector u_0 and the estimated design rework output vector U for automotive water pump

Components	Expected design issues	Percentage judged to resolve issues	Design effort vector for the expected issues (hours)	
			u_0	U
Gear			0	6.87
Impeller	Fatigue (Accelerate-coolant)	10%	15.54	27.87
Water pump body			0	16.56
Ball bearing	Failure due to torsional activity (Support-rotational)	30%	46.29	51.63
Needle bearing			0	5.12
Shaft			0	2.89
Water seal	Leak (Prevent-coolant)	60%	33.38	36.88
Oil seal			0	1.94
Outer clip			0	0.78
Inner clip			0	1.26
Gasket			0	4.50
Back plate			0	4.29
Bolt			0	1.20
Total			95.21 ($Ef_{expected}$)	161.79 ($Ef_{estimated}$)

From Table 6-11, U is calculated from the input vector u_0 with Eq. 6-5 as well as the constant matrix (Table 6-9a). In addition, the calculation is carried out with the MATLAB software because an EXCEL spread sheet has no capability to calculate Eigen value and Eigen vector. Moreover, the knock-on effects to other components due to design rework on three issues are shown in column five (vector U). This table visualises a worst case scenario in terms of design rework effort required.

It seems that the major part of the estimation is not from the knock-on effects from the automotive water pump case but from the judgement on the expected design issues. However, the estimated design rework effort depends on three important factors as follows:

- Number of components in the input vector. The many more components lead to the greater design rework effort.
- The significant the percentage assigned to the judgement will increase the level of design rework effort required.
- The relationships among components are positively related to the level of design rework effort. Either the number of relationships or the stronger level of relationships strength influences on the design effort required.

Hence, the design rework from knock-on effect is possible to be more than the initial estimation. Even though the worst case inferred that all components need to be re-considered, but this situation does not interpret that every components must be reworked. The real meaning of the design rework effort due to knock-on effect is that the designers should be at least thinking about them during resolving all three design issues. In a real-life situation, designers prefer to confine the issues within the failed components; however, they should at least concentrate on the thinking effort in conjunction to other components to prevent the knock-on effect.

6.3 CONNECT THE DRePOE AND DREE METHODS

There are two points in this section. Converting design effort to design lead time in order to validate the estimated results with experts is the first activity revealed in this section. The latter sub-section is illustrating the connection between of the DREE method in this chapter and the DRePOE method from chapter 5. The details for both methods are as follows:

6.3.1 Convert design rework effort to design lead time

As mentioned in section 2.1, the design effort and the lead time are interchangeable. For company E, even though the team consists of many members, each team's individual would belong to more than one project team. So, the effort to resolve design issues for a particular product is assumed to be equal to one person working full time.

The working standards from Table 6-4 are still implemented, so the lead time to determine all design issues is shown in Table 6-12, which is approximately one month. The estimated lead time shown is expressed as a worst case scenario to resolve issues and it does not include the re-testing period. However, the lead time to resolve design rework issues would be lower than the estimated results, if the design team decides to instigate more human resources to resolve the problems.

Table 6-13: Lead time for resolving design issues for automotive water pump case

Items	Quantities	Units
Estimated design effort	161.79 $(Ef_{estimated})$	Hours
Lead time for one engineer	$161.79 \div 1 \approx 161.79$	Hours
Convert to be working day (8 hours/day)	$161.79 \div 8 \approx 20.22$	Days
Convert to be working week (5 days/ week)	$20.22 \div 5 \approx 4.04$	Weeks
Convert to be working month (4 weeks/month)	$4.04 \div 4 \approx 1$	Month
Worst case lead time to resolve three issues (Experts' judgement)	1	Month

The lead time is easier to validate the estimated results than the design rework effort result. For example, it is the limitation that the automotive water pump design is a small project within an engine's development project; but documentation separately for design effort of water pump project is not provided. Therefore, validating with the experts' judgement seems to be only the possible method. Hence, asking experts on how much extra time required resolving the design issues has better access than trying to retrive the hours of effort. However, the full validations with experts are shown in section 8.3.

The experts mentioned that all design issues had been resolved in UK and India, and the experts mentioned that the lead time to resolve them was approximately one month. So, the result is reasonable in the experts' point of view.

6.3.2 The association between the DREE and the DRePOE methods

This section is the interpretation of the connection between the DREE and the DRePOE methods, both of which are developed from risk assessment principle, as shown in Eq. 2-3. The estimated probability of design rework occurrence and effort required are summarised in Table 6-13.

Table 6-14: The results from DRePOE and DREE methods for automotive water pump

Methods	Results
DRePOE	$\approx 4.88\%$
DREE	≈ 161.79 Hours (1 month)

It is interpreted that the new automotive water pump being designed would have approximately 4.88% of design rework from the total supplies in the testing and refinement phase. In addition, the probability would be possible from impeller, ball bearing and water seal because they were previously noted as severe issues in benchmark 1 and the design team still has less confidence to prevent them. If they occur in the testing and refinement phase, the worst case design rework effort would be around 161.79 hours or one month lead time.

It is clearly illustrated that the probability of design rework occurrence is not specific for a particular or groups of components. However, it provides the likeliness of design rework occurrence in an overall. Hence, the judgements on components which has less confidence are come from experts' opinion.

Once the insecure components are raised, the design team would say that they have an equal probability of occurrence as estimated and the impact in terms of re-design effort is presented. Therefore, the combination of DRePOE and DREE methods are fundamentally different from FMEA in terms of assigning probability and impact o each component; but the DREE method has the advantage to evaluate the impact of design failures from the group of components.

6.4 KEY OBSERVATIONS FROM DREE METHOD DEVELOPMENT

The key observations from the development of DREE method are as follows:

- The design rework effort assessment can be achieved in the early design phase as hypothesised, if the process to estimate follows every single step in the DREE method, as developed in section 6.2.
- Two key successes in this method are composed of developing the indirect method to attain components' relationships by functions (direct relationships), and obtaining components' failure relationships (indirect relationships). In addition both of them are further developed from literature.
- The design effort allocation for each component and function, which has a stronger supporting logic than "guess", in section 0 is achieved by a standard process.
- Procuring the percentage effort for u_0 is to clearly separate the initial estimation and the design rework effort induced from knock-on effect.

- In terms of combining with the result of the DRePOE and the DREE methods can evaluate the impact from the design rework occurrence.
- This method can be implemented to invention products as long as its functional structure is clearly defined.
- The DREE method focuses on the estimation of the effort required to resolve the design issues. On the other hand, FMEA requires the Severity score which is a judgement on the consequences of the issue but it does not indentify the level of effort required.
- So, the DREE method focuses directly on the effort required; and it allows considering design rework effort from multiple issues. Whilst, Severity score in FMEA is a judgment upon a particular design issue.
- There are two categories of the limitations. Even though the method is well structured, it still heavily relies on experts' opinion. The method reaches to its limits when there are completely no qualified team members. The mathematical limitation is another key concern when the component-component relationship matrix is a singularity matrix. Nonetheless, this situation has low chance to exist in practices, as discussed in section 6.2.6.
- Addressing the critical components into input vector to estimate design rework effort is a challenge task in this method because it is very much relied on experience.
- The Expected design rework effort ($Ef_{expected}$) is the "*optimistic*" assessment which is "*expected*" by the experts, while, the Estimated design rework effort shows the worst case or "*pessimistic consequence*" of the design issues.

6.5 CHAPTER SUMMARY

The principle of risk assessment mentioned in chapter 5 and the recommendations from Table 4-9 lead to the development of the DREE method. The hypothesis is set and then the DREE method is developed and conciliated under the set of assumptions which are initially accepted from the experts from company E. Moreover, the DREE method is validated with two additional case studies and represented in chapter 8; so there are three cases in total that validate this method.

The method combines FAST, AHP, a matrix multiplication and failure modes in the development. Developing indirect methods to capture components' relationships based on their function is a significant innovation in this chapter. Another innovation is applying a zigzag method from Axiomatic Design to consummate relationships among components based on failure modes.

The design rework effort estimation is achieved by addressing the expected failure components and providing the initial design effort for each of them; and subsequently the design rework effort with a knock-on effect are obtained. As a result, the estimated design rework effort shows the worst case scenario of the design rework issues.

The key challenge for this method is to address the expected failure components when the product is relatively new for the design team. However, this challenge is accomplished in chapter 7.

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CHAPTER 7

THE DEVELOPMENT OF PRIORITISATION DESIGN BY DESIGN REWORK EFFORT BASED METHOD

The aim of this chapter is to reach research objective four, as represented in Table 7-1. Therefore, the outcome of this method provides the design team with a warning of which components would require a huge amount of design rework effort to resolve the problems. Thus, the design team can focus them earlier in the design phase.

This method is the extended development of the DREE method by overcoming the challenge of identifying the components which are prone to deliver design rework issues, as mentioned in section 6.5, and it is set as a main challenge in this chapter. Therefore, the development of the PriDDREB method by using Pareto Analysis prevails over this challenge, as shown in section 7.1 and 7.2.1. It provides the guideline that 80% of undesirable situations clearly result from 20% of the causes. So, the huge unwanted scenario can be reduced if their root causes are addressed and eliminated in advance. In brief, the main challenge is related to the '*how many*' issues to focus, while the cascade challenge addresses '*what*' components to look for. Therefore, a combination and optimisation technique is to search for the component group that potentially provides the most significant design rework effort.

Table 7-1: The summary of the development in chapter 7

Research objective	Proposed method/methods	
To extend the methodology in the third objective to provide a warning about the components which would require the extensive design rework effort to resolve.	PriDDREB	
Challenges	Proposed methods	Sections
The method to address expected failure components or critical components.	Pareto Analysis	7.1, 7.2.1
The method to select which components are likely to produce high design rework effort.	Combination, Optimisation technique	7.2.1, 7.2.2, 7.2.3, 7.2.4

Section 7.1 sets up the conceptual requirements which are the hypothesis and assumptions of the method. All outcomes from section 7.1 are used in section 7.2. Section 7.2 develops a detailed procedure to identify critical components in terms of design rework effort and how to prioritise them; however, each sub-section leads to a

cascaded challenge, as shown in Table 7-1. Once the Pareto Analysis is applied to calculate the amount of components in each group, the components are arranged into groups in order to generate the possible component combinations. The cascaded challenge is how to select the components that potentially lead to high design rework effort in which the optimisation technique is proposed to resolve this challenge.

7.1 CONCEPTUAL SETTING FOR PRIORITISATION DESIGN BY DESIGN REWORK EFFORT BASED (PriDDREB) METHOD

The method was iteratively developed with the automotive water pump case from company E; however, the procedure shown in this thesis is final version. The concept of this PriDDREB method is to imitate the scenario when design rework issues happen in the testing and refinement phase. However, this section is to illustrate the concept in the method development. The hypothesis of the method is listed in section 7.1.1 and then the assumptions are represented in section 7.1.2, while section 7.1.3 is to identify the experts participated in this method development.

7.1.1 Hypothesis to develop the PriDDREB method

The hypothesis of this method is ultimately to assure that the huge design rework effort is potentially come from the technical issues which are apparently small. In addition, it is possible to find more than one issues in the testing and refinement phase. The hypothesis of the PriDDREB method is as follows:

"A group of components that seem to cause small technical issues are potentially creating more than expected design rework effort."

The term "*technical issues*" is captured during the method development with company E; and it is inferred to the issues specifically on iteratively design a product (mistakes, un-optimised design). Therefore, changes from markets are out control of by design team, so they are not covered in this method. If this hypothesis is true, its outcome is useful to prioritise design by stratifying on the critical components.

7.1.2 The assumptions of the PriDDREB method

The assumptions from the PriDDREB method are as follows:

- The Pareto Analysis (80/20) is applicable to explain the components which are potentially creating high design rework effort impact.
- All issues found in the testing and refinement phase are solved concurrently.
- Technical issues of design rework in the testing and refinement phase (5% of total design effort) might cause huge impacts to the whole product design project.

Assumption one is proposed to this thesis. The Pareto Analysis is well known in literature related to quality. If the 20% of components lead to high design rework impact are captured early, the risk of design phase delay due to design rework would be minimal. Assumption two is industrial practices, as illustrated in Table 4-9, while assumption three is the inference from theme 9, as shown in Table 4-2.

Theme 9 in chapter 4 is explains about the reactive action to resolve design rework issues. The researcher has tried to raise the concern on the technical issues, so, they are represented as percentage to the original design effort and 5% in the method has been proposed in order to define their characteristics. Hence, all assumptions were validated by experts especially for assumption one and three. The challenge from section 7.1.1 and 7.1.2 is the method to identify the group of components which would cause high design rework effort; however, this challenge has been resolved and the results are in section 7.2.

7.1.3 The experts involved in the method development

Two participating experts in the method development are the similar group from chapter 5; however, both experts' details are revisited as follows: Two experts from the automotive water pump case are arranged by company E both of whom have experience related to the automotive water pump for 30 and two years consecutively. The expert who has more experience has been working as CPPD Oil & Cooling, whereas the other is a Product Management Graduate, which is a trainee role in the company.

7.2 THE PROTOCOL OF THE PriDDREB METHOD

The additional development from chapter 6 is the means to put the DREE method in to optimisation. The key contributions are the assumptions proposed in section 7.1.2 because they are put into the objective function and constraints in optimisation. The detailed process of the PriDDREB method is shown in Figure 7-1.

One of the expected outcomes from this method is to resolve the challenge from section 7.1. As stated earlier, addressing the expected design issues would be a difficult task if the product being designed is relatively new to the design team. Therefore, to visualise the groups of components which would deliver a distinctively design rework effort is useful for the design team members to put their intention. Putting effort and resources to evaluate critical components in the early phase is crucial; however, scarcity is sometime inevitable. If the design team members concentrate on components which would deliver significantly design rework effort, it will be a helpful strategy.

However, identifying the critical components is questioning; hence, the Pareto Analysis (assumption one), as shown in Figure 7-1, is a candidate because it is a well known quality tool in both academics and industries. Assumption one and three controls the method in stage one and two, while assumption two allows to implement the WTM technique (Eq. 6-5) to set up the objective functions.

The PriDDREB method receives the component-component relationships and an ideal design effort matrix from the DREE method as an input which proceeds automatically with the MATLAB programming. In addition, the optimisation technique is to search for the possible biggest design rework effort from the constraints of each component group, as represented in stage three. The optimisation conducts for one component group at a time. Therefore, the feedback is to pick up the component groups until all of them are optimised. Then, the component groups can be prioritised from the greatest to the smallest design rework effort.

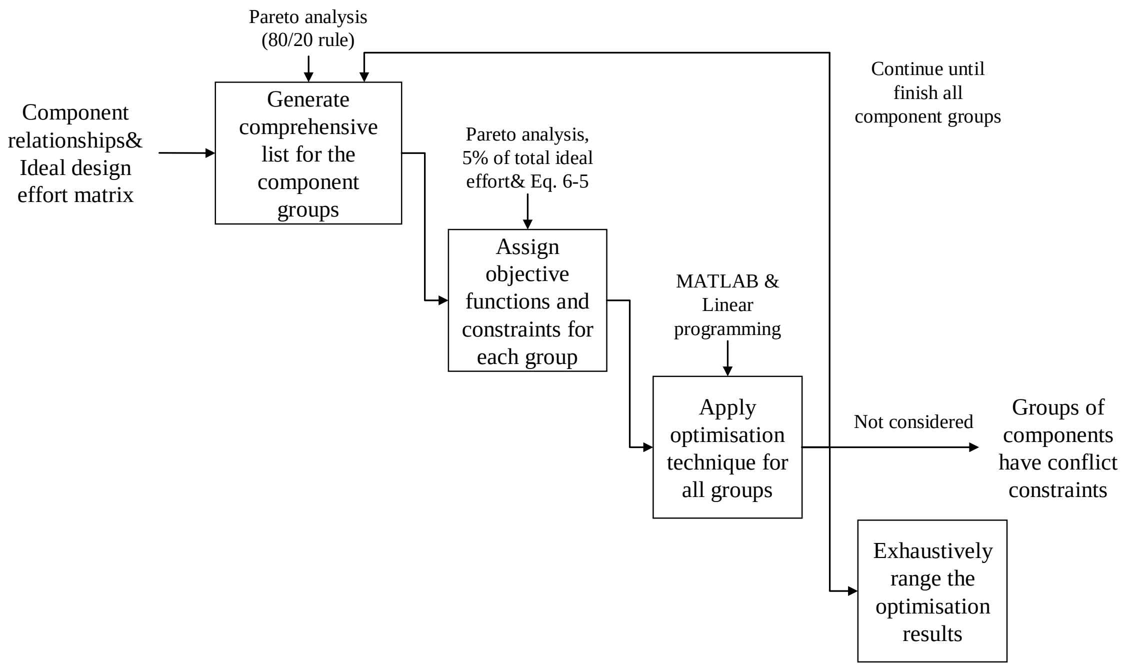


Figure 7-1: The methodology of the PriDDREB method

The human assessment involves after the last stage finished and the purpose is to confirm and interpret the prioritisation results. Even though the results are helpful in planning, it is considered as out of scope in this thesis. The detailed explanation of the method is as follows:

7.2.1 Generate possible component groups

This stage is the starting point to address the critical component which is the key challenge, as summarised in section 6.5. This thesis proposes the combination of Pareto Analysis and the exhaustively method to create the group of components in order to cover all possible critical components.

Rationale to select the Pareto Analysis to set up the component groups

The rationales to select the Pareto Analysis are as follows:

- In practice, it is possible that there are more than one design rework issues in the testing and refinement phase, and the knock-on effect which would lead to unexpected design rework effort is one of the most undesirable situations. Moreover, addressing such the components precisely in the very early design phase is the ambition. Whilst, Pareto Analysis is the approach to focus the components that lead to high impact. So, it is suitable to set the critical component groups especially when the knowledge in the product being design is not fully understood.

- The Pareto Analysis is the well known approach in both academics and industrial sectors.

The detailed sub-sections to achieve the comprehensive list of component groups are as follows:

Calculate the component number in each group with the Pareto Analysis

This sub-section is the first step to find the critical components by the Pareto Analysis. The critical components are defined as follows:

"The critical components are those tend to required significant amount of design rework effort to resolve the issues"

This thesis proposes to implement the Pareto Analysis to define the number of critical components by searching for the 20% of the total components which they potentially create high amount of design rework effort. There is one guideline to calculate below.

- If 20% of the total components is not integer, the number of components in each group is set as the biggest integer close to the calculated result.

The combination of Pareto Analysis and the guideline stated is implemented in Eq. 7-1 belows.

$$k_{Pareto} = (0.2 \times n)_{\text{integer}} \quad (7\text{-}1)$$

where n is the total components in a product being design, the subscripted "*integer*" represents the guideline to leverage calculation in the case of which the calculation is not integer, and k_{Pareto} is the number of components in a group complied with the Pareto Analysis.

The guideline listed eariler visualises the “*worst case scenario*”. For example, the automotive water pump has 13 components; so, k_{Pareto} is 2.6; and it is round up to be 3. If the value 2.6 is lowered down to 2, it means the critical components would be 2 rather than 3. Therefore, the many more critical components lead to “*worst case*” rather than less.

In practice, the critical components are defined by either experts or historical records; however, it is increasingly challenge if the product is newly designed. To resolve this issue, the number of components that should be carefully addressed are from the Pareto Analysis. Nonetheless, the consequence challenge is how to identify the critical components, while the answer is in the adjacent sub-section.

Calculate the optimistic number of component groups

Applying Pareto Analysis does not explain the critical component groups; therefore, this thesis proposes to address them from all possible combinations. The prerequisite to achieve this method is calculation the optimistic number of component groups. It is defined, as follows:

“The optimistic number of component groups is existed only when every function in a considered product is achieved by a particular component without repetition.”

The inference from the recent definition is that the number of functions and components as well as the relationships among them is equal. Eq. 7-2 is to calculate the optimistic number of component groups, and they are derived from every function that directly connects to components. From Table 6-2, the Contain-coolant function does not directly connect to components because there are two sub-functions under it. On the other hand, the Input-coolant function directly links to components thereby; it has no sub-functions.

$$G_{Op} = \frac{f_c!}{k_{Pareto}!(f_c - k_{Pareto})!} \qquad (7\text{-}2)$$

where f_c is the total functions directly connected to components, and G_{Op} is the optimistic number of component groups.

There are 9 functions directly connected to components. So, the G_{Op} is calculated as follows:

$$G_{Op} = \frac{9!}{3!(9-3)!} = 84$$

So, the optimistic number of function groups is 84 as shown in Table 7-2a, while the function nomenclature and its component quantity is shown in Table 7-2b. Considering of functions always a beginning point to design products; so, exhaustively making combinations from functions is proposed. Possible component groups are from the multiplication component number under each function.

Create the possible component groups

This sub-section is to create all possible component groups. From Table 6-2, each function is not necessary to be achieved by one component. To set components into a group with k_{Pareto} components, there are two guidelines to form a component group, as follows:

- The number of components in each group is k_{Pareto}.
- Components in the same function are not selected to form a group.

All possible component groups are set with guideline one and two. All possible component combination numbers are calculated by Eq. 7-3.

$$G_{Possible} = \sum_{m=1}^{G_{Op}} (\alpha_i A_i \times \alpha_j A_j \times \alpha_k A_k \times \ldots \alpha_o A_o)_m \quad (7\text{-}3)$$

where $A_i, A_j, A_k, \ldots, A_o$ are the number of components in each function, The total members in the term $A_i \times A_j \times A_k \times \ldots A_o$ are equal to k_{Pareto}, The sub-script $i, j, k, \ldots, o$ represent the function names, as exampled in Table 7-2, $\alpha_i, \alpha_j, \alpha_k, \ldots, \alpha_o$ is equal to 1, if it is selected otherwise 0, $G_{Possible}$ is the possible number of component groups.

Table 7-2b shows the number of components under a particular function, moreover, they are calculated the total possible groups, as shown in Table 7-2a. There are 946 possible combinations all of which are not put into optimisation, but there is a selection method, as revealed in the next sub-section. Moreover, the combinations are set in MATLAB programming.

Table 7-2: The optimistic combinations and component groups a) Combinations b) Nomenclatures

(a)

Possible combinations (function numbers)							
Function groups	Possible component groups	Function group	Possible component groups	Function group	Possible component groups	Function group	Possible component groups
1, 2, 3	$1\times7\times4=28$	1, 5, 9	$1\times1\times1=1$	2, 5, 9	$7\times1\times1=7$	3, 8, 9	$4\times1\times1=4$
1, 2, 4	$1\times7\times2=14$	1, 6, 7	$1\times4\times1=4$	2, 6, 7	$7\times4\times1=28$	4, 5, 6	$2\times1\times4=8$
1, 2, 5	$1\times7\times1=7$	1, 6, 8	$1\times4\times1=4$	2, 6, 8	$7\times4\times1=28$	4, 5, 7	$2\times1\times1=2$
1, 2, 6	$1\times7\times4=28$	1, 6, 9	$1\times4\times1=4$	2, 6, 9	$7\times4\times1=28$	4, 5, 8	$2\times1\times1=2$
1, 2, 7	$1\times7\times1=7$	1, 7, 8	$1\times1\times1=1$	2, 7, 8	$7\times1\times1=7$	4, 5, 9	$2\times1\times1=2$
1, 2, 8	$1\times7\times1=7$	1, 7, 9	$1\times1\times1=1$	2, 7, 9	$7\times1\times1=7$	4, 6, 7	$2\times4\times1=8$
1, 2, 9	$1\times7\times1=7$	1, 8, 9	$1\times1\times1=1$	2, 8, 9	$7\times1\times1=7$	4, 6, 8	$2\times4\times1=8$
1, 3, 4	$1\times4\times2=8$	2, 3, 4	$7\times4\times2=56$	3, 4, 5	$4\times2\times1=8$	4, 6, 9	$2\times4\times1=8$
1, 3, 5	$1\times4\times1=4$	2, 3, 5	$7\times4\times1=28$	3, 4, 6	$4\times2\times4=32$	4, 7, 8	$2\times1\times1=2$
1, 3, 6	$1\times4\times4=16$	2, 3, 6	$7\times4\times4=122$	3, 4, 7	$4\times2\times1=8$	4, 7, 9	$2\times1\times1=2$
1, 3, 7	$1\times4\times1=4$	2, 3, 7	$7\times4\times1=28$	3, 4, 8	$4\times2\times1=8$	4, 8, 9	$2\times1\times1=2$
1, 3, 8	$1\times4\times1=4$	2, 3, 8	$7\times4\times1=28$	3, 4, 9	$4\times2\times1=8$	5, 6, 7	$1\times4\times1=4$
1, 3, 9	$1\times4\times1=4$	2, 3, 9	$7\times4\times1=28$	3, 5, 6	$4\times1\times4=16$	5, 6, 8	$1\times4\times1=4$
1, 4, 5	$1\times2\times1=2$	2, 4, 5	$7\times2\times1=14$	3, 5, 7	$4\times1\times1=4$	5, 6, 9	$1\times4\times1=4$
1, 4, 6	$1\times2\times4=8$	2, 4, 6	$7\times2\times4=56$	3, 5, 8	$4\times1\times1=4$	5, 7, 8	$1\times1\times1=1$
1, 4, 7	$1\times2\times1=2$	2, 4, 7	$7\times2\times1=14$	3, 5, 9	$4\times1\times1=4$	5, 7, 9	$1\times1\times1=1$
1, 4, 8	$1\times2\times1=2$	2, 4, 8	$7\times2\times1=14$	3, 6, 7	$4\times4\times1=16$	5, 8, 9	$1\times1\times1=1$
1, 4, 9	$1\times2\times1=2$	2, 4, 9	$7\times2\times1=14$	3, 6, 8	$4\times4\times1=16$	6, 7, 8	$4\times1\times1=4$
1, 5, 6	$1\times1\times4=4$	2, 5, 6	$7\times1\times4=28$	3, 6, 9	$4\times4\times1=16$	6, 7, 9	$4\times1\times1=4$
1, 5, 7	$1\times1\times1=1$	2, 5, 7	$7\times1\times1=7$	3, 7, 8	$4\times1\times1=4$	6, 8, 9	$4\times1\times1=4$
1, 5, 8	$1\times1\times1=1$	2, 5, 8	$7\times1\times1=7$	3, 7, 9	$4\times1\times1=4$	7, 8, 9	$1\times1\times1=1$

(b)

Number	Functions	Components in a considered function	Number	Functions	Components in a considered function
1	Input-coolant	1	6	Support-rotational	4
2	Prevent-coolant	7	7	Receive-rotational	1
3	Store-coolant	4	8	Decrease-velocity	1
4	Accelerate-coolant	2	9	Output-coolant	1
5	Transfer-rotational	1			

Create component groups for optimisation (G_{Opt})

Not all possible combinations are suitable to put into optimisation especially the groups contained with repetitive components. This situation leads to over assign initial guess effort which is resulting of the biased vector U. There is another guideline to limit component group in optimisation is as follows:

- Even though one component performs dissimilar functions, it is not selected to form a group.

In addition, guideline two from the previous sub-section and this guideline are set in order to diversify the combination of functions and components rather than concentrate into each of them. The guideline in this sub-section limits the possible component groups down to 641 groups by applying MATLAB programming, as represented in Appendix I. All groups are ready to put into optimisation in section 7.2.3. The examples of the component groups are shown in Table 7-3. The example shown in Table 7-3 is engaged from the function combination namely 1, 2 and 3, as represented in Table 7-2. Entities in column one of Table 7-3 are the order of component groups and they are continuously counted from every function groups in Table 7-2. Components in column two to four are under different functions as a result the component combinations are illustrated as 28 possible combinations. Nevertheless, column five in this table is to consider whether to put the component combinations to be optimised in section 7.2.3 or not. Each component combination is filtered by the proposed guideline in this sub-section.

The combination that fills with the repetitive components is not allowed to put in the optimisation due to the guideline in this sub-section. Therefore, there are 15 out of 28 combinations ready to optimise. This guideline is to reduce bias in the method, and the logic supported this guideline is explained in section 7.2.4. Similar method is applied to every combination in Table 7-2. All obtained variables before optimisation are sequentially summarised in Table 7-4.

Table 7-3: The example of component groups arranged from functions

No.	Functions			Put into optimisation
	Input-coolant (1)	Prevent-coolant (2)	Store-coolant (3)	
1	Water pump body	Water pump body	Water pump body	No
2	Water pump body	Water pump body	Gasket	No
3	Water pump body	Water pump body	Back plate	No
4	Water pump body	Water pump body	Bolt	No
5	Water pump body	Water seal	Water pump body	No
6	Water pump body	Water seal	Gasket	Yes
7	Water pump body	Water seal	Back plate	Yes
8	Water pump body	Water seal	Bolt	Yes
9	Water pump body	Oil seal	Water pump body	No
10	Water pump body	Oil seal	Gasket	Yes
11	Water pump body	Oil seal	Back plate	Yes
12	Water pump body	Oil seal	Bolt	Yes
13	Water pump body	Outer clip	Water pump body	No
14	Water pump body	Outer clip	Gasket	Yes
15	Water pump body	Outer clip	Back plate	Yes
16	Water pump body	Outer clip	Bolt	Yes
17	Water pump body	Gasket	Water pump body	No
18	Water pump body	Gasket	Gasket	No
19	Water pump body	Gasket	Back plate	Yes
20	Water pump body	Gasket	Bolt	Yes
21	Water pump body	Back plate	Water pump body	No
22	Water pump body	Back plate	Gasket	Yes
23	Water pump body	Back plate	Back plate	No
24	Water pump body	Back plate	Bolt	Yes
25	Water pump body	Bolt	Water pump body	No
26	Water pump body	Bolt	Gasket	Yes
27	Water pump body	Bolt	Back plate	Yes
28	Water pump body	Bolt	Bolt	No

Table 7-4: Required variables for optimisation in support of automotive water pump case

Variables	Definitions	Purposes	Means to obtain	Values
k_{Pareto}	Component quantity in each group derived from Pareto Analysis	To achieve G_{Op}	Eq. 7-1	3 components per group
f_c	Total functions directly connected to components	To achieve G_{Op}	Manually defined from function-component relationships	9 functions
G_{Op}	Optimistic amount of component groups	To achieve $G_{Possible}$	Eq. 7-2	84 groups
$G_{Possible}$	Possible amount of component groups	To achieve G_{Op}	Eq. 7-3	946 groups
G_{Opt}	Total component groups being put in optimisation	To achieve $G_{Possible}$	Manually selected from given guideline.	641 groups

7.2.2 *Assign objective function and constraints to component groups*

This stage is to find the combination likely to provide the highest design rework effort with the optimisation principle. The Pareto Analysis is proposed to determine the size of each component group. Therefore, it is to signify non-zero elements in the initial design rework effort vector input, as shown in the objective function. Each constituent in the vector represents the percentage of the ideal design effort from the individual root cause component. In reality, the design rework issues are not always equal to 20% of the total components; however, assessing them earlier would be able to reduce impacts from design rework effort.

The single objective optimisation to search for the maximum design rework effort is proposed in this thesis. The optimisation constraints are modified from the assumptions expressed in section 7.1.2. The objective function and constraints for each component group are as follows:

<u>*Objective function*</u>

$$Maximise: \sum_{i=1}^{n} a_i$$

where

n is the number of total components,

a_i is the design rework effort for each component in vector format which is the result of matrix multiplication identified below

$$a_i \in (S(I-\Lambda_{component})^{-1}S^{-1})(\alpha_1 b_1 E_{ideal\,k}, \alpha_2 b_2 E_{ideal\,l}, \alpha_3 b_3 E_{ideal\,m}, \ldots, \alpha_{n_n} b_n E_{ideal\,nf})^T$$

$b_1, b_2, b_3, \ldots, b_{n_1}$ are the estimated percentage of the ideal design rework effort of each component against the considered function,

$\alpha_1, \alpha_2, \alpha_3, \ldots, \alpha_n$ are 0 or 1. If the i is selected in the component group, $\alpha_i = 1$ otherwise 0, and the selection are equals to k_{Pareto} at a time,

$E_{ideal_{k_1}}, E_{ideal_{l_1}}, E_{ideal_{m_1}}, \ldots, E_{ideal_{nf_1}}$ are the ideal design effort of each component against a particular function, as calculated with Eq. 6-7.

nf is the total components which directly link to functions as illustrated in Table 7-7.

Constraints

Subject to: $\sum_{i=1}^{n} a_i \geq 0.05 \times Ef_{ideal}$

$$0 < b_1, b_2, b_3, \ldots, b_n < 1$$

where

Ef_{ideal} is the total ideal design effort.

5% of $Ef_{ideal} \approx$ 92 hours (for automotive water pump case).

The objective function is prepared to maximise the design rework effort which it is applied from Eq. 6-5. However, the additional development is the application of the Pareto Analysis (assumption one) to group components. The term $(\alpha_1 b_1 E_{ideal_k}, \alpha_2 b_2 E_{ideal_l}, \alpha_3 b_3 E_{ideal_m}, \ldots, \alpha_{n_n} b_n E_{ideal_{nf}})^T$ is in the vector form and its dimension is $1 \times n$. The vector represents the component group followed the Pareto Analysis. Once the i^{th} component is selected α_i is one otherwise 0; and this selection is automatically performed with MATLAB programming. Whilst, the variable b_i is the percentage which is continuously in range $0 < b_i < 100$. Whereas, E_{ideal_i} is the ideal design rework effort, as taken from section 6.2.6. The term $(S(I - \Lambda_{component})^{-1} S^{-1})$ reveals as the $n \times n$ matrix; moreover, it is originated from the function-component relationships, as developed in section 6.2.1 to 6.2.5.

Constraint one is set in an inequality format, as given from assumption one and three. Its purpose is to limit the aggregated initial guess on the design rework effort not more than 5% of the total ideal design effort, as mentioned with assumption three. Hence, this constraint is to explain the scenario when there are components in a group providing issues that appear to bring small impacts in terms of the design rework effort. However, they could deliver greater impacts because of knock-on effect and this undesirable is expected to be foreseen by optimisation, as proposed in section

7.2.3. Constraint one is to filter the objective function to be more than 5% of Ef_{ideal}, because the estimated design rework effort lower than this threshold are small and reasonably to be neglect. Other constraints are to confirm that the initial estimated design rework effort are more than zero. Once the objective function and constraints are ready, the optimisation is prompt to proceed in the next step.

7.2.3 Apply optimisation technique to the assigned groups

When design rework issues occur in the testing and refinement phase, it is the ambitious task to predict exactly what they are. Therefore, the researcher decide to find out what is the maximum design rework effort would be with the given constraints. Subsequently, the linear programming is selected to search for the maximum design rework effort in each component group; moreover, all component groups are optimised exhaustively. This optimisation activity complies with the assumptions in section 7.1.2.

From constraints, each b_i is a continuous variable and it is individually varied in the optimisation for each component group, while α_i, $E_{ideal\,i}$ and Ef_{ideal} are fixed for each component combination. Noted that each component group is imitating the combination starting with functions and then components; moreover, there are no repetitive in terms of functions and components in each group.

The component groups to optimise, as created in section 7.2.1, are individually considered as a discrete group and ready for optimisation, furthermore, the objective function and constraints are assigned to them. Hence, the optimisation is separately complete for each component group.

The optimisation is arranged in MATLAB and the linprog command is selected. The Exit flag is the stop criteria, and value “1” means the result is optimised.

Rationales to select linear programming to search for the maximum design rework effort

There are a lot of optimisation techniques, as conferred in section 2.7.1, however, the linear programming and exhaustive search is chosen. The rationales support the decisions are as follows:

- The linear programming (*linprog* command in MATLAB) is selected in this stage because the objective function, as shown in section 7.2.2, is linear.
- The variables in the objective function are less than 10; moreover, constraints are less than 20, as discussed in section 2.7. So, both reasons fit to the linear programming at present. If the product being evaluated exceed these limits, this optimisation technique is not suitable.

Interpretation of the optimisation results

The optimisation results are plotted and shown in Figure 7-2; however, they are scattered and some of them have repetitive values. The optimised results in this figure are interpreted as follows:

- Each point represents the optimised result for a particular component group according to constraints.
- It is the fact that some component can appear in more than one groups, but there is no identical component group.
- The horizontal axis in Figure 7-2 represents the ordinal position of component combinations, while, design rework effort value reveals in the vertical axis. The optimisation results are summarised in Table 7-6. Only the results more than 5% of Ef_{ideal} are selected; therefore, there are 628 out of 641 component groups in the prioritisation stage. All optimisation results are in Appendix G.

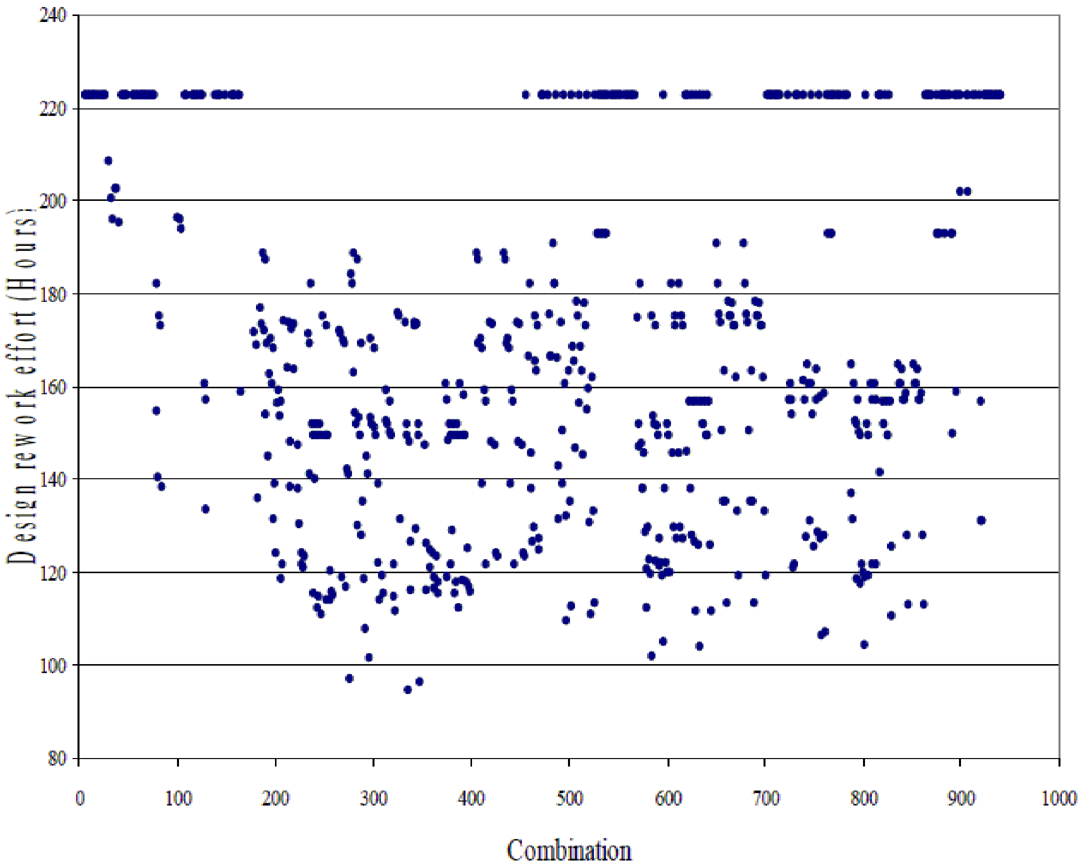


Figure 7-2: The optimisation results from automotive water pump's component groups

Prepare the optimisation results for prioritisation

The optimisation results from Figure 7-2 are explicitly represented against the component groups as exampled in Table 7-5. Column one to four in Table 7-5 are the selected component groups taken from Table 7-3 (15 out of 28 combinations), and there are no repetitive components within a particular component groups from all of them. Column five consists of the optimised results. Figure 7-2 shows the optimisation results, and there are 628 component groups in total.

It is remarkably that each result from every component combination, as listed in Table 7-5, is equal. Nevertheless, all component groups are under the similar function combination, as revealed in the column heading two to four. However, there are hetero results represented in Appendix G. Therefore, it is a challenge to prioritise components being designed based on the design rework effort impacts. The next section provides the suggestion to overcome this issue; as a result, prioritisation the component design based on the design rework effort is achieved. However, the results are arranged in each design rework effort range, as shown in Table 7-6. The explicit explanation for the prioritisation process is in the next section.

Table 7-5: The example of optimisation results from component groups shown in Table 7-3

No.	Functions			Design rework effort (hours)
	Input-coolant (1)	Prevent-coolant (2)	Store-coolant (3)	
6	Water pump body	Water seal	Gasket	222.51
7	Water pump body	Water seal	Back plate	222.51
8	Water pump body	Water seal	Bolt	222.51
10	Water pump body	Oil seal	Gasket	222.51
11	Water pump body	Oil seal	Back plate	222.51
12	Water pump body	Oil seal	Bolt	222.51
14	Water pump body	Outer clip	Gasket	222.51
15	Water pump body	Outer clip	Back plate	222.51
16	Water pump body	Outer clip	Bolt	222.51
19	Water pump body	Gasket	Back plate	222.51
20	Water pump body	Gasket	Bolt	222.51
22	Water pump body	Back plate	Gasket	222.51
24	Water pump body	Back plate	Bolt	222.51
26	Water pump body	Bolt	Gasket	222.51
27	Water pump body	Bolt	Back plate	222.51

Table 7-6: The summary for automotive water pump design rework effort optimisation

Maximum design rework effort	222.51 hours (12.12% of Ef_{ideal})
Minimum design rework effort	94.67 hours (5.16% of Ef_{ideal})
Range	222.51-94.67=127.83 hours
Optimisation results for prioritising component design	628 results

7.2.4 Priroritise component design with optimisation results

The results from the previous section are difficult to prioritise because there are a lot of recurring values. For instance, there are 172 component groups deliver the 222.51 hours of design rework effort. Therefore, the repetitive counting is the major concern because it leads to over emphasis the criticality. In addition, the diverse optimisation result issue is another concern. The frequency counting method is proposed in this section to resolve these two challenges. The mean to class the design rework effort is necessary, and it is the key success in prioritisation component design. The detailed development is shown through three sub-sections as follows:

Identify clusters of optimisation results

Clustering optimised results intends to resolve the diversity. The total design rework effort clusters is calculated with Eq. 7-4.

$$Cl = \left(\frac{nf}{k_{Pareto}} \right)_{integer} \tag{7-4}$$

where nf is the total linkages among components and functions, k_{Pareto} is similar to Eq. 7-1, Cl is the total cluster which is the lowest integer close to the result from Eq. 7-4.

Table 7-7 demonstrates the component relationships. In fact, some functions are achieved by more than one component, as discussed in section 6.2.1. On the other hand, each relationship in the mentioned table illustrates the individually association between a couple of component and function; hence, the total associations are equal to nf which is equal to 22 linkages for the automotive water pump.

Table 7-7: The component-function relationships to represent nf (Automotive water pump)

Functions / Components	Input-coolant	Contain-coolant		Increase-velocity				Decrease-velocity	Output-coolant
		Prevent-coolant	Store-coolant	Accelerate-coolant	Transfer-rotational	Support-rotational	Receive-rotational		
Gear							✓		
Impeller				✓					
Water pump body	✓	✓	✓	✓		✓		✓	✓
Ball bearing						✓			
Needle bearing						✓			
Shaft					✓				
Water seal		✓							
Oil seal		✓							
Outer clip		✓							
Inner clip						✓			
Gasket		✓	✓						
Back plate		✓	✓						
Bolt		✓	✓						
nf	22								

Eq. 7-4 is the beginning point to prioritise the component design. Ultimately, it is to obtain the total cycle to complete prioritisation of the entire components, as exampled below.

$$Cl_{Automotive\ \ water\ \ pump} = \left(\frac{22}{3}\right)_{integer} = 7.33 \approx 7$$

From calculation, the automotive water pump requires 7 times to evaluate component design during prioritisation. Nonetheless, the consequence challenge from clustering activity is the method to determine the design rework effort range for each class because of the results' diversification, while this challenge is resolved in the next sub-section.

Identify range of design rework effort for each cluster

The optimised results are scattered, as clearly illustrated in Figure 7-2; hence, finding the design rework effort range for each cluster is attained with Eq. 7-5.

$$DreR_C = \left(\frac{Max - Min}{Cl}\right) \tag{7-5}$$

where Max and Min are the maximal and the minimal optimisation results, Cl is the cluster of the design rework effort from the optimisation, $DreR_C$ is the design rework effort range for each component group cluster

After the design rework effort range is acquired, they are assigned into each cluster. The example to apply Eq. 7-5 is below, while the approximated design rework effort for each cluster is shown in Table 7-8.

$$DreR_C = \left(\frac{222.51 - 94.67}{7}\right) \approx 18.26 \text{ hours}$$

The optimisation results from Appendix G are classified by the upper and lower bounds of the design rework effort in Table 7-8. Furthermore, the number of the component groups in each cluster are shown in column four. It is interesting to notice that the greatest number of the component groups is in cluster one while the minimal is in the last cluster.

Table 7-8: The design rework effort ranges of each cluster (Automotive water pump)

Clusters	Upper bound (hours)	Lower bound (hours)	Component groups in each cluster
1	222.51	222.51-18.26 $\approx$ 204.24	173
2	204.24>	204.24-18.26 $\approx$ 185.98	36
3	185.98>	185.98-18.26 $\approx$ 167.72	86
4	167.72>	167.72-18.26 $\approx$ 149.46	128
5	149.46>	149.46-18.26 $\approx$ 131.20	75
6	131.20>	131.20-18.26 $\approx$ 112.93	109
7	112.93>	112.93-18.26 $\approx$ 94.67	21
Total			628

Prioritise component design with frequency counting

Conceptual setting for the frequency counting method: This sub-section is to identify the component's criticality and to prioritise component design with the frequency counting. The concept is originates from Table 7-5. It is distinctively seen that the water pump body deliver the Input-coolant function. Even though there are other components in the combinations, but the design rework effort are from the combinations which are composed of the water pump body. The 222.51 hours of the design rework effort occur 15 times all of which relate with the water pump body, while the water seal contributes only three times. Therefore, it is interpreted as follows:

"Considered a particular function, the component under a particular function which has the more frequencies in a cluster leads to the higher criticality."

This observation directs to the guidelines to address the critical components by counting their frequencies. There are four guidelines as follows:

- The components, which are unalike functions, have to be separately counted the frequency in order to avoid repetitive counting.
- The component should be reviewed with k_{Pareto} components (20% of total components) at a time until complete, and this factor complies with the Pareto Analysis.
- In a considered cluster, the components that have high frequencies should be carefully evaluated; because they have high opportunity to combine with other components as a result of delivering the design rework effort in the considered range. Then the issues related to them could be reviewed and eliminated.

Hence, they are not considered in the later cluster. In addition, the similar principle is applied into other clusters.

- From the Pareto Analysis, the components with the top k_{Pareto} frequencies are critical components. Once they are addressed, other components are assumed as non-critical in the considered cluster. Hence, the in-prioritised components are re-evaluated in the later cluster until all components are completed.

The example from guideline one is in Table 7-9. The gasket can deliver either the Prevent-coolant or the Store-coolant functions both of which have their frequencies as three and five consecutively. Therefore, it seems that the water pump body under the Input-coolant function is more critical than the water seal due to the frequencies at this stage. The rational to realise each frequency separately is maintained from the guidelines to set up component groups, as provided from sub-section four of section 7.2.1. Once the analogous principle is executed to all optimised results (628 results), the critical component based on the frequency could be captured as well as prioritised component design.

Table 7-9: The frequency counting with the example from Table 7-5

Components	Functions			Frequencies
	Input-coolant (1)	Prevent-coolant (2)	Store-coolant (3)	
Water pump body	✓			15
Water seal		✓		3
Oil seal		✓		3
Outer clip		✓		3
Gasket		✓		2
Back plate		✓		2
Bolt		✓		2
Gasket			✓	5
Back plate			✓	5
Bolt			✓	5

Interpretation of the prioritisation results

There are two elements to interpret the prioritised results: reading the prioritisation results and the meaning of frequency. The detailed discussions for both elements are as follows:

Reading the results: In Table 7-10, the optimisation results from 628 component groups are applied with guideline one in this sub-section. Each row heading composes of the functions and its components. Hence, there are 22 linkages (nf) of the functions and the components for the automotive water pump. Each cluster's range (design rework effort range) is acquired from Table 7-8. A numeric value shown in each cell of Table 7-10 is to illustrate the frequency of each function-component combination; moreover, it is considered under the design rework effort range shown in the column heading. Even though the optimisations are executed specifically for the components in a group, but their frequencies are counted separately in order to show their repetitiveness against the design rework effort range. Furthermore, a component working to deliver different functions is counted separately as if it is a different component.

Meaning of frequency: As stated earlier, a component can deliver more than one function, moreover, it can combine with other components to form a group with various pattern, as detailed in section 7.2.1. Therefore, its frequency within a particular design rework effort range has the meaning as follows:

- The frequency means the opportunity to form the different component group.
- The high frequency for a particular component interprets as critical, because the considered component has lofty chance to deliver the design rework effort in an emphasised range regardless of other components in groups.

In Table 7-10, the water pump body, the impeller and the gear are the component working to achieve the Input-coolant, the Accelerate-coolant and the Receive-rotational functions consecutively and they have the top k_{Pareto} frequency in the design rework effort range 222.51 to 204.24 hours. Therefore, they have the utmost opportunity to deliver the design rework effort in this range compared with others. They are not necessary to form a component group, but any component groups which have at least one of these component with the giving functions would potentially provide the mentioned design rework effort values.

Interpretation of each component group: The highlighted cells in Table 7-10 show the implementation of guideline one, two and three. All of the mentioned cells show the top three (k_{Pareto}) frequencies in each design rework effort ranges. Once k_{Pareto} components (20%) are addressed and cautiously evaluated, it is inferred from the

Pareto Analysis that the major issues (80%) in the considered range should be minimal. For example, if the water pump body, the impeller and the gear as mentioned earlier are reviewed, 80% of the issues from them should be diminished. Once guideline three is implemented, the highlighted cells for other design rework effort ranges are revealed. If guideline two is applied again to other design rework effort ranges, the k_{Pareto} components would be captured for each range. This activity infers that 80% of issues which induce the critical design rework effort in the considered range should be lower. There are four components should be evaluated together in cluster three, because the shaft and the ball bearing have equal frequencies. The water pump body considered under the support-rotational function is the final component to be reviewed. Even though, it has zero frequency, but it is the last component after other components are prioritised.

The potential application of the prioritisation results

The component prioritisation reveals in Table 7-11. It is reminded that design rework effort is not only the exertion to redesign the root cause components themselves but also knock-on effects. Hence, the early prioritised components are very sensitive to create knock-on effects to others.

The potential application is to create the component list to be focused by the design team. One outcome from the prioritisation results is the guidance for the design team to allocate human resources in designing critical components. However, the detailed activities to review the critical component should be is not the main focus in this thesis. In addition, this method is not covered how to exactly identify on what the issues would be.

The prioritise results were positively accepted by two experts from the automotive water pump project. Moreover, there are other two cases to validate the method, as confirmed in chapter 8.

Table 7-10: The frequency counting from the optimisation results (Automotive water pump)

Functions directly linked to components	Components	Clusters and ranges of design rework effort (hours)						
		222.51 to 204.24	204.24> to 185.98	185.98> to 167.72	167.72> to 149.46	149.46> to 131.20	131.20> to 112.93	112.93> to 94.67
Input-coolant	Water pump body	63	8	3	4	3	0	0
Prevent-coolant	Water pump body	8	0	9	3	6	3	1
	Water seal	15	12	22	11	10	6	1
	Oil seal	14	2	11	13	22	8	4
	Outer clip	14	2	0	20	8	22	7
	Gasket	13	2	22	15	7	5	0
	Back plate	13	2	22	11	10	6	1
	Bolt	13	2	0	5	4	36	3
Store-coolant	Water pump body	8	0	12	4	9	12	1
	Gasket	16	6	13	46	0	14	1
	Back plate	16	6	13	33	13	14	0
	Bolt	16	2	4	6	21	36	10
Accelerate-coolant	Impeller	53	25	10	25	11	12	3
	Water pump body	15	3	15	15	7	10	2
Transfer-Rotational	Shaft	34	4	18	29	21	40	6
Support-rotational	Water pump body	21	2	8	4	4	6	0
	Ball bearing	24	5	18	44	4	12	0
	Needle bearing	24	2	14	24	20	22	1
	Inner clip	18	3	7	13	14	22	17
Receive-rotational	Gear	63	12	3	31	17	21	5
Decrease-velocity	Water pump body	29	4	17	14	7	10	0
Output-coolant	Water pump body	29	4	17	14	7	10	0

Table 7-11: The component prioritisation based on design rework effort and frequencies (Automotive water pump)

Functions directly linked to components	Components	Design rework effort ranges (hours)	Frequencies
Input-coolant	Water pump body	222.51 to 204.24	63
Receive-rotational	Gear		63
Accelerate-coolant	Impeller		53
Prevent-coolant	Water seal	204.24> to 185.98	12
Store-coolant	Gasket		6
Store-coolant	Back plate		6
Prevent-coolant	Gasket	185.98> to 167.72	22
Prevent-coolant	Back plate		22
Transfer-rotational	Shaft		18
Support-rotational	Ball bearing		18
Prevent-coolant	Outer clip	167.72> to 149.46	20
Support-rotational	Needle bearing		24
Accelerate-coolant	Water pump body		15
Prevent-coolant	Oil seal	149.46> to 131.20	22
Store-coolant	Bolt		21
Support-rotational	Inner clip		14
Prevent-coolant	Bolt	131.20> to 112.93	36
Decrease-velocity	Water pump body		10
Output-coolant	Water pump body		10
Prevent-coolant	Water pump body	112.93> to 94.67	1
Store-coolant	Water pump body		1
Support-rotational	Water pump body		0

7.3 KEY OBSERVATIONS FROM THE PriDDREB METHOD DEVELOPMENT

The key observations from the development of the PriDDREB method are as follows:

- The PriDDREB method is extended from the DREE method; therefore, both of them are strongly related.
- The small technical issues from component groups would potentially lead to enormous design rework effort, as hypothesised in section 7.1.1. For example, only 5% of the total ideal design effort (Ef_{ideal}), 92 hours, which is initially guessed from component group could induced the maximum design rework effort up to 222.51 hours. Hence, it is amazingly shown that the increasing is potentially more than 100% from initial estimation.
- The challenge on "*how many*" components should be focused is overcome with the application of the Pareto Analysis.
- Obtaining the percentage to be reworked from each component design effort was the challenge tasks in DREE method, as raised in section 6.4. However, it

is worked out in this chapter with applying the linear programming and exhaustively method to estimate the maximum design rework effort for every component group.

- This method assist the design team to identify the critical components and their functions based on the design rework effort, but the precise issues connected to them are not covered yet. Hence, this is the challenge for future development.
- One potential source of bias is from too much emphasis on components because of over counting their frequencies. Nonetheless, this bias is not from this method itself, but from the predecessor method. The potential root cause of this bias is from the function-component relationship matrix. If the design team defines that a particular component serves too many functions due to wrong justification, it could potentially be arranged into too many component groups. Thus, its frequency is likely to be too high.

7.4 CHAPTER SUMMARY

The critical components due to design rework effort in the testing and refinement phase can be assessed in the early design phase. Moreover, the outcome from this method can be used to prioritise component design. All assumptions are initially accepted by company E, where the automotive water pump case is applied. In addition, the PriDDREB method is validated with two case studies, as represented in chapter 8; therefore there are three cases in total that validate this method. The method enhances optimisation to obtain the possible maximum design rework effort for each component group. Specifically, Pareto Analysis is the key success to form component groups and to set the optimisation objective and constraints. Once the maximum design rework effort for component groups are achieved, frequency counting is the means to prioritise component design.

The developed method becomes even more crucial when the human resources limitation is taken into account. This method helps to address the critical components and their related functions, so it enhances the design team to focus rather than allocate the work force without direction. Nevertheless, the issues arising from critical components can not be extracted with the PriDDREB method; hence, this is the challenge for future development.

CHAPTER 8
VALIDATION FOR THREE DEVELOPED METHODS

The aim of this chapter is to answer research question five as well as to complete research objective five. Hence, there are two main sections in this chapter. There are two additional industrial case studies to validate the DRePOE, DREE and PriDDREB methods. In addition, the validation results in section 8.3 cover the automotive water pump as represented in chapters 5 to 7; so there are three cases in total that validate the methods. The Validation Square Method is applied to the validation activities, as shown in section 8.4. Furthermore, in section 8.5, the cross-case study analysis evaluates the common aspects of a particular method as well as the associations among them.

The challenge in this chapter, raised earlier in sections 1.2 and 3.5.7, is that there is a limited number of participants to be assigned a statistical method for validation. Therefore, all three methods are confirmed through the validation square method which is extended from the case study research method, as proposed by Perdersen et al. (2000). Hence, the method validation is completed by qualitative assessments and from multi-data sources as well as by testing the methods on the given industrial case studies, as summarised in Table 8-1.

Table 8-1: Summary of the method validations

Research objective	Proposed method	
To validate each individual method with industrial experts and case studies.	Validation square	
Challenge	Proposed methods	Sections
The cases for validation are not enough to be validated statistically.	Multi-industrial case studies, multi-data sources	8.1, 8.2
	Validation square method	8.3

The validations with company E’s experts were conducted during meetings in the company’s design centre; however, the activities for the automotive water pump and turbocharger were completed separately, whereas the Macpherson strut case provided by company K was completed by telephone and email. The common procedure for validation is as follows:

- The experts must experience the scoring activities for every method.

- The experts must evaluate the results from every method and provide their opinions on the method. This activity has to be performed as permitted by the validation square method, and as represented in section 8.3.

8.1 INDUSTRIAL CASE STUDY 1: THE TURBOCHARGER

The turbocharger is another sub-system within the engine development project provided by company E. In addition, it was developed in parallel with the automotive water pump (as represented in chapters 5 to 7) during the engine development project. The expert who was a steward in Industrial Power Systems Division (IPSD) was the main participant in this activity. All expert’s details are shown in Table 8-48.

Air is the working fluid for diesel and gasoline engines both of which are called piston engines. In principle, the turbocharger helps to amplify the power output by increasing a greater air mass flow rate and boosting up an engine within the engine, while the engine’s original and manufactured capacity is still maintained. The turbocharger recovers wasted heat from an engine’s exhaust gas to be a work output to compress air, as shown in Figure 8-1. The emission legislations are the key drivers of engine development, because the greenhouse gas produced from the new engine must be less than other engines available in the market place. This industrial case study is represented tagged alongside the methodology for each method as shown below.

8.1.1 Apply the DRePOE Method to the Turbocharger Industrial Case Study

Define a new product

The engine series is defined into Tiers following American legislation, as explained in chapter 6. Therefore, the new product for this case is Tier 4. The considered turbocharger is for engines ranging from 63.5 kW to 97 kW output power.

Define benchmark products and their design rework probabilities

Benchmark products: A turbocharger is a part of an inlet air system of engines. Tiers 2 and 3 engines are used as the benchmark products in this case study, but Tier 2 engine has no turbocharger which is commonly known as a normally aspirated internal combustion engine. In principle, designing an inlet air system of an engine is generally a straightforward procedure and it has relatively minimal challenges compared to an engine which is combined with a turbocharger. Once a turbocharger becomes an additional and intricate sub-system of the air inlet system, it becomes a major design effort for the system. If there are any design rework issues occurring within a turbocharger, it will have an affect not only upon itself but also the entire air intake system. Therefore, it is reasonable to acknowledge the air inlet system from Tier 2 engine to be benchmark 1 and the system from Tier 3 engine as benchmark 2.

The two experts involved with the turbocharger development concluded that the design rework probability of occurrence for turbocharger in Tier 3 would be between 5 to 10% approximately. There are no historical data available because this project was conducted ten years ago, and there was no in place system to record data at that time. On the other hand, the probability of design rework occurrence of Tier 2 is 0%, because its air inlet system is relatively easy compared to others, so it can be disregarded.

Table 8-2: The probability of design rework occurrence from previous turbocharger

Products	Probabilities of design rework occurrences	Sources
Benchmark 1 (Tier 2)	0%	Experts' judgement
Benchmark 2 (Tier 3)	5 to 10%	Experts' judgement

Structure drivers in AHP format

Structure drivers for reducing design rework occurrence: The drivers structured are generic, so there is no change in the structure. In addition, there are two benchmarked products being compared, so there are three products being evaluated as previous cases. Hence, the structure is similar to Figure 5-2.

Structure products under the Novelty Level: The novelty between the Tier 2 and Tier 3 air inlet system is the addition of the turbocharger. From Figure 8-1, if there is no turbocharger, fresh air will enter an intake manifold via the air cleaner and air pipe. The longer the distance between these two components the greater resistance to induce the air into the engine. In the Tier 2 engine, optimising the length of the air pipe as well as the pipe elbows is the main task for the design team because either too long or too short will lead to an inefficient engine. Once the turbocharger is taken into consideration, optimising the turbocharger becomes the main task in designing the air system. Similar to the driver structure, the structure to be compared in each product against the Novelty Level, as shown in Figure 5-3, is applicable to this case.

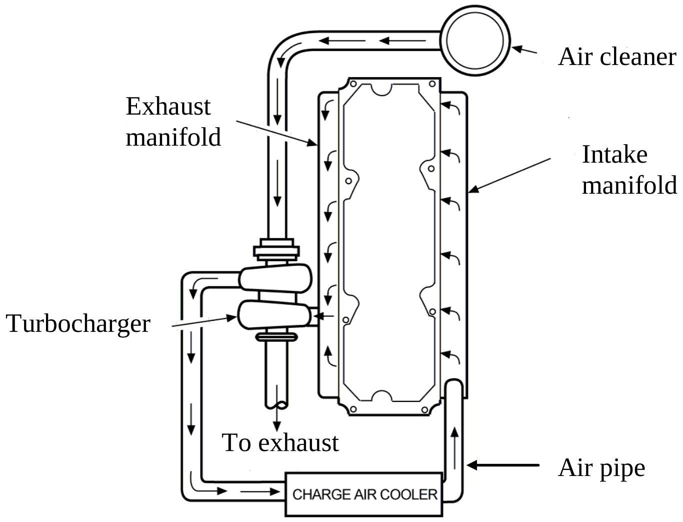


Figure 8-1: Schematic engine air inlet system enhanced by turbocharger (adapted from justanswer.com)

The new requirements forces the new engine version to reduce the emission gas to be lower than the existing engine, which is a Tier 3 engine in this thesis. Therefore, the design team for the Tier 4 engine has decided to use the Exhaust Gas Recirculation (EGR) system to overcome this challenge. This system reduces the flame temperature in the engine with the exhaust gas, so the balance between engine and turbocharger is crucial. In addition, the major turbocharger improvement is the dual compressor outlets.

Pair-wise comparisons of drivers for reducing design rework occurrence and the Novelty Level

Both full and incomplete comparisons are implemented in this case, and the full results are given in Appendix I. In addition, all *CR* and *LOC* of the drivers for reducing design rework occurrence are in the acceptable range. The weighted average scores results are shown in Table 8-3a. The Clarity of Specification driver is still the most critical factor to reduce design rework occurrence in this case. The numeric values shown in each column heading of Table 8-3b are the strengths of each driver to "Design Rework Occurrence".

Table 8-3: The weighted average scores of design rework drivers for turbocharger case a) Drivers for reducing design rework occurrence b) Comparing drivers against products

(a)

Drivers for reducing design rework occurrence	Weighted average
Exploitation of CAE Software	0.04
Coordination across Team Members	0.05
Lessons Learnt	0.26
Supplier expertise	0.06
Clarity of Specifications	0.48
Open Communication to Inform Design Time Issues	0.11
Total	1.00

(b)

Products	Weighted average					
	Exploitation of CAE Software (0.04)	Coordination across Team Members (0.05)	Lessons Learnt (0.26)	Supplier expertise (0.06)	Clarity of specifications (0.48)	Open Communication to Inform Design Time Issues (0.11)
New products	0.72	0.71	0.73	0.70	0.70	0.73
Benchmark 1	0.07	0.08	0.06	0.07	0.07	0.08
Benchmark 2	0.21	0.21	0.21	0.23	0.23	0.19
Total	1.00	1.00	1.00	1.00	1.00	1.00

From Table 8-4, the new product has the highest weighted average score of the Novelty Level as expected, then the new product's score is revealed in column four of Table 8-4, as calculated using Eq. 5-2.

Table 8-4: The weighted average scores of Novelty Level from turbocharger case

Products	Weighted Average for product Novelty Level	NL_{es}/NL_i	Estimated Novelty Level for the new product (NL)
New product	0.78 (NL_{es})	Being estimated	8.51
Benchmark 1	0.07 (NL_1)	11.65 (NL_{es}/NL_1)	
Benchmark 2	0.15 (NL_2)	5.37 (NL_{es}/NL_2)	

Estimated design rework probability of occurrence

Obtain total weighted average: The total weighted average scores from the drivers for reducing design rework occurrence are still the target at this stage and the results are obtained by Eq. 5-4. The vector D from the mentioned equation is taken from Table 8-3a, while the matrix A_D is provided in Table 8-3b, and the result is given in Table 8-5. Even though the new product has the most significant score, the design rework probability of occurrence cannot be evaluated until the Novelty Level is considered.

Table 8-5: The total weighted average scores for design rework occurrences from products in turbocharger case

Products	Total weighted average scores
New product	0.71 (w_{es})
Benchmark 1	0.07 (w_1)
Benchmark 2	0.22 (w_2)
Total	1.00

Perform estimation: The estimated probability of design rework occurrence is in column six of Table 8-6 which is calculated using Eq. 5-1. The required data to estimate are in columns two, three and four which are obtained from Tables 8-2, 8-4 and 8-5 respectively. The estimated results are initially accepted by the experts. Moreover, the detailed validation results of this method are discussed in section 8.3.1.

Table 8-6: The estimating design rework probability of occurrence for turbocharger

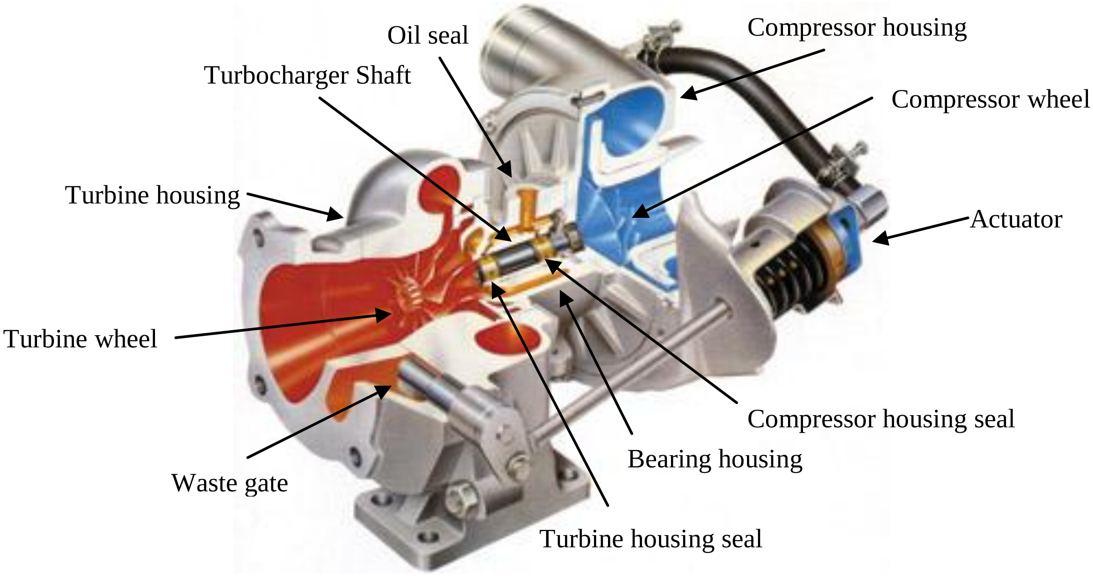
Products	Actual probability of design rework occurrence	Estimated Novelty Level for the New product (*NL*)	Total weighted average scores for each product	w_{es}/w_i	Estimated design rework probability of occurrence for the New product
New product	Being estimated	8.51	0.71 (w_{es})		$\approx$ 6.56-13.15%
Benchmark 1	5 to 10%		0.07 (w_1)	0.10	
Benchmark 2	0%		0.22 (w_2)	0.31	

8.1.2 Apply the DREE Method to the Turbocharger Case Study

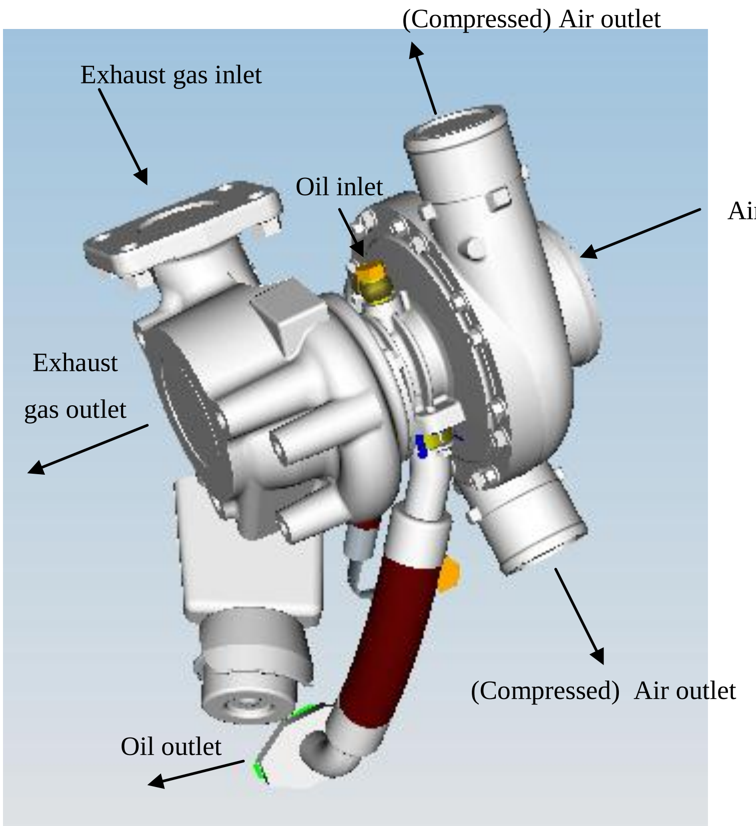
Develop product functional structure and function-component relationships

Develop product functional structure: The FAST principle is applied to the turbocharger by considering the schematic drawing of a turbocharger, as shown in Figure 8-2. In principle, it has two sides, the compressor and turbine sides. The compressor compresses air while being driven by the turbine.

Figure 8-2a represents a cutaway schematic drawing of the turbocharger. This figure is taken from the Internet because it is not provided by company E; however, it is selected as being the most similar turbocharger to that of the obtained case study. Figure 8-2b is provided by company E; moreover, it shows the initial explanation of the turbocharger operation; and Deliver-working fluid is its basic function.



(a)



(b)

Figure 8-2: Schematic drawing of the turbocharger (a) The cutaway schematic drawing of turbocharger (www.miriturbo.com) b) Turbocharger's schematic drawing

The turbocharger with the centrifugal flow type is selected to satisfy the mentioned basic function. The term "working fluid" is applied to structure FAST because either air or exhaust gas is the working fluid for the turbocharger. Hence, working fluid is the generic term implemented in this case. From Figure 8-2b, the exhaust gas with high pressure and temperature from a piston engine flows into a turbine housing and its enthalpy is converted to become shaft work (rotational movement) to drive a compressor wheel. Hence the pressure and temperature of the exhaust gas is reduced and ejected from the turbine housing. Once the shaft work is transferred to the compressor wheel, it turns and induces air into the compressor housing. The air pressure from the outlet of the compressor is boosted as well as temperature; however, the temperature increase is undesirable. Therefore, an intercooler is a standard component to reduce the air temperature, but it is considered as out of the scope of this case study. FAST principle is applied to the turbocharger is represented in Figure 8-3. The basic function to achieve the Deliver-working fluid function is Compress-working fluid (air) while others in the same level are support functions denoted by the dashed line.

The basic function to complete the Compress-working fluid function is Convert-energy which requires another six functions. The Increase-velocity and Reduce-velocity functions of the working fluid (air) are the basic functions to satisfy the Convert-energy function. The Increasing working fluid velocity function adds up the kinetic energy into fluid while slowing it down later is the method used to convert energy from the moving fluid to become static energies (stagnation property).

The Accelerate-velocity function cannot be reached without support from the Receive-rotational function which is the shaft work transmitted from the turbine wheel. The Maintain-pressure function acting on the working fluid (air) is important otherwise it causes engine fluctuation during operation. The Compressor pressure function is measured by a sensor (Measure-pressure), which then triggers an actuator (Actuate-control system function) to either close or open the waste gate to control the exhaust gas passing through the turbine side (Control-working fluid). Moreover in Figure 8-2a, the actuator is directly connected to the waste gate, both of which are considered to be a control system. This controlling directs the turbocharger speed into the optimal range.

The Compress-working fluid function is supported by the Drive-compressor and the Support-rotational functions. Drive-compressor is the function to explain the source of the compressor's shaft rotational function. The energy conversion is accomplished by reducing enthalpy (Reduce-enthalpy function) of the working fluid (exhaust gas) by the Drive-turbine function. After the exhaust gas is equally distributed (Distribute-working fluid), the gas is ready to perform the Drive-turbine function by passing through the turbine wheel. Turbine over-speed is governed by the Control-rotational function. The turbine rotational speed is maintained by controlling the mass flow rate of the exhaust gases (Control-working fluid). The signal from the actuator sent from the compressor actuates the mechanism to the mass flow rate by opening the waste gate in the turbine housing (Control-working fluid). Finally, the work output from the turbine is transferred to the compressor (Provide-rotational). The turbocharger cannot complete its operation without the Support-rotational function. The shaft definitely needs a cavity to allow rotational movement (Allow-rotational); furthermore, to restrict the centre of rotation is desirable (Position-rotation). Finally, there would not be any movement at all if a lubrication system is not provided (Provide-lubricant). Not only is the lubricant crucial for shaft rotating but also for heat removal (Transfer-heat). Any movement leads to heat generation as a result of down grading the lubrication capability.

Develop function-component relationships: Each function of FAST of the turbocharger is completed and classified into levels, as represented in Figure 8-3. The classification is suitable for developing the function-component relationship, as shown in Table 8-7. Only the bottom most function in each branch is revealed in Table 8-7, and it is noted that each of them is directly linked to the components. The letters a, b, c up to s are in brackets, and they signify the component group which directly connects to the particular function, as shown in Figure 8-4.

Structure FAST and components into AHP format

FAST of the turbocharger is arranged into AHP format, as shown in Figure 8-4. The bottom boxes embodied as a, b, c up to s are assigned to the component groups, as explained in Table 8-7. The principle to complete this structure is revisited from section 6.2.2; moreover, the structure is ready to perform a pair-wise comparison.

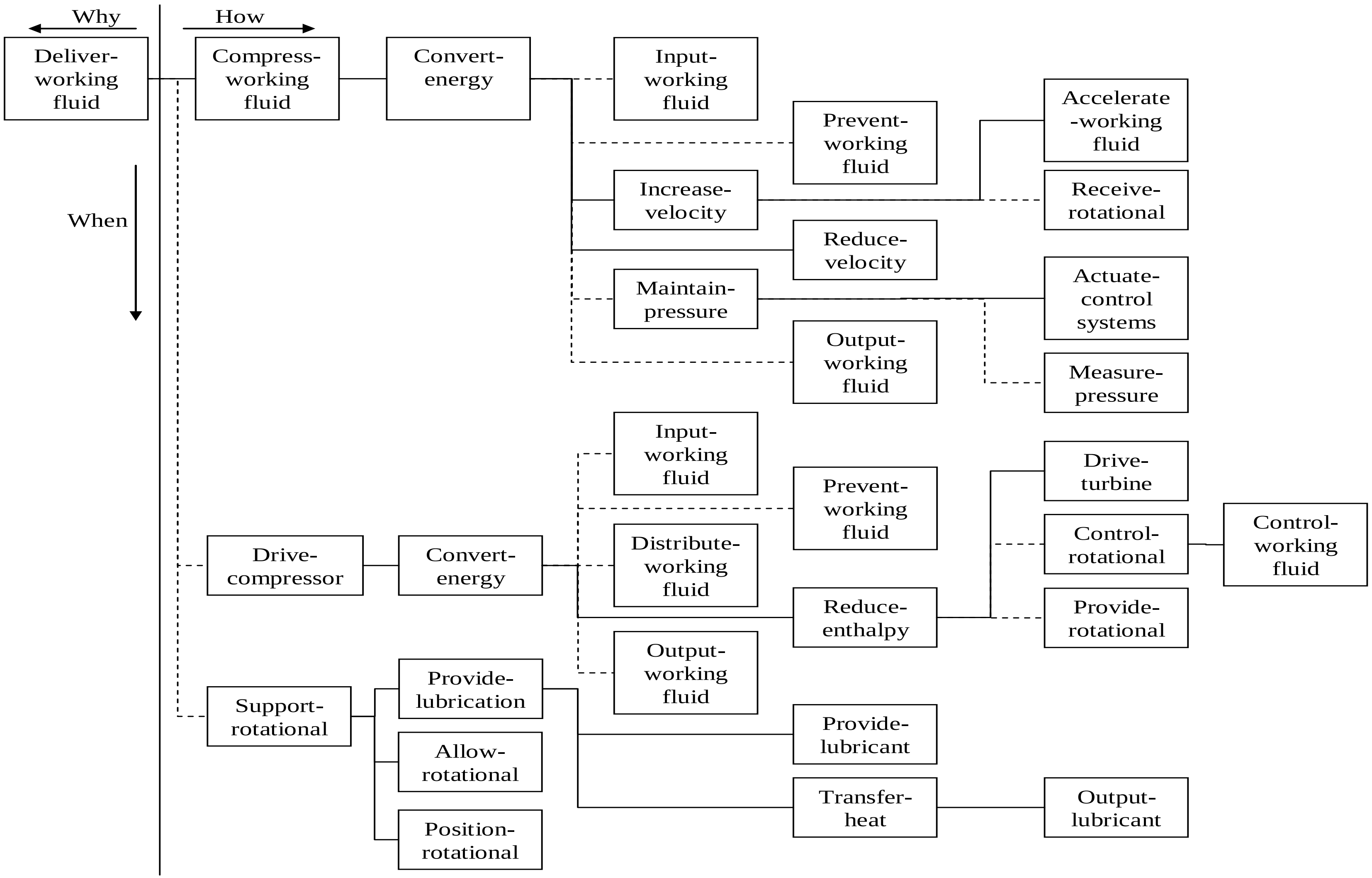


Figure 8-3: FAST of a turbocharger from company E

Table 8-7: Function-component relationships matrix of the turbocharger

Sub-functions	Components										
Functions directly linked to components	Turbine wheel	Turbine housing	Compressor wheel	Compressor housing	Actuator	Waste gate	Turbine housing seal	Compressor housing seal	Turbocharger shaft	Bearing housing	Oil seal
Input-working fluid (a)				×							
Prevent-working fluid (b)				×				×			
Accelerate-working fluid (c)			×	×							
Receive-rotational (d)									×		
Reduce-velocity (e)				×							
Measure-pressure (f)				×							
Actuate-control systems (g)					×	×					
Output-working fluid (h)				×							
Input-working fluid (i)		×									
Prevent-working fluid (j)		×					×				
Distribute-working fluid (k)		×									
Drive-turbine (l)	×	×									
Control-working fluid (m)		×				×					
Provide-rotational (n)									×		
Output-working fluid (o)		×									
Provide-lubricant (p)										×	×
Output-lubricant (q)										×	
Allow-rotational (r)									×	×	
Position-rotational (s)		×		×						×	

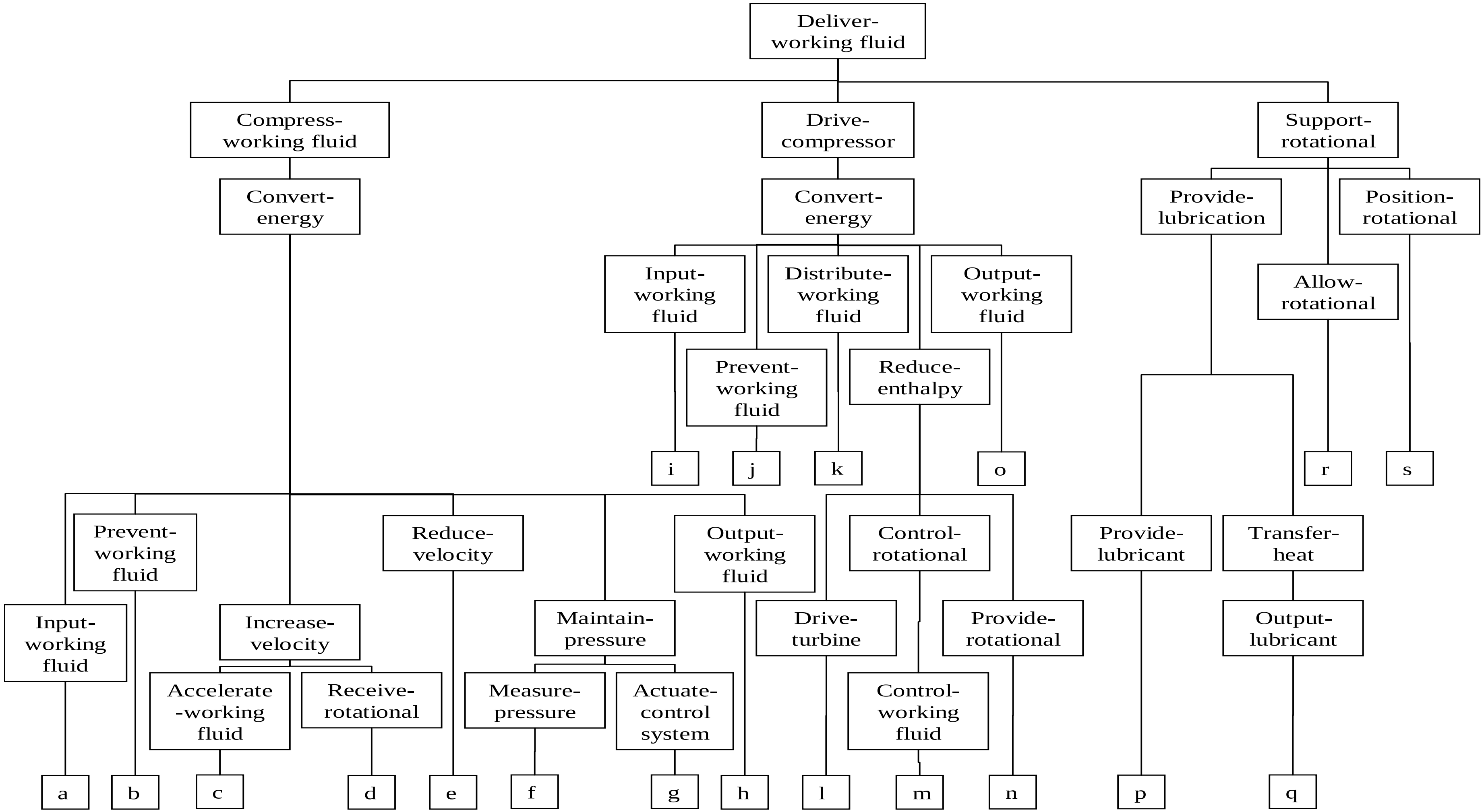


Figure 8-4: The AHP structure for FAST and components supported turbocharger functions

Table 8-8: Function-component relationship matrix with the level of effort spent on functions and components for turbocharger

Sub-functions	Weighted average for each component									
Functions directly linked to components	Turbine wheel	Turbine housing	Compressor wheel	Compressor housing	Actuator	Waste gate	Turbine housing seal	Compressor housing seal	Turbocharger shaft	Bearing housing	Oil seal
Input-working fluid (a)				1, *0.0147*							
Prevent-working fluid (b)				0.5, *0.0261*				0.5, *0.0261*			
Accelerate-working fluid (c)			0.9, *0.0419*	0.10, *0.0047*							
Receive-rotational (d)									0.5, *0.0466*		
Reduce-velocity (e)				1, *0.0829*							
Measure-pressure (f)				1, *0.0123*							
Actuate-control systems (g)					0.5, *0.0308*	0.5, 0.0308					
Output-working fluid (h)				1, *0.0165*							
Input-working fluid (i)		1, *0.0266*									
Prevent-working fluid (j)		0.5, *0.0289*					0.5, *0.0289*				
Distribute-working fluid (k)		1, *0.0209*									
Drive-turbine (l)	0.5, *0.0586*	0.5, *0.0586*									
Control-working fluid (m)		0.5, *0.0373*				0.5, *0.0373*					
Provide-rotational (n)									1, *0.0119*		
Output-working fluid (o)		1, *0.0245*									
Provide-lubricant (p)										0.5, *0.0154*	0.5, *0.0154*
Output-lubricant (q)										1, *0.0062*	
Allow-rotational (r)									0.5, *0.0741*	0.5, *0.0741*	
Position-rotational (s)		0.2, *0.0296*		0.2, *0.0296*						0.6, *0.0889*	

Pair-wise comparisons for functions and components

The pair-wise comparison method is applied to the AHP structure (Figure 8-4) of the turbocharger. Both full and chain wise paired comparisons are implemented in this exercise, and the pair-wise comparison results are in Table 8-8. The values in italics are local relationships while the others are the global relationships, as defined in section 6.2.3. All sub-functions are similar to those shown in Table 8-7a. The detailed comparison results for function and component levels are given in Appendix J.

Design effort allocations

In practice, the turbocharger is a subsystem within an engine. If it is considered as a stand alone development project, it requires approximately 2.5 years by two engineers working full-time to design it. UK working standards are also applied to this case; the design effort, (E_{given}) in this case, is summarised in Table 8-9.

Table 8-9: The total design effort given for the turbocharger provided by company E

Items	Quantities	Units
Provided lead time	2.5	Years
Staff required	2	Engineers
Working hours	8	hours/day
Working day	5	Days/week
Working week (except holiday)	46	Weeks/year
Total design effort given (E_{given})	$2.5 \times 2 \times 8 \times 5 \times 46 = 9{,}200$	Hours

The E_{given} is allocated to each component by multiplying with the global relationship matrix and the results are approximately displayed as integers in Table 8-10. All sub-functions are similar to those shown in Table 8-7a.

Component relationship matrix

This section is to develop a component relationship matrix. The direct and indirect relationship matrixes are as follows:

Table 8-10: The allocated design effort from the given design effort (E_{given}) for turbocharger

Functions directly linked to components	Weighted average for each component										
	Turbine wheel	Turbine housing	Compressor wheel	Compressor housing	Actuator	Waste gate	Turbine housing seal	Compressor housing seal	Turbocharger shaft	Bearing housing	Oil seal
Input-working fluid (a)				135							
Prevent-working fluid (b)				240				240			
Accelerate-working fluid (c)			385	43							
Receive-rotational (d)									428		
Reduce-velocity (e)				763							
Measure-pressure (f)				113							
Actuate-control systems (g)					283	283					
Output-working fluid (h)				151							
Input-working fluid (i)		245									
Prevent-working fluid (j)		265					265				
Distribute-working fluid (k)		192									
Drive-turbine (l)	539	539									
Control-working fluid (m)		343				343					
Provide-rotational (n)									110		
Output-working fluid (o)		226									
Provide-lubricant (p)										142	142
Output-lubricant (q)										57	
Allow-rotational (r)									681	681	
Position-rotational (s)		273		273						818	
Total	539	2,082	385	1,719	283	626	265	240	1,220	1,698	142

Note: The hour is the unit applied in this table

Develop component direct relationships: The component direct relationships are developed with the local relationship matrix into Eq. 6-2 and the diagonal values are not taken into account as recommended in section 6.2.5. The component direct relationships are those represented as the non-highlighted cells in Table 8-11, while the others are indirect relationships.

Develop component indirect relationships: There are no historical failure data provided in this case study, hence, failure modes from the FMEA document are considered. In addition, the skimmed version of the FMEA document is shown in Table 8-12. Only the open issues from the FMEA are shown in the table. They are the outstanding issues from others; so the failure relationships among them still exist. In Table 8-12, companies, names and RPN information are covered. Columns one to three are from the provided document while columns four and five are from the analysis by two experts. Both columns are contained within the criteria to select issues for analysis with the zigzag method. Only the design issues, as shown in column four, are selected; therefore, issues two and eight are not considered. Even though there is more than one solution to solve a considered failure mode, such as issues four and five, they are counted as one issue in this method. The failure modes which are not directly related to the turbocharger are not considered, as defined by column five. Hence, failure modes one, two and eight are not further considered because the problems are from the engine not the turbocharger.

Apply zigzag method to capture failure relationships: Failure modes three, nine and ten are not further considered because there is only one component involved in each of them, so there is no failure relationship to the other component. Therefore, only failure modes four and five (considered as one), and seven are analysed with the zigzag technique, as shown in Table 8-13.

Failure mode three does not satisfy the Maintain-pressure function; however, this function is achieved with the Actuate-control system function. Therefore, the first component related to this failure is the actuator. The failure cause is denoted as "Incorrect function of smart waste gate", but the smart waste gate is composed of an electronics control actuator and a waste gate. Therefore, "*unoptimise operation*" is stated in the table to satisfy the zag action, and the component related to this failure is the waste gate. Lastly, excessive oil entering the air system does not satisfy the

Prevent-working fluid function and the component engaged to this failure is the compressor housing seal. The failure cause stated in the document is shaft seal failure or wear which is explained as surface fatigue in Collins et al. (1976). Hence, the inttermittent loads created by the compressor wheel and turbine wheel are the critical components resulting from the surface fatigue.

<u>*Assign relationships into DSM matrix:*</u> Once the failure relationships are addressed, they are ready to be assigned to the DSM matrix. Nevertheless, the linkages between the actuator and the waste gate are similar to the direct relationship shown in Table 8-11. Therefore, only failure relationships from issue two, as taken from Table 8-13, are put into the DSM matrix (Table 8-14). Once the relationships are signified as one, the normalised values are calculated using Eq. 6-3 and these are shown in Table 8-14, in italics. Moreover, the calculated values are revealed as the painted cells in Table 8-11; and then the relationships matrix is ready to estimate, as represented in the adjacent sub-section.

Table 8-11: Component-component relationship matrix of the turbocharger given by company E

Components	Turbine wheel	Turbine housing	Compressor wheel	Compressor housing	Actuator	Waste gate	Turbine housing seal	Compressor housing seal	Turbocharger shaft	Bearing housing	Oil seal
Turbine wheel		0.25						0.25			
Turbine housing	0.25			0.04		0.25	0.25	0		0.12	
Compressor wheel				0.09				0.25			
Compressor housing		0.04	0.09					0.25		0.12	
Actuator						0.25					
Waste gate		0.25			0.25						
Turbine housing seal		0.25									
Compressor housing seal	0.25		0.25	0.25							
Turbocharger shaft										0.25	
Bearing housing		0.12		0.12					0.25		0.25
Oil seal										0.25	

Table 8-12: The opened failure modes issues captured from FMEA document

Failure mode	Failure cause	Actions	Issue types	Components
Exhaust temp outside limit	Performance sensitivity unknown	Confirmation of exhaust temp prior to Turbo Charger design freeze	Design	Engine
Exhaust temp outside limit	Exceeds altitude limit	-Bring forward to Phase 1B -Preliminary review with MATLAB input	Operation	Engine
Excessive energy extracted from exhaust gas (higher shaft speed & boost)	Incorrect function of waste gate	-Supplier selection to be confirmed -Review Supplier FMEA -Review supplied APQP and quality data	Design	Waste gate
Excessive induction air pressure	Incorrect function of smart waste gate	-Supplier selection to be confirmed -Review Supplier FMEA -Review supplied APQP and quality data	Design	Actuator, Waste gate
Excessive induction air pressure	Incorrect function of smart waste gate	-Supplier selection to be confirmed -Review Supplier FMEA	Design	Actuator, Waste gate
Unstable induction air pressure	Excessive inlet restriction causing compressor instability	-Specific Engine Testing in Design Validation (DV) Phase -Investigate variation of inlet restriction with Smart Waste gate operational	Design	Engine filter
Excessive oil enters air system	Shaft seal failure	Note: this from in-cylinder FMEA Plan examination of Turbo charger seals and induction system on Phase 1A & 1B engines	Design	Compressor wheel, Turbine wheel, Compressor housing seal
Insufficient oil feed	Prime time after filter change	-Environmental test -Pressure monitoring at turbocharger	Operation	Oil filter
Does not drain	Incorrect hose material selected	Demonstrate capability to achieve grade ability objective with drainage margin	Design	Bearing housing
Does not drain	Incorrect hose material selected	Conduct Rig Test to establish temperature margin for material selected	Design	Bearing housing

Table 8-13: Analysis of the turbocharger's component failure relationships

Functions (Obtained from FAST)	Detailed analysis for failure modes	Components related to failures
Actuate-control system (under Maintain-pressure)	Excessive induction air pressure Un-optimise operation	Actuator Waste gate
Prevent-coolant	Excessive oil enters air system Shaft seal failure (wear/surface fatigue) Intermittences/cyclical movements	Compressor housing seal Compressor wheel Turbine wheel

Table 8-14: Component-component relationships due to failures of the turbocharger

Components	Turbine wheel	Compressor wheel	Compressor housing seal
Turbine wheel			1, *0.25*
Compressor wheel			1, *0.25*
Compressor housing seal	1, *0.25*	1, *0.25*	

Estimate design rework effort

This sub-section still applies the WTM method to calculate the design rework effort. Therefore, the ideal design effort and constant for Eq. 6-5 are obtained as follows:

Calculate the ideal design effort: The allocated ideal design effort for the turbocharger is calculated using the similar principle, as represented in section 6.2.6. The required elements to calculate the ideal design effort are shown in Table 8-15a, while the ideal design effort for each component is in column five of Table 8-15b. Once $Ef_{given}/Ef_{extreme}$ is calculated, the ideal design effort matrix of the turbocharger can be shown, as in Table 8-16.

Develop input vector u_0 by using expected design issues: There are two open issues in which the design team still has no confidence to design the new product. So, they are treated as expected design issues to estimate design rework effort, as revealed in column two of Table 8-17. Both issues are from the waste gate and the compressor housing seal when they complete the Control-working fluid and the Prevent-working fluid functions respectively. Once the percentage of each issue is assigned, the vector u_0 is calculated automatically from the components' ideal design effort, as shown in column four, and then the estimated design rework effort embedded with a knock-on effect to each component is achieved in column five. It is seen that the estimated design rework effort $(Ef_{estimated})$ is approximately 100% more than expected $(Ef_{expected})$. Hence, the majority of the additional design rework effort is from the components which were not expected in the first attempt. In addition, this is the evidence to support the existence of the knock-on effect.

Table 8-15: Calculating $Ef_{extreme}$ for turbocharger a) Matrix for $S(1-\Lambda)^{-1}S^{-1}$ of $\mathrm{M}_{component}$ b) u_0 and U vector for extreme case

(a)

1.1747	0.3515	0.0974	0.1174	0.0234	0.0937	0.0879	0.3474	0.0161	0.0643	0.0161
0.3515	1.2805	0.0412	0.1092	0.0854	0.3415	0.3201	0.1255	0.0476	0.1906	0.0476
0.0974	0.0412	1.1044	0.192	0.0027	0.011	0.0103	0.3484	0.008	0.032	0.008
0.1174	0.1092	0.192	1.1322	0.0073	0.0291	0.0273	0.3604	0.0426	0.1702	0.0426
0.0234	0.0854	0.0027	0.0073	1.0724	0.2894	0.0213	0.0084	0.0032	0.0127	0.0032
0.0937	0.3415	0.011	0.0291	0.2894	1.1577	0.0854	0.0335	0.0127	0.0508	0.0127
0.0879	0.3201	0.0103	0.0273	0.0213	0.0854	1.08	0.0314	0.0119	0.0476	0.0119
0.3474	0.1255	0.3484	0.3604	0.0084	0.0335	0.0314	1.2641	0.0167	0.0666	0.0167
0.0161	0.0476	0.008	0.0426	0.0032	0.0127	0.0119	0.0167	1.0745	0.2981	0.0745
0.0643	0.1906	0.032	0.1702	0.0127	0.0508	0.0476	0.0666	0.2981	1.1923	0.2981
0.0161	0.0476	0.008	0.0426	0.0032	0.0127	0.0119	0.0167	0.0745	0.2981	1.0745

(b)

Components	Design rework effort vector for extreme case (hours)		$Ef_{given}/Ef_{extreme}$	Ideal design effort for each component (hours)
	u_0	U		
Turbine wheel	539	1,907	0.4358	235
Turbine housing	2,082	3,801		907
Compressor wheel	385	1,053		168
Compressor housing	1,719	2,772		749
Actuator	283	723		123
Waste gate	626	1,757		273
Turbine housing seal	265	1,216		116
Compressor housing seal	240	1,673		105
Turbocharger shaft	1,220	2,027		531
Bearing housing	1,698	3,231		740
Total	9,200 (Ef_{given})	21,110 $(Ef_{extreme})$		4,009 (Ef_{ideal})

Table 8-16: E_{ideal} of the turbocharger

Functions directly linked to components	Weighted average for each component										
	Turbine wheel	Turbine housing	Compressor wheel	Compressor housing	Actuator	Waste gate	Turbine housing seal	Compressor housing seal	Turbocharger shaft	Bearing housing	Oil seal
Input-working fluid (a)				59							
Prevent-working fluid (b)				105				105			
Accelerate-working fluid (c)			168	19							
Receive-rotational (d)									187		
Reduce-velocity (e)				333							
Measure-pressure (f)				49							
Actuate-control systems (g)					123	123					
Output-working fluid (h)				66							
Input-working fluid (i)		107									
Prevent-working fluid (j)		116					116				
Distribute-working fluid (k)		84									
Drive-turbine (l)	235	235									
Control-working fluid (m)		149				149					
Provide-rotational (n)									48		
Output-working fluid (o)		98									
Provide-lubricant (p)										62	62
Output-lubricant (q)										25	
Allow-rotational (r)									297	297	
Position-rotational (s)		119		119						356	
Total	235	907	168	749	123	273	116	105	531	740	62

Note: The hour is the unit applied in this table

Table 8-17: The input vector u_0 and the estimated design rework output vector U of the turbocharger

Components	Expected design issues	Percentage judged to resolve issues	Design effort vector for the expected issues (hours)	
			u_0	U
Turbine wheel			0	21.00
Turbine housing			0	16.78
Compressor wheel			0	18.58
Compressor housing			0	19.75
Actuator			0	9.09
Waste gate	Incorrect function of waste gate (Control-working fluid)	20%	29.89	36.35
Turbine housing seal			0	4.19
Compressor housing seal	Excessive oil enters air system (Prevent-working fluid)	50%	52.38	67.21
Turbocharger shaft			0	1.25
Bearing housing			0	5.01
Oil seal			0	1.25
Total			82.27 ($Ef_{expected}$)	200.45 ($Ef_{estimated}$)

8.1.3 Connect the DRePOE and DREE methods

Convert design rework effort to design lead time

The estimated design rework effort is converted to be the lead time with the assumptions and requirements proposed in section 6.3.1, so it is equivalent to one engineer working full-time to resolve the issues. From the estimation with the DREE method, the estimated lead time is approximately one month and one week.

During the testing of this method, the new product was not yet finished. Nonetheless, the experts mentioned that the worst case to resolve these issues including re-testing would be approximately two and a half months. However, the experts accepted the validity of the lead time calculated, because the lead time to revisit the design and re-testing are almost equal. The full validation of this method is expressed in section 8.3.

Table 8-18: Lead time for resolving design issues for turbocharger case

Items	Quantities	Units
Estimated design effort	200.45 $(Ef_{estimated})$	hours
Lead time for one engineer	$200.45 \div 1 \approx 200.45$	hours
Convert to be working day (8 hours/day)	$200.45 \div 8 \approx 25.06$	days
Convert to be working week (5 days/ week)	$25 \div 5 \approx 5.01$	weeks
Convert to be working month (4 weeks/month)	$25 \div 5 \approx 1.26$ (Estimated)	months
Worst case design rework and re-testing lead time to resolve two issues	2.5 (Experts' judgement)	months

The association between the DREE and the DRePOE methods

A summary of the design rework probability and the design rework effort from the expected design issues are given in Table 8-19. The linkage between the DRePOE and DREE method, as proposed in section 6.3.2, is also implemented in this case study.

Table 8-19: The results from DRePOE and DREE methods for turbocharger case

Methods	Results
DRePOE	$\approx$ 6.56-13.15%
DREE	$\approx$ 200.45 hours (1 month and 1 week)

In summary, it is interpreted that the new design would have approximately 6.56-13.15% of the design rework from the total supplied products in the testing and refinement phase. Moreover, the probability would be a result of the waste gate and the compressor housing seal because the design team has less confidence in designing them successfully.

If these two issues occur in the testing and refinement phase, the worst case design rework effort would be 200.45 hours or one month and one week of lead time.

8.1.4 Apply the PriDDREB Method to the Turbocharger Industrial Case Study

Generate possible component groups

The methodology to obtain the possible component groups proposed in section 7.2.1 is applied to the turbocharger case as follows:

Calculate the component number in each group with the Pareto Analysis: There are 11 components in the turbocharger. Once Eq. 7-1 is applied to this case the component number in each group (k_{Pareto}) is calculated and is shown as follows:

$$k_{Pareto} = (0.2 \times 11)_{integer} \approx 3$$

However, the guideline for Eq. 7-1 requests levelling up the non-integer result to the highest integer close to it; therefore, the k_{Pareto} for the turbocharger case is three.

Calculate the optimistic amount of component groups: From Table 8-7, there are 19 functions directly linked to components and this number is realised as f_c for Eq. 7-2. Hence, G_{Op} is derived by the mentioned equation and there are optimistically 969 component groups.

$$G_{Op} = \frac{19!}{3!(19-3)!} = 969$$

Create the possible component groups: The possible component groups for the turbocharger case are calculated by MATLAB complied with Eq. 7-3 and the $G_{Possible}$ is 3,359 groups.

Create component groups for optimisation (G_{Opt}): There are 2,174 component groups to put into the optimisation and they are selected by the guidelines prearranged in section 7.2.1 and MATLAB programming. Table 8-20 collects all required variables to optimise as follows:

Table 8-20: Required variables to optimise in support of the turbocharger case

Variables	Values
k_{Pareto}	3 components per group
f_c	19 functions
G_{Op}	969 groups
$G_{Possible}$	3,359 groups
G_{Opt}	2,174 groups

Assign objective function and constraints to component groups

There is no difference in terms of principle to assign the objective function and constraints in the turbocharger case compared with the automotive water pump case; however, 5% of the ideal design effort is approximately 200.47 hours.

Apply optimisation technique to the assigned groups

The linear programming, as implemented in chapter 7, is valid in this case study. The optimisation results are summarised in Table 8-21. All results are plotted against component combination labels as shown in Figure 8-5.

Table 8-21: The summary for turbocharger design rework effort optimisation

Maximum design rework effort	568.56 hours (14.63% of Ef_{ideal})
Minimum design rework effort	217.78 hours (5.43% of Ef_{ideal})
Range	568.56-217.78=368.78 hours
Optimisation results to prioritise component design	2,174 groups

Prioritise component design with optimisation results

Identify clusters of optimisation results: There are 29 linkages (nf) among components and functions considered from Table 8-7; hence, the clusters for optimisation results are calculated by Eq. 7-4. There are nine clusters for optimisation results.

$$Cl_{Turbocharger} = \left(\frac{29}{3}\right)_{integer} = 9.67 \approx 9$$

Identify range of design rework effort for each cluster: Once total clusters are identified, the range for each cluster is attained by Eq. 7-5. The range for each cluster is approximately 40.98 hours, which is about one week if there are 8 working hours per day. The component group number in each cluster is in column four of Table 8-22.

$$DreR_C = \left(\frac{568.56 - 217.78}{9}\right) \approx 40.98 \text{ hours}$$

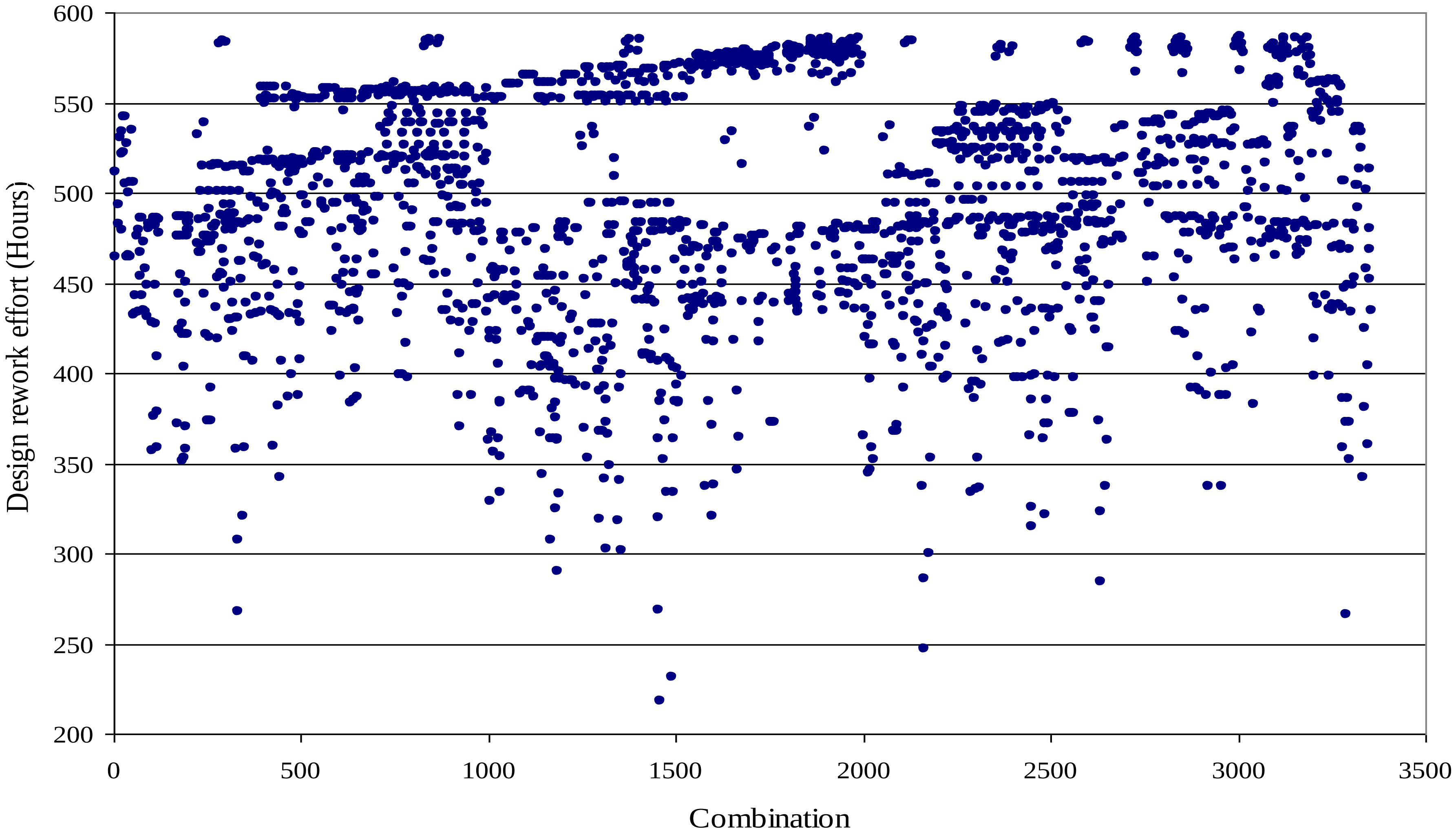


Figure 8-5: The optimisation results from turbocharger's component groups

Table 8-22: The design rework effort ranges of each cluster (Turbocharger case)

Clusters	Upper bound (hours)	Lower bound (hours)	Component groups in each cluster
1	586.56	$568.56 - 40.98 \approx 545.59$	526
2	545.59>	$545.59 - 40.98 \approx 504.61$	442
3	504.61>	$504.61 - 40.98 \approx 463.64$	557
4	463.64>	$463.64 - 40.98 \approx 422.66$	365
5	422.66>	$422.66 - 40.98 \approx 381.69$	169
6	381.69>	$381.69 - 40.98 \approx 340.71$	76
7	340.71>	$340.71 - 40.98 \approx 299.74$	30
8	299.74>	$299.74 - 40.98 \approx 258.76$	6
9	258.76>	$258.76 - 40.98 \approx 217.78$	2
Total			2,174

Prioritise component design with frequency counting: The prioritisation component design results are in Table 8-23.The prioritisation is completed for three components (k_{Pareto}) in each cluster at a time. The first group required to put more effort into to prevent design rework issues is the compressor housing seal, the compressor wheel and the turbocharger shaft; moreover, they serve the Prevent-working fluid, the Accelerate-working fluid, and the Receive-rotational functions respectively.

In Table 8-23, the components which have the top k_{Pareto} frequency for the design rework effort range from 586.56 to 545.59 hours as mentioned earlier and have the considerably opportunity to deliver the design rework effort in this range compared with others. They are not necessary to form a component group, but any component groups which have at least one of these components with the providing functions would potentially deliver the mentioned design rework effort. This interpretation is implemented to other clusters and the component prioritisation is achieved. The component prioritisation based on the design rework effort is summarised in Table 8-24. The components recommended to focus on in each cluster comply with the Pareto Analysis. There are six components in the last two clusters (Table 8-24) which have zero frequencies. Therefore, they are the last component groups to be prioritised; however, they are interpreted as indifferent to prioritise due to their null frequencies.

Table 8-23: The frequency counting from the optimisation results (Turbocharger case)

Functions directly linked to components	Components	Clusters and ranges of design rework effort (hours)								
		586.56 to 545.59	545.59> to 504.61	504.61> to 463.64	463.64> to 422.66	422.66> to 381.69	381.69> to 340.71	340.71> to 299.74	299.74> to 258.76	258.76> to 217.78
Input-working fluid	Compressor housing	3	29	93	40	11	14	2	1	0
Prevent-working fluid	Compressor housing	3	88	24	41	15	1	0	0	0
	Compressor housing seal	117	76	71	25	4	2	0	0	0
Accelerate-working fluid	Compressor wheel	118	17	52	57	39	12	0	0	0
	Compressor housing	10	5	39	50	35	16	12	2	1
Receive-rotational	Turbocharger shaft	104	19	49	57	17	15	5	0	0
Reduce-velocity	Compressor housing	98	13	34	48	0	0	0	0	0
Measure-pressure	Compressor housing	24	20	63	52	20	10	2	1	1
Actuate-control systems	Actuator	34	51	79	46	42	24	13	1	0
	Waste gate	45	68	61	64	25	2	0	0	0
Output-working fluid	Compressor housing	24	41	62	44	14	5	2	1	0
Input-working fluid	Turbine housing	69	72	36	12	3	2	0	0	0
Prevent-working fluid	Turbine housing	65	67	27	9	4	1	0	0	0
	Turbine housing seal	27	46	90	51	47	25	9	0	0
Distribute-working fluid	Turbine housing	70	63	33	17	8	1	2	0	0
Drive-turbine	Turbine wheel	78	59	91	61	6	0	0	0	0
	Turbine housing	85	41	38	8	1	0	0	0	0
Control-working fluid	Turbine housing	90	41	34	8	1	0	0	0	0
	Waste gate	46	51	70	74	30	0	0	0	0
Provide-rotational	Turbocharger shaft	34	33	73	52	34	20	12	5	1
Output-working fluid	Turbine housing	77	59	33	17	4	2	2	0	0
Provide-lubricant	Bearing housing	43	54	57	47	15	5	1	1	0
	Oil seal	43	30	57	65	49	30	14	2	1
Output-lubricant	Bearing housing	43	35	62	48	26	17	9	4	2
Allow-rotational	Turbocharger shaft	30	45	79	43	28	14	5	0	0
	Bearing housing	49	65	94	8	6	3	0	0	0
Position-rotational	Turbine housing	70	41	32	13	6	1	0	0	0
	Compressor housing	36	41	37	34	11	3	0	0	0
	Bearing housing	43	56	101	4	6	3	0	0	0

Table 8-24: The component prioritisation based on design rework effort and frequencies (Turbocharger case)

Functions directly linked to components	Components	Design rework effort ranges (hours)	Frequencies
Prevent-working fluid	Compressor housing seal	586.56> to 545.59	117
Accelerate-working fluid	Compressor wheel		118
Receive-rotational	Turbocharger shaft		104
Prevent-working fluid	Compressor housing	545.59> to 504.61	88
Input-working fluid	Turbine housing		72
Prevent-working fluid	Turbine housing		67
Input-working fluid	Compressor housing	504.61> to 463.64	93
Allow-rotational	Bearing housing		94
Position-rotational	Bearing housing		101
Actuate-control systems	Waste gate	463.64> to 422.66	64
Control-working fluid	Waste gate		74
Provide-lubricant	Oil seal		65
Accelerate-working fluid	Compressor housing	422.66> to 381.69	35
Actuate-control systems	Actuator		42
Prevent-working fluid	Turbine housing seal		47
Provide-rotational	Turbocharger shaft	381.69> to 340.71	20
Output-lubricant	Bearing housing		17
Allow-rotational	Turbocharger shaft		14
Measure-pressure	Compressor housing	340.71> to 299.74	2
Output-working fluid	Compressor housing		2
Distribute-working fluid	Turbine housing		2
Output-working fluid	Turbine housing		2
Provide-lubricant	Bearing housing	299.74> to 258.76	1
Reduce-velocity	Compressor housing		0
Drive-turbine	Turbine wheel		0
Drive-turbine	Turbine housing	258.76> to 217.78	0
Control-working fluid	Turbine housing		0
Position-rotational	Turbine housing		0
Position-rotational	Compressor housing		0

8.2 INDUSTRIAL CASE STUDY 2: THE Macpherson STRUT SUSPENSION SYSTEM

The front macpherson strut suspension system for a passenger car is applied as the case study, and a Tier 1 automotive supplier from Detroit, USA is the participating company. The product engineer for the suspension system, in particular a knuckle, contributed his time to validate all methods, which were were sent over by email. However, they were implemented with close guidance from the researcher through telephone conversations. The expert’s details are shown with those of other experts in Table 8-48.

8.2.1 Apply the DRePOE Method to the Macpherson Strut Suspension System Case Study

Define a new product

The new product in this case is defined as the front suspension system developed with an American car OEM in 2010. Previously this company designed only the rear suspension. Hence, the additional function of the front suspension compared with the rear suspension is the ability to turn, while the latter system does not.

Define benchmark products and their design rework probabilities

Benchmark products: There are two rear suspension systems regarded as benchmark products in this case study. Benchmarks 1 and 2 were conducted in 2006 and 2007 respectively. There were 30% and 10% from benchmarks 1 and 2 sequentially. The expert raised concerns about experience as a major driver for design rework occurrences; hence, benchmark 1 requires a significantly higher percentage of design rework occurrences because the expert did not have an equivalent design skill when compared with benchmark 2.

Table 8-25: The probability of design rework occurrence from previous suspension system

Products	Probabilities of design rework occurrences	Sources
Benchmark 1	30%	Experts' judgement
Benchmark 2	10%	Experts' judgement

Structure drivers in AHP format

Structure drivers reducing design rework occurrence: The drivers are generic, so there is no change in the structure. In addition, there are two benchmarked products being compared as well as one new product, hence the structure is similar to the automotive water pump and the turbocharger, and the structure from the previous case is applicable to this exercise.

Structure products under the Novelty Level: The major novelty step in the new product compared with Benchmarks 1 and 2 is designing the front suspension system, as stated earlier. Figure 8-6 reveals the front and the rear suspension systems. The suspension system accommodates the passengers in a car. The key components of the suspension system are a spring and a shock absorber, both of which are assembled to be struts as shown in Figure 8-6. The spring receives disturbance from road roughness while the shock absorber dissipates the conceived energy. The suspension's major movement is in a vertical direction and it is supported by the control arms. The cross member from the rear suspension and the engine cradle from the front suspension are to connect the systems to the vehicle body. Therefore, the critical difference between the front and the rear suspension systems is the ability to steer. The front suspension system allows a driver to change direction with the steering wheel through the steering gear; therefore, the steering knuckle arm and the steering knuckle itself are crucial. The additional functions lead to more complicated loads to analyse in the front suspension which is defined as the novelty of the design team members who are familiar with the rear suspension system. This case is focused only on the front suspension system. The steering gear is a part that interfaces the suspension systems with the steering wheel, so it is not considered further in the DREE method.

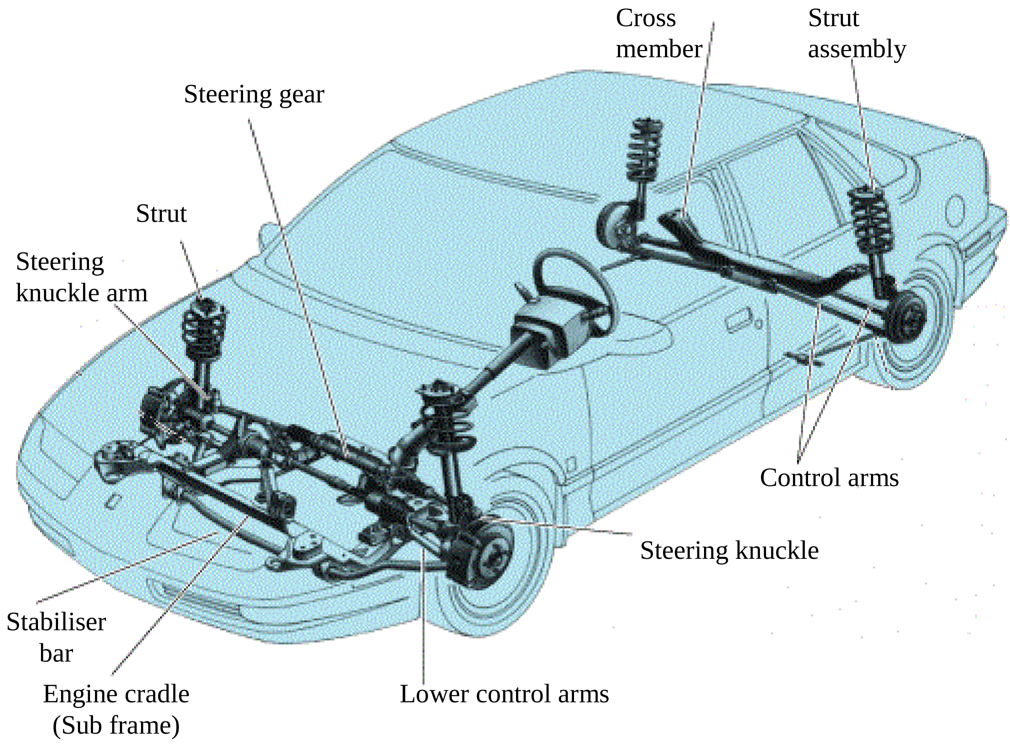


Figure 8-6: Schematic car suspension systems (adapted from www.answers.com)

Pair-wise comparisons of drivers for reducing design rework occurrence and Novelty Level

Either a full or incomplete comparison is implemented in this case, and the complete results are given in Appendix K; moreover, all *CR* and *LOC* of the drivers for reducing design rework occurrence are in the acceptable range, and the results are shown in Table 8-26a. Based on the company's context, the Clarity of Specification driver is not critical to design rework occurrence compared with the Exploitation of CAE Software. The numeric values shown in the column headings of Table 8.26b are the strength of each driver to "Design Rework Occurrence" taken from Table 8-26a.

Table 8-26: The weighted average scores of the design rework drivers of the front suspension a) Drivers for reducing design rework occurrence b) Comparing drivers against products

(a)

Drivers for reducing design rework occurrence	Weighted average
Exploitation of CAE Software	0.44
Coordination across Team Members	0.06
Lessons Learnt	0.21
Supplier expertise	0.19
Clarity of Specifications	0.03
Open Communication to Inform Design Time Issues	0.07
Total	1.00

(b)

Products	Weighted average					
	Exploitation of CAE Software (0.44)	Coordination across Team Members (0.06)	Lessons Learnt (0.21)	Supplier expertise (0.19)	Clarity of specifications (0.03)	Open Communication to Inform Design Time Issues (0.07)
New products	0.58	0.72	0.62	0.47	0.14	0.72
Benchmark 1	0.16	0.14	0.10	0.47	0.43	0.14
Benchmark 2	0.26	0.14	0.28	0.06	0.43	0.14
Total	1.00	1.00	1.00	1.00	1.00	1.00

The new product has the maximum weighted average score in the Novelty Level, as exposed in Table 8-27. The Novelty Level of the new product is approximately three as shown in column four of Table 8-28 and it is calculated using Eq. 5-2.

Table 8-27: The weighted average scores of Novelty Level of the suspension system

Products	Weighted Average for product Novelty Level	NL_{es}/NL_i	Estimated Novelty Level for the new product (LN)
New product	0.4545 (NL_{es})	Being estimated	3
Benchmark 1	0.0909 (NL_1)	5 (NL_{es}/NL_1)	
Benchmark 2	0.4545 (NL_2)	1 (NL_{es}/NL_2)	

Estimate design rework probability of occurrence

Obtain total weighted average: The total weighted scores from the drivers for reducing design rework occurrence are acquired using Eq. 5-4. The vector *D* from the mentioned equation is from Table 8.26a, while the matrix A_D is attained from Table 8-26b, so that the result is Table 8-28. In addition, the total weighted average scores are ready to estimate the design rework occurrence in the next sub-section.

Table 8-28: The total weighted average scores for design rework occurrence of each product

Products	Total weighted average scores
New product	0.57 (w_{es})
Benchmark 1	0.21 (w_1)
Benchmark 2	0.22 (w_2)
Total	1.00

Perform estimation: The estimated probability of design rework occurrence is in column six of Table 8-29 which is obtained using Eq. 5-2. The data in columns two, three and four are acquired from Tables 8-25, 8-27 and 8-28 respectively. From the estimation, the design rework probability of occurrence for the new product is approximately 22.33%. The estimated result is reasonable from the expert viewpoint; moreover, the detailed validation results for this method are discussed in section 8.3.1.

Table 8-29: The estimating design rework probability of occurrence of the suspension system

Products	Actual probability of design rework occurrence	Estimated Novelty Level for the New product (*LN*)	Total weighted average scores for each product	w_i/w_{es}	Estimated design rework probability of occurrence for the New product
New product	Being estimated	3	0.57 (w_{es})		≈ 22.33%
Benchmark 1	30%		0.21 (w_1)	0.37	
Benchmark 2	10%		0.22 (w_2)	0.38	

8.2.2 Apply the DREE Method to the Macpherson Strut Suspension System Industrial Case Study

Develop product functional structure and function-component relationships

Develop product functional structure: The Macpherson strut front suspension system is offered as case study two in this thesis. In reality, there are varieties of suspension systems; however, the Macpherson strut is an optimal design solution between ride comfort and cost for a light passenger car. The schematic drawing of the Macpherson strut design is shown in Figure 8-7. The cross member is to support the suspension system; hence, it is not considered in this thesis. The suspension system is one of the complicated systems in a road vehicle because it is designed to achieve either static or dynamic conditions. From Figure 8-8, the ultimate function is realised as the basic function (Provide-ride comfort) and the other three sub-functions are Isolate-road imperfection, Maintain-tyre contact, and Control-traction. From interviews, the suspension is designed to provide passengers' comfort mainly when the vehicle is moving. In addition, the vehicle is necessary to allow the driver to control in longitudinal and curving directions with minimal effort. Hence, safe driving cannot be achieved without good suspension. The Isolate-road imperfection function is considered when a vehicle moves on a rough road surface. Without this function, the passenger will feel all the road bumpiness. Moreover, this function is achieved by the Receive-road disturbance and the Control-road disturbance functions. Wheels must receive the road disturbance while they are rotating, known as shock, which transfers to the front hub, the wheel bearing, the hub seal, the knuckle, the lower ball joint, the lower control arm, the strut, the lower spring insulator, the coil spring, the strut bumper, the upper spring insulator, the strut bearing and the strut mount.

The strut in this case is working as a shock absorber to absorb the energy created from the road surface imperfection. It must be protected from an environment otherwise dust and humidity will make it deteriorate. Therefore, the dust shield is a crucial component. Moreover, heat is generated as the shock absorber takes up the energy from the road disturbance, so the strut must dissipate energy to the environment.

The Maintain tyre contact function is considered in longitudinal and cornering movements. This function is for safety considerations, because the driver cannot control the car if the tyres do not make contact with the road surface. There are both static and dynamics aspects to be conceived for longitudinal movement. If the vehicle is carrying loads, the riding height, see Figure 8-9b, will be lower than the unloaded suspension. This characteristic is crucial, because changing the height is directly related to a spring constant. One term necessary to understand is "*sprung mass*", which is the vehicle's mass supported by the coil spring, e.g. engine, transmission. In dynamics conditions, exceeding the load transferred between the front and back wheels during braking or acceleration is undesirable because it could make tyres have no contact with the road due to pitching (Figure 8-9b). Hence, Restrict-vehicle pitching function is to prevent this undesirable event. The components related to this function are composed of the spring, strut and stabiliser bar.

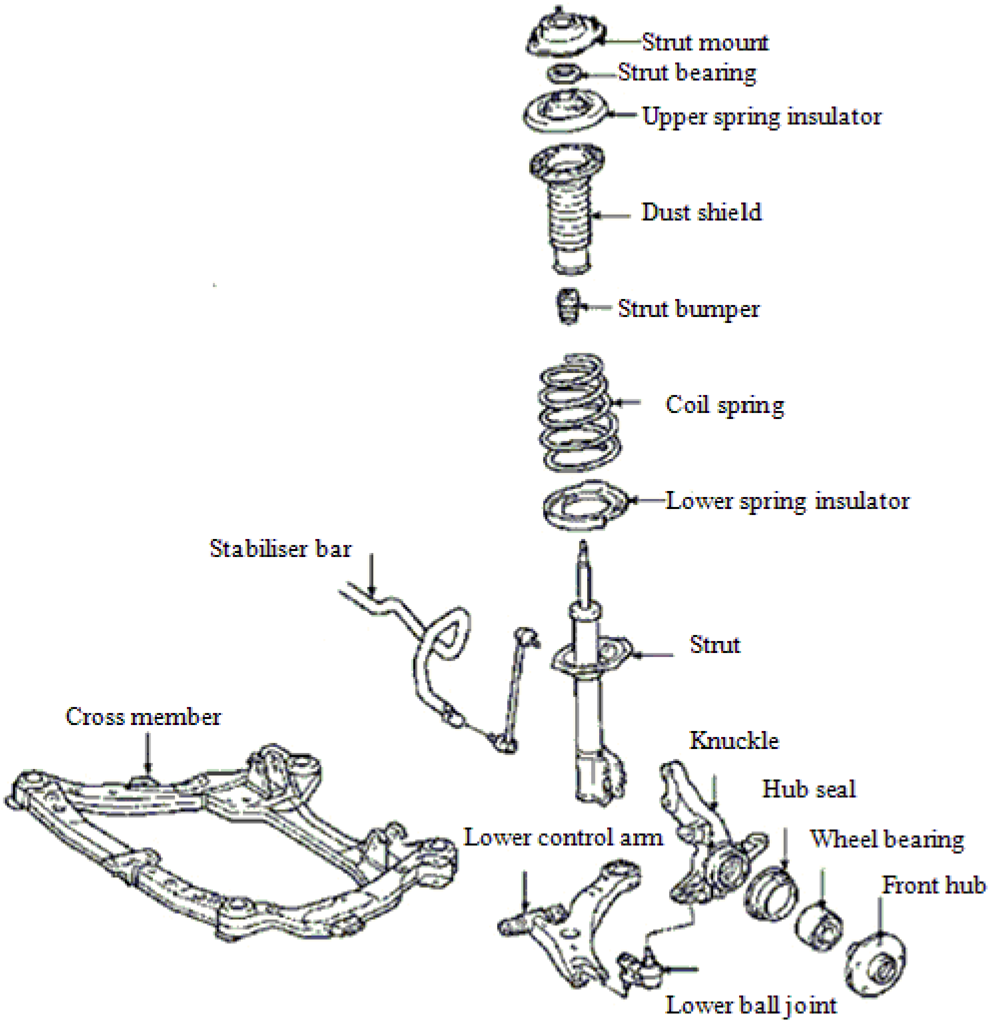


Figure 8-7: Schematic drawing for Macpherson strut front suspension system

When the car moves into a curve, it will roll because of the interactions between centrifugal forces and inertia. The Restrict-rolling load transferred function will keep tyres in contact with the road surface and this can be achieved by stabilsation between the left and right wheels (Stabilise-level function). The components to stabilise wheel levels consist of the spring, strut, lower ball joint, lower control arm and stabiliser bar. The Control-traction function is defined as the Provide-steering ability function. The suspension must keep the car in a straight direction with minimum driver effort to handle the steering wheel. The caster and toe angles are the key to achieving this function. The camber angle (Figure 8-9a) measures the tyre angle when looking at the car's front view. If the wheel leans toward the true vertical line, the camber is positive otherwise it is negative. The caster (Figure 8-9b) is to define the steering pivot from the car's side view. If the pivot tilts backwards, the caster is positive, otherwise it is negative. When the car's top view is evaluated, the toe angle is considered – either the wheels point inward or outward from the front direction, as revealed in Figure 8-9c. Restrictions to these three angles to optimise suspension characteristics are based on performances required. The front suspension needs to receive a steering input from the driver; moreover, it must be turned with minimal driver effort. The bracketed letters in FAST are the functions directly linked to components and they are to signify the relationships with components, as represented in Table 8-30.

Structure FAST and components into AHP format

FAST structure for the Macpherson strut is arranged into the AHP format, as shown in Figure 8-10. The principle to complete this structure is similar to section 6.2.2; moreover, the structure is ready to finish the pair-wise comparison.

Pair-wise comparisons for functions and components

The pair-wise comparison method is applied to the AHP structure (Figure 8-10) of the Macpherson strut suspension system. The full and chain wise comparison methods are applied in this study. The pair-wise comparison results are shown in Table 8-31. The values in italics are global relationships while the others are local relationships. Only sub-functions directly linked to components are shown in the table. The detailed comparison results for function and component levels are given in Appendix L.

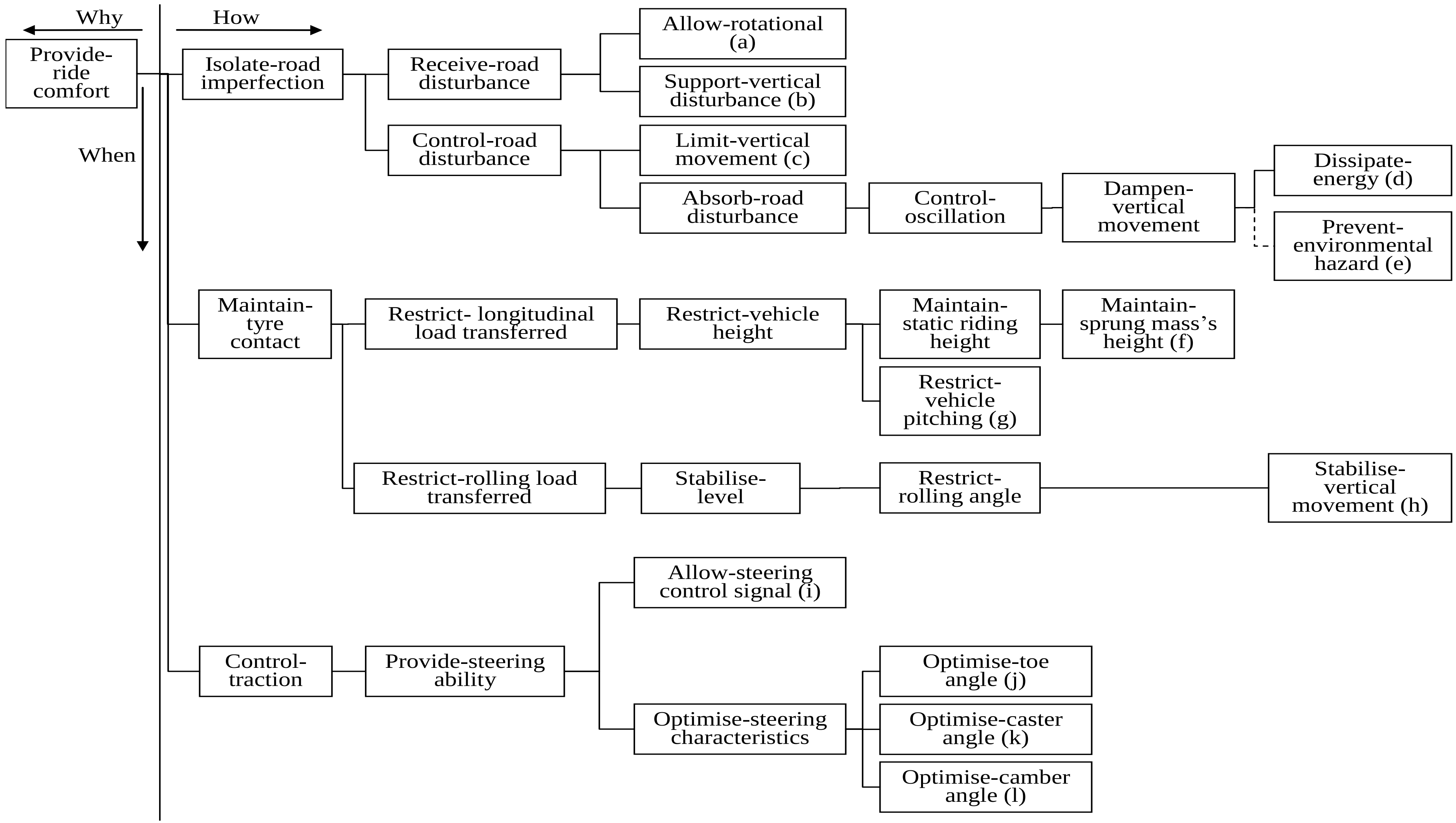
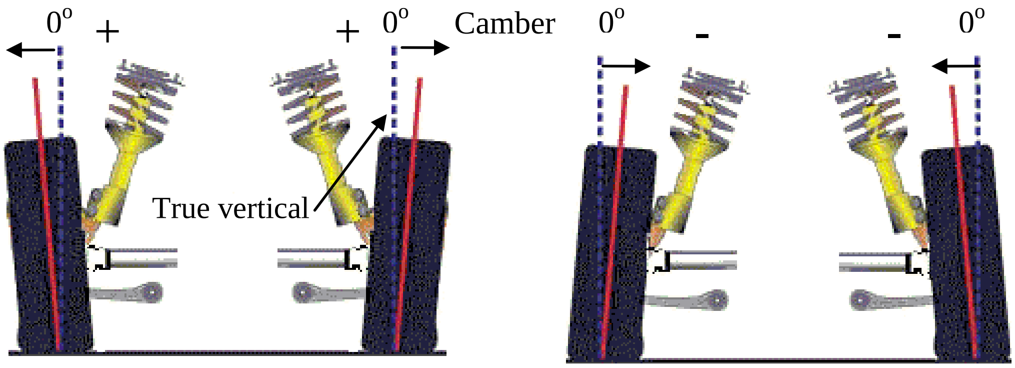
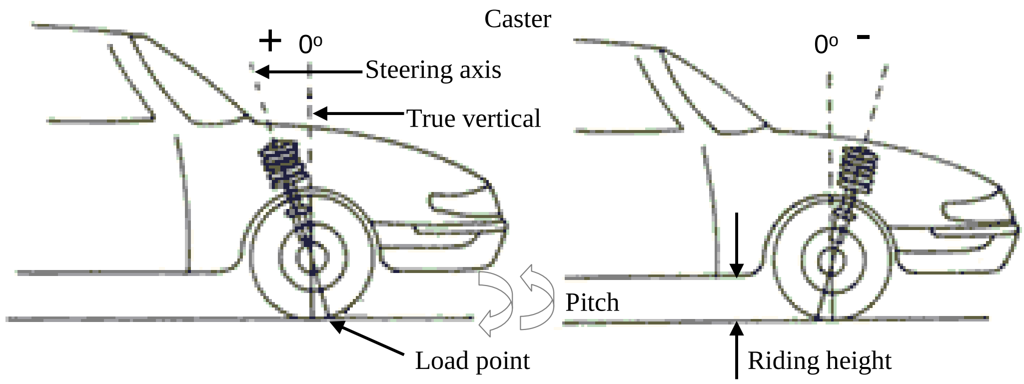


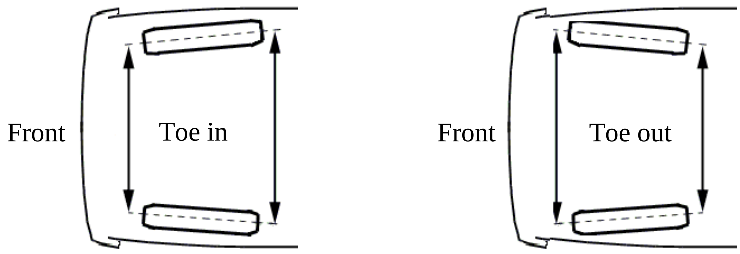
Figure 8-8: FAST of the Macpherson strut front suspension from company K



(a)



(b)



(c)

Figure 8-9: Wheel alignment (Adapted from www.anewtoronto.com) a) Camber angle b) Caster angle c) Toe angle

Table 8-30: Function-component relationship matrix of the Macpherson strut

Functions directly linked to components	Components														
	Front hub	Wheel bearing	Hub seal	Knuckle	Strut	Strut mount	Strut bearing	Coil spring	Lower spring insulator	Strut bumper	Dust shield	Upper spring insulator	Lower ball joint	Lower control arm	Stabiliser bar
Allow-rotational (a)	×	×	×	×											
Support-vertical disturbance (b)	×	×		×	×	×	×	×	×			×	×	×	
Limit-vertical movement (c)					×			×		×				×	
Dissipate-energy (d)					×										
Prevent-environmental hazard (e)					×				×		×	×			
Maintain-sprung mass's height (f)					×			×							
Restrict-vehicle pitching (g)					×			×							×
Stabilise-vertical movement (h)					×			×					×	×	×
Allow-steering control signal (i)				×	×	×	×						×	×	
Optimise-toe angle (j)	×	×	×	×	×								×	×	
Optimise-caster angle (k)	×			×	×	×							×	×	
Optimise-camber angle (l)				×	×	×							×	×	

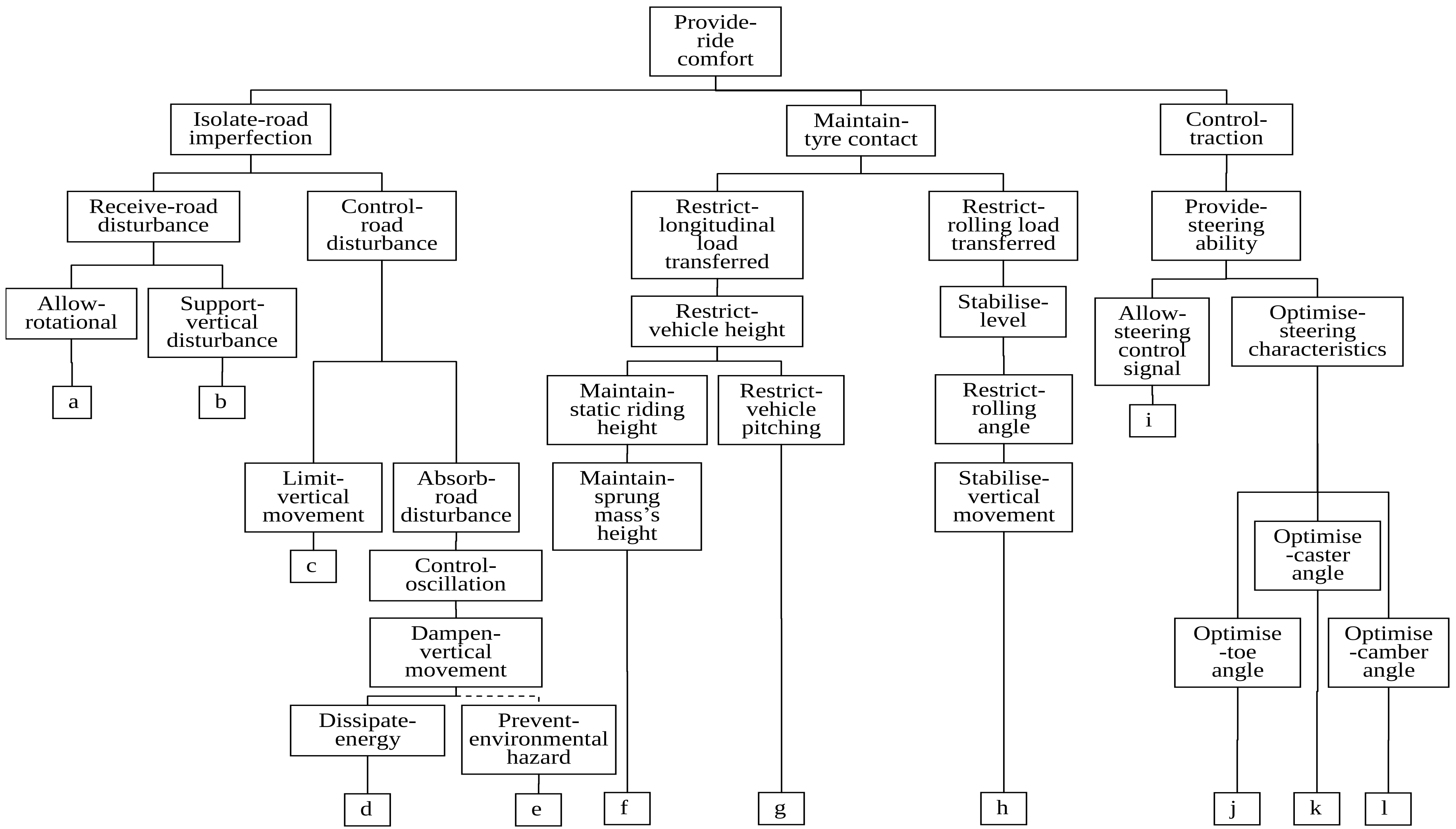


Figure 8-10: The AHP structure for FAST and components supported the Macpherson strut functions

Table 8-31: Function-component relationship matrix with the level of effort spent on functions and components of the Macpherson strut suspension system

Functions directly linked to components	Components														
	Front hub	Wheel bearing	Hub seal	Knuckle	Strut	Strut mount	Strut bearing	Coil spring	Lower spring insulator	Strut bumper	Dust shield	Upper spring insulator	Lower ball joint	Lower control arm	Stabiliser bar
Allow-rotational (a)	0.0736, *0.0011*	0.4265, *0.0062*	0.0549, *0.0008*	0.4450, *0.0065*											
Support-vertical disturbance (b)	0.0487, *0.0035*	0.4016, *0.0291*		0.1381, *0.0100*	0.0285, *0.0021*	0.0033, *0.0002*	0.0011, *0.0001*	0.0081, *0.0001*	0.0009, *0.0001*			0.0038, *0.0003*	0.0356, *0.0026*	0.3303, *0.0240*	
Limit-vertical movement (c)					0.4722, *0.0360*			0.0936, *0.0071*		0.0371, *0.0028*				0.3971, *0.0303*	
Dissipate-energy (d)					1, *0.4800*										
Prevent-environmental hazard (e)					0.7317, *0.0390*				0.0749, *0.0040*		0.0345, *0.0018*	0.1589, *0.0085*			
Maintain-sprung mass's height (f)					0.5000, *0.0121*			0.5000, *0.0121*							
Restrict-vehicle pitching (g)					0.5000, *0.0844*			0.2500, *0.0422*							0.2500, *0.0422*
Stabilise-vertical movement (h)					0.0427, *0.0016*			0.0490, *0.0019*					0.1126, *0.0043*	0.6470, *0.0250*	0.1486, *0.0057*
Allow-steering control signal (i)				0.3310, *0.0040*	0.0529, *0.0006*	0.0085, *0.0001*	0.0473, *0.0006*						0.2645, *0.0032*	0.2959, *0.0035*	
Optimise-toe angle (j)	0.1500, *0.0090*	0.0500, *0.0083*	0.1500, *0.0009*	0.1500, *0.0040*	0.0500, *0.0004*								0.1500, *0.0026*	0.3000, *0.0024*	
Optimise-caster angle (k)	0.0620, *0.0003*			0.4031, *0.0019*	0.0624, *0.0003*	0.1160, *0.0005*							0.3232, *0.0015*	0.0334, *0.0002*	
Optimise-camber angle (l)				0.4286, *0.0118*	0.0612, *0.0017*	0.0204, *0.0006*							0.0612, *0.0017*	0.4286, *0.0118*	

Design effort allocations

In practice, the suspension system is a crucial system for road vehicles. The industrial standard to design and develop one car is three years. Hence, the suspension system is also designed and developed by this lead time. The design team requires approximately 10 engineers. However, each of them has responsibility for more than one project; therefore, each one spends approximately 10 hours per week on designing the suspension system, so its design effort is calculated in Table 8-32.

Table 8-32: The total design effort given for the turbocharger provided by company E

Items	Quantities	Units
Provided lead time	3	Years
Staff required	10	Engineers
Working hours	10	hours/week
Working week (except holiday)	46	weeks/year
Total design effort given (E_{given})	$3 \times 10 \times 10 \times 46 = 13{,}800$	Hours

Each component's design effort is allocated with a multiplying Eigenvalue and the global relationship matrix, while the results are approximately displayed as integers in Table 8-33.

Component relationship matrix

This section is to develop the component relationship matrix. The direct and indirect relationship matrixes are as follows:

Develop component direct relationships: The component direct relationships are developed by applying the local relationship matrix with Eq. 6-2 and the diagonal values are not considered, as recommended in section 6.2.5. The direct relationships are represented by the non-highlighted cells in Table 8-34, while the others are indirect relationships.

Develop component indirect relationships: Due to company confidentiality, the potential failure modes in this case (Table 8-35) were extracted from the expert's knowledge rather than the project's historical records.

Table 8-33: The allocated design effort matrix from the given design effort (E_{given}) of the Macpherson suspension system

Functions directly linked to components	Components														
	Front hub	Wheel bearing	Hub seal	Knuckle	Strut	Strut mount	Strut bearing	Coil spring	Lower spring insulator	Strut bumper	Dust shield	Upper spring insulator	Lower ball joint	Lower control arm	Stabiliser bar
Allow-rotational (a)	15	85	11	89											
Support-vertical disturbance (b)	49	402		138	29	3	1	8	1			4	36	331	
Limit-vertical movement (c)					496			98		39				417	
Dissipate-energy (d)					6623										
Prevent-environmental hazard (e)					539				55		25	117			
Maintain-sprung mass's height (f)					166			166							
Restrict-vehicle pitching (g)					1165			583							583
Stabilise-vertical movement (h)					23			26					60	345	79
Allow-steering control signal (i)				55	9	1	8						44	49	
Optimise-toe angle (j)	124	115	12	55	6								36	34	
Optimise-caster angle (k)	4			26	4	7							21	2	
Optimise-camber angle (l)				163	23	8							23	163	
Total (hours)	192	602	23	526	9083	20	9	881	56	39	25	121	220	1341	662

Note: The hour is the unit applied in this table

Table 8-34: Component-component relationship matrix of the Macpherson strut suspension system provided by company K

Components	Front hub	Wheel bearing	Hub seal	Knuckle	Strut	Strut mount	Strut bearing	Coil spring	Lower spring insulator	Strut bumper	Dust shield	Upper spring insulator	Lower ball joint	Lower control arm	Stabiliser bar
Front hub		0.149264	0.014144	0.111189	0.010055	0.007347	0.000055	0.000394	0.000045	0.041667	0.041667	0.000187	0.052839	0.046881	
Wheel bearings	0.149264		0.032749	0.288443	0.015880	0.001311	0.000451	0.003255	0.000373	0.041667	0.041667	0.001539	0.043027	0.159232	
Hub seals	0.014144	0.032749		0.028864	0.000456					0.041667	0.041667		0.002953	0.002731	
Knuckle	0.111189	0.288443	0.028864		0.074949	0.058739	0.015806	0.001119	0.000128	0.041667	0.041667	0.000529	0.262626	0.353294	
Strut	0.010055	0.015880	0.000456	0.074949		0.009027	0.002533	0.421521	0.054829	0.017520	0.025241	0.116363	0.045135	0.269808	0.131345
Strut mount	0.007347	0.001311		0.058739	0.009027		0.000403	0.000026	0.000003			0.000013	0.041080	0.016195	
Strut bearing	0.000055	0.000451		0.015806	0.002533	0.000403		0.000009	0.000001			0.000004	0.012546	0.014362	
Coil spring	0.000394	0.003255		0.001119	0.421521	0.000026	0.000009		0.000008	0.003472		0.000031	0.005812	0.071566	0.069788
Lower spring insulator	0.000045	0.000373		0.000128	0.054829	0.000003	0.000001	0.000008		0.041667	0.002583	0.011902	0.000033	0.000307	
Strut bumper	0.041667	0.041667	0.041667	0.041667	0.017520			0.003472	0.041667				0.041667	0.014732	
Dust shield	0.041667	0.041667	0.041667	0.041667	0.025241				0.002583			0.005480	0.041667	0.041667	
Upper spring insulator	0.000187	0.001539		0.000529	0.116363	0.000013	0.000004	0.000031	0.011902		0.005480		0.000136	0.001266	
Lower ball joint	0.052839	0.043027	0.002953	0.262626	0.045135	0.041080	0.012546	0.005812	0.000033	0.041667	0.041667	0.000136		0.208312	0.016744
Lower control arm	0.046881	0.159232	0.002731	0.353294	0.269808	0.016195	0.014362	0.071566	0.000307	0.014732	0.041667	0.001266	0.208312		0.096169
Stabiliser bar					0.131345			0.069788					0.016744	0.096169	

Apply zigzag method to capture failure relationships Only the failure modes that show the failure relationships among components, are focused on. From the interviews, the root cause of loosening is normally from selecting incorrect tolerances in design, hence, it does not link to the others. Corrosion is classified as a failure due to exposure to environmental hazards; therefore, these are not further evaluated with the zigzag technique. Selecting improper springs would mean a too soft or too hard spring. Hence, to apply this issue into the zigzag method is not necessary because the problem is constrainted within the spring itself. In addition, the strut bumper problems are also confined within itself. "*No bearing rotation*" failure mode of the wheel and the strut bearings can take place either from incorrect tolerance designs for putting bearings into position or from mechanical load interactions. Only later causes will be further examined. Therefore, the failure modes classified as failure relationships are analysed with the zigzag method and are shown in Table 8-36. This activity was developed with company K's expert.

The unsprung mass is the mass that does not carry the coil spring; hence, it is composed of the front hub, wheel bearing, hub seal, knuckle, lower spring insulator, tyre and wheel. High unsprung mass could bump into the passenger compartment due to its momentum when the suspension receives road disturbance. Therefore, unsprung mass appears in most of the failure modes. Even though the failure relationships shown as non-highlighted rows can be extracted with the zigzag technique, they are similar to the direct relationships. Therefore, only relationships in the highlighted rows in Table 8-36 will be put into the relationship matrix.

Table 8-35: Potential failure modes extracted from the expert's knowledge

Components	**Failure Modes**
1) Front hub	Loosened from the wheel bearing
2) Wheel bearing	No bearing rotation, Loosened from knuckle
3) Hub seals	Seal leakage
4) Knuckle	Fracture, Deformation, Corrosion
5) Strut	Oil/gas leakage, Clevis bracket fracture, Too quick or too long damping
6) Strut mount	Fracture, Deformation, Corrosion, Loosened from the car body
7) Strut bearing	No bearing rotation
8) Coil spring	Fracture, Too soft or Too hard spring
9) Lower strut insulator	Relative movement between spring and insulator, Fracture
10) Strut bumper	Fracture, Too soft or Too hard bumper
11) Dust shield	Shield fracture
12) Upper spring insulator	Relative movement between spring and insulator, Fracture
13) Lower ball joint	Fracture, Loosened from lower control arm and knuckle
14) Lower control arm	Fracture, Deformation, Corrosion
15) Stabiliser bar	Fracture, Deformation, Corrosion

Table 8-36: The analysis of the Macpherson strut's component failure relationships

Functions (Obtained from FAST)	Detailed analysis for failure modes	Components related to failures
Allow-rotational	No rotational movement Impact fatigue Transfer road imperfection	Wheel bearing Tyre&Wheel
Allow rotational	Leakage Wear Not perfect fit due to incorrect tolerance between components	Hub seals Knuckle
Support-vertical disturbance	Insecure to support vehicle Fracture Transfer road imperfection	Knuckle Tyre &Wheel
Support-vertical disturbance	Insecure to support vehicle Deformation Transfer road imperfection	Knuckle Tyre &Wheel
Support-vertical disturbance	Insecure to support vehicle Fracture Transfer road imperfection	Strut (Clevis bracket) Usprung mass
Support-vertical disturbance	Insecure to support vehicle Deformation Transfer road imperfection	Strut mount Unsprung mass
Support-vertical disturbance	Insecure to support vehicle Fracture Transfer road imperfection	Strut mount Unsprung mass
Dissipate-energy	Fail to dampen road disturbance Oil/gas leakage Transfer road imperfection	Strut Unsprung mass
Allow-steering control signal	Difficult to steer Impact fatigue Transfer road imperfection	Strut bearing Unsprung mass
Support-vertical disturbance	Insecure to support vehicle Fracture Transfer road imperfection	Coil spring Unsprung mass

Table 8.36: (continued)

Functions (Obtained from FAST)	Detailed analysis for failure modes	Components related to failures
Prevent-environmental hazard	Fail to protect environmental hazard Fracture Repetitive contraction/expansion Transfer road imperfection	Lower strut insulator Coil spring Unsprung mass
Limit-vertical movement	Fail to limit vertical movement Fracture Transfer road imperfection	Strut bumper Unsprung mass
Prevent-environmental hazard	Fail to protect environmental hazard Fracture Transfer road imperfection	Dust shield Unsprung mass
Prevent-environmental hazard	Fail to protect environmental hazard Fracture Repetitive contraction/expansion Transfer road imperfection	Upper strut insulator Coil spring Unsprung mass
Support-vertical disturbance	Insecure to support vehicle Fracture Transfer road imperfection	Lower ball joint Unsprung mass
Support-vertical disturbance	Insecure to support vehicle Fracture Transfer road imperfection	Lower control arm Unsprung mass
Support-vertical disturbance	Insecure to support vehicle Deformation Transfer road imperfection	Lower control arm Unsprung mass
Stabilise-vertical movement	Fail to stabilise vertical movement Deformation Transfer road imperfection	Stabiliser bar Unsprung mass
Stabilise-vertical movement	Fail to stabilise vertical movement Fracture Transfer road imperfection	Stabiliser bar Unsprung mass

<u>*Assign relationships into the DSM matrix*</u> Even though the tyre and the wheel are involved in most failure modes, they are not the members of the suspension system in this case. Hence, they are not put into the relationship matrix. Only the failure relationships, as highlighted in Table 8-36, are placed into the relationship matrix, while the other relationships are not because each of them resembles the direct relationships.

The strut bumper and the dust shield link to the unsprung mass due to failure relationships among the components as signified as “1” in Table 8-37. Once Eq. 6-3 is applied, the normalised relationships are shown as values in italics in Table 8-37, and shown as painted cells in Table 8-34.

Table 8-37: Component-component relationships due to failures for turbocharger

Components	Front hub	Wheel bearing	Hub seal	Knuckle	Lower spring insulator	Strut bumper	Dust shield	Lower ball joint	Lower control arm
Front hub						1, *0.041667*	1, *0.041667*		
Wheel bearings						1, *0.041667*	1, *0.041667*		
Hub seals						1, *0.041667*	1, *0.041667*		
Knuckle						1, *0.041667*	1, *0.041667*		
Lower spring insulator						1, *0.041667*			
Strut bumper	1, *0.041667*	1, *0.041667*	1, *0.041667*	1, *0.041667*	1, *0.041667*			1, *0.041667*	
Dust shield	1, *0.041667*	1, *0.041667*	1, *0.041667*	1, *0.041667*				1, *0.041667*	1, *0.041667*
Lower ball joint						1, *0.041667*	1, *0.041667*		
Lower control arm							1, *0.041667*		

Estimate design rework effort

This sub-section applies the WTM method to calculate the design rework effort. Therefore, the ideal design effort and constant for Eq. 6-5 are obtained as follows:

Calculate the ideal design effort: The allocated ideal design rework effort of the Macpherson strut suspension system is calculated with the principle revealed in section 6.2.6. The required elements to calculate the ideal design effort are shown in Table 8-38a, while the ideal design effort is shown in column five of Table 8-38b.

Table 8-38: Calculating $Ef_{extreme}$ for Macpherson strut suspension system a) Matrix for $S(1-\Lambda)^{-1}S^{-1}$ of $\mathrm{M}_{component}$ b) u_0 and U vector of the extreme case

(a)

1.20955	0.493082	0.066304	0.633068	0.35846	0.076015	0.024623	0.206656	0.026658	0.133631	0.150428	0.044966	0.406514	0.577039	0.123804
0.493082	1.651415	0.118676	1.178778	0.660496	0.127207	0.04551	0.384182	0.047436	0.203296	0.235049	0.083457	0.694262	1.090929	0.230103
0.066304	0.118676	1.015372	0.152833	0.081502	0.016128	0.005668	0.046901	0.007541	0.06392	0.067637	0.010398	0.089366	0.12954	0.027932
0.633068	1.178778	0.152833	2.456589	1.070924	0.236746	0.081817	0.615268	0.074306	0.282923	0.333313	0.132926	1.18345	1.723958	0.369206
0.35846	0.660496	0.081502	1.070924	2.0057	0.136117	0.050616	0.981616	0.121924	0.184151	0.228476	0.239553	0.732539	1.325416	0.471673
0.076015	0.127207	0.016128	0.236746	0.136117	1.026119	0.009652	0.077296	0.009253	0.03209	0.038204	0.016795	0.167601	0.207951	0.046077
0.024623	0.04551	0.005668	0.081817	0.050616	0.009652	1.003366	0.029091	0.003415	0.011355	0.013762	0.006241	0.058686	0.082291	0.017575
0.206656	0.384182	0.046901	0.615268	0.981616	0.077296	0.029091	1.497111	0.060488	0.106442	0.12833	0.117706	0.424977	0.788051	0.316313
0.026658	0.047436	0.007541	0.074306	0.121924	0.009253	0.003415	0.060488	1.009369	0.054326	0.01812	0.026538	0.051123	0.087889	0.029544
0.133631	0.203296	0.06392	0.282923	0.184151	0.03209	0.011355	0.106442	0.054326	1.046638	0.052759	0.023215	0.202157	0.262319	0.060228
0.150428	0.235049	0.067637	0.333313	0.228476	0.038204	0.013762	0.12833	0.01812	0.052759	1.062593	0.033653	0.236248	0.335612	0.075196
0.044966	0.083457	0.010398	0.132926	0.239553	0.016795	0.006241	0.117706	0.026538	0.023215	0.033653	1.028806	0.090634	0.163213	0.056892
0.406514	0.694262	0.089366	1.18345	0.732539	0.167601	0.058686	0.424977	0.051123	0.202157	0.236248	0.090634	1.671253	1.166249	0.266014
0.577039	1.090929	0.12954	1.723958	1.325416	0.207951	0.082291	0.788051	0.087889	0.262319	0.335612	0.163213	1.166249	2.537135	0.492605
0.123804	0.230103	0.027932	0.369206	0.471673	0.046077	0.017575	0.316313	0.029544	0.060228	0.075196	0.056892	0.266014	0.492605	1.135854

(b)

Components	Design rework effort vector for extreme case (hours)		$Ef_{given}/Ef_{extreme}$	Ideal design effort for each component (hours)
	u_0	U		
Front hub	192	5,264	0.1212	23.2
Wheel bearings	602	9,847		73
Hub seals	23	1,187		2.8
Knuckle	526	15,258		63.7
Strut	9083	22,417		1100.9
Strut mount	20	1,892		2.4
Strut bearing	9	706		1.1
Coil spring	881	12,218		106.9
Lower spring insulator	56	1,445		6.8
Strut bumper	39	2,550		4.7
Dust shield	25	3,122		3.1
Upper spring insulator	121	2,813		14.6
Lower ball joint	220	10,287		26.6
Lower control arm	1341	18,444		162.5
Stabiliser bar	662	6,405		80.2
Total	13,800 (Ef_{given})	113,855 ($Ef_{extreme}$)		1,672.5 (Ef_{ideal})

Develop input vector u_0 by using expected design issues: The open design issues are from historical projects. There were recently two issues from two components leading to a serious delay: the lower control arm and the knuckle. Both components work to achieve the Support-vertical disturbance function. The design issues in a suspension system are always from the joint location of both components.

Both components are treated as the expected design issues in the estimation of the design rework effort, as shown in column two of Table 8-40, and the percentages judged to resolve issues are 30% for both components. Once the percentage for each issue is assigned, the vector u_0 is automatically calculated from the components' ideal design effort, as shown in column four. Then the estimated design rework effort with the knock-on effect for each component appears in column five. It is noted that the estimated design rework effort ($Ef_{estimated}$) is approximately 10 times greater than expected ($Ef_{expected}$).

Table 8-39: E_{ideal} of the Macpherson strut suspension system

Functions directly linked to components	Components														
	Front hub	Wheel bearing	Hub seal	Knuckle	Strut	Strut mount	Strut bearing	Coil spring	Lower spring insulator	Strut bumper	Dust shield	Upper spring insulator	Lower ball joint	Lower control arm	Stabiliser bar
Allow-rotational (a)	1.51	8.76	1.13	9.14											
Support-vertical disturbance (b)	5.00	41.23		14.18	2.92	0.34	0.12	0.83	0.10			0.39	3.65	33.91	
Limit-vertical movement (c)					50.90			10.09		4.00				42.80	
Dissipate-energy (d)					679.09										
Prevent-environmental hazard (e)					55.21				5.65		2.60	11.99			
Maintain-sprung mass's height (f)					17.07			17.07							
Restrict-vehicle pitching (g)					119.48			59.74							59.74
Stabilise-vertical movement (h)					2.33			2.68					6.15	35.34	8.12
Allow-steering control signal (i)				5.61	0.90	0.14	0.80						4.48	5.01	
Optimise-toe angle (j)	12.75	11.79	1.21	5.60	0.58								3.73	3.45	
Optimise-caster angle (k)	0.40			2.63	0.41	0.76							2.11	0.22	
Optimise-camber angle (l)				16.76	2.39	0.80							2.39	16.76	
Total	<u>19.66</u>	<u>61.78</u>	<u>2.34</u>	<u>53.91</u>	<u>931.28</u>	<u>2.03</u>	<u>0.92</u>	<u>90.41</u>	<u>5.75</u>	<u>4.00</u>	<u>2.60</u>	<u>12.38</u>	<u>22.51</u>	<u>137.49</u>	<u>67.86</u>

Note: The hour is the unit applied in this table

Table 8-40: The input vector u_0 and the estimated design rework output vector U for turbocharger

Components	Expected design issues	Percentage judged to resolve issues	Design effort vector for the expected issues (hours)	
			u_0	U
Front hub			0	8.56
Wheel bearings			0	16.1
Hub seals			0	1.97
Knuckle	Fracture (Support-vertical disturbance)	30%	4.25	27.97
Strut			0	18.03
Strut mount			0	3.12
Strut bearing			0	1.18
Coil spring			0	10.63
Lower spring insulator			0	1.21
Strut bumper			0	3.87
Dust shield			0	4.83
Upper spring insulator			0	2.23
Lower ball joint			0	16.89
Lower control arm	Fracture (Support-vertical disturbance)	30%	10.17	33.13
Stabiliser bar			0	6.58
Total			14.42 ($Ef_{expected}$)	156.30 ($Ef_{estimated}$)

8.2.3 Connect the DRePOE and DREE methods

Convert design rework effort to design lead time

To resolve the design issues, one product engineer, and two designers (CAD and finite element analysis, FEA) are assigned. Each of them worked for approximately 20 hours per week on the project. Hence, there were 60 hours of effort per week to resolve issues. Nonetheless, the experts mentioned that the latest lead time to complete the design rework was about four weeks.

The estimated effort to resolve these issues is approximately 156.30 hours. If the design team spent 60 hours of effort to resolve the problems, the estimated lead time would be around three weeks. The expert initially accepted the estimated result. The summary for design rework effort estimation resulting from this method is given in Table 8-41. The full validation for the DREE method is in section 8.3.2.

Table 8-41: Lead time to resolve design issues of the turbocharger case

Items	Quantities	Units
Required engineers (Experts' judgement)	3	People
Approximate time spent per person to resolve issues (Experts' judgement)	20	Hours
Approximate effort spent per team to resolve issues (Experts' judgement)	$3 \times 20 = 60$	Hours
Estimated design effort	156.30 $(Ef_{estimated})$	Hours
Convert to be working weeks (60 hours/week)	$156.30 \div 60 \approx 2.6$	Weeks
Worst case lead time to resolve two issues (Experts' judgement)	4	Weeks

The association between the DREE and the DRePOE methods

The design rework probability and the design rework effort from the expected design issues are summarised in Table 8-42. The connection between the DRePOE and the DREE methods, as proposed in section 6.3.2, is also implemented in this case study.

Table 8-42: The results from DRePOE and DREE methods for the turbocharger case

Methods	Results
DRePOE	$\approx$ 22.33%
DREE	$\approx$ 156.30 hours

In summary, it is interpreted that the new design would have approximately 22.33% of design rework from the total supplied products in the testing and refinement phase. Moreover, the probability would be possible from the lower control arm and the knuckle because they are complicated components in terms of receiving multi-directional loads, especially at the joint location. If these two issues occur in the testing and refinement phase, the worst case design rework effort would be 156.30 hours or acknowledged as approximately three weeks' lead time.

8.2.4 Apply the PriDDREB Method to the Macpherson Strut Suspension System Industrial Case Study

Generate possible component groups

The methodology to obtain the possible component groups proposed in section 7.2.1 is applied to the Macpherson strut suspension system case as follows:

Calculate the component number in each group by applying the Pareto Analysis: There are 15 components within the Macpherson suspension system case. Once Eq.7-

1 is applied to this case the component number in each group (k_{Pareto}) is calculated and the k_{Pareto} for the Macpherson strut suspension system is three.

$$k_{Pareto} = (0.2 \times 15)_{integer} = 3$$

Calculate the optimistic number of component groups: From Table 8-30, there are 12 functions directly linked to components and this amount is realised as f_c for Eq. 7-2. Hence, G_{Op} is derived by the mentioned equation and there are optimistically 220 component groups.

$$G_{Op} = \frac{12!}{3!(12-3)!} = 220$$

Create the possible component groups: The possible component groups for the Macpherson strut suspension system are calculated with MATLAB complied with Eq. 7-3 and the $G_{Possible}$ is 23,114 groups.

Create component groups for optimisation (G_{Opt}): There are 17,320 component groups to optimise and they are selected with the guidelines specified in section 7.2.1 and MATLAB programming. All necessary variables for optimisation are summarised in Table 8-43.

Table 8-43: Required variables for optimisation in support of the Macpherson strut case

Variables	Values
k_{Pareto}	3 components per group
f_c	12 functions
G_{Op}	220 groups
$G_{Possible}$	23,114 groups
G_{Opt}	17,320 groups

Assign objective function and constraints to component groups

There is no difference in terms of principle to assigning the objective function and constraints in the Macpherson strut suspension system case when compared with the previous cases; however, 5% of the ideal design effort is approximately 70.75 hours.

Apply optimisation technique to the assigned groups

Similar optimisation techniques from previous cases are applied to this case study. The optimisation results are summarised in Table 8-44. There are 4,408 component groups that provide optimisation results less than 5% of Ef_{ideal}; so there are 12,912 groups that are plotted against the component combination labels, as shown in Table 8-44.

Table 8-44: The summary for Macpherson strut suspension system design rework effort optimisation

Maximum design rework effort	776.09 hours (54.85% of Ef_{ideal})
Minimum design rework effort	70.75 hours (9.12% of Ef_{ideal})
Range	776.09-70.75=705.34 hours
Optimisation results for prioritising component design	12,912 groups

Prioritise component design with optimisation results

Identify clusters of optimisation results: There are 58 linkages (nf) among components and functions considered, as from Table 8-30; hence, the clusters for optimisation results are calculated with Eq. 7-4 and there are 19 clusters.

$$Cl_{Mcpherson\ \ strut\ \ suspension} = \left(\frac{58}{3}\right)_{integer} \approx 19.33 \approx 19$$

Identify the range of design rework effort for each cluster: Once total clusters are identified, the range for each cluster is attained using Eq. 7-5. The range for each cluster is approximately 37.12 hours, which is approximately half of a week if there are 60 hours per week. The component groups in each cluster are in column four of Table 8-45.

$$DreR_C = \left(\frac{776.09 - 70.75}{19}\right) \approx 37.12 \text{ hours}$$

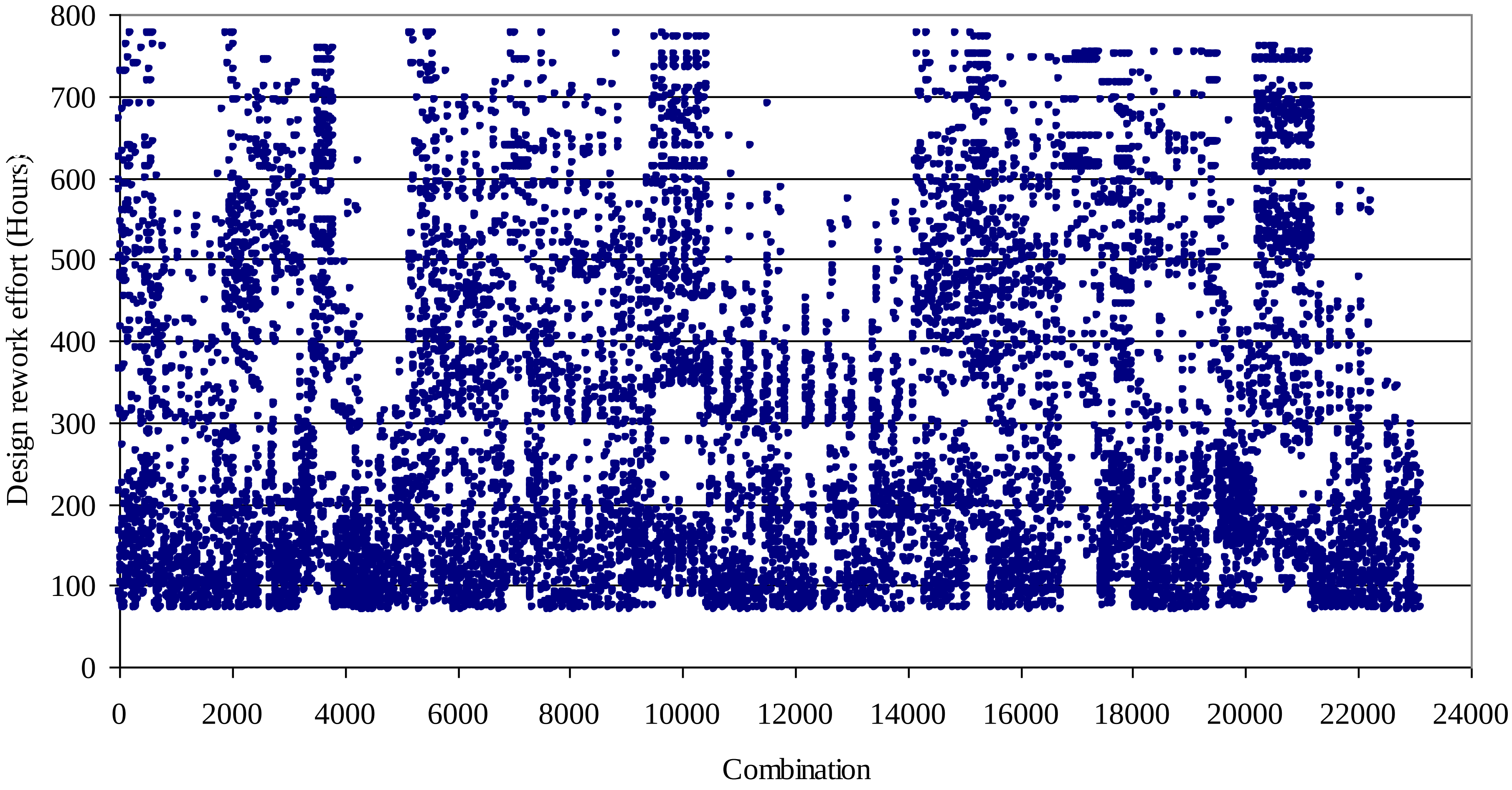


Figure 8-11: The optimisation results from Macpherson strut suspension's component groups

Table 8-45: The design rework effort ranges of each cluster (macpherson strut suspension)

Clusters	Upper bound (hours)	Lower bound (hours)	Component groups in each cluster
1	776.09	$776.09 - 37.12 \approx 738.91$	338
2	738.91>	$738.91 - 37.12 \approx 701.85$	161
3	701.85>	$504.61 - 37.12 \approx 664.72$	286
4	664.72>	$664.72 - 37.12 \approx 627.60$	370
5	627.60>	$627.60 - 37.12 \approx 590.48$	759
6	590.48>	$590.48 - 37.12 \approx 553.36$	364
7	553.36>	$553.36 - 37.12 \approx 516.23$	486
8	516.23>	$516.23 - 37.12 \approx 479.11$	509
9	479.11>	$479.11 - 37.12 \approx 441.99$	536
10	441.99>	$441.99 - 37.12 \approx 404.86$	406
11	404.86>	$404.86 - 37.12 \approx 367.74$	512
12	367.74>	$367.74 - 37.12 \approx 330.62$	561
13	330.62>	$330.62 - 37.12 \approx 293.49$	535
14	293.49>	$293.49 - 37.12 \approx 256.37$	426
15	256.37>	$256.37 - 37.12 \approx 219.25$	711
16	219.25>	$219.25 - 37.12 \approx 182.12$	1072
17	182.12>	$182.12 - 37.12 \approx 145.00$	1290
18	145.00>	$145.00 - 37.12 \approx 107.88$	1595
19	107.88>	$107.88 - 37.12 \approx 70.75$	1995
Total			12,912

Prioritise component design with frequency counting The component prioritisation results are given in Table 8-46. The prioritisation is completed for three components (k_{Pareto}) at a time in each cluster. The first component group required to have more effort put into it to prevent design rework issues consists of the strut and the stabiliser bar; moreover, they serve the Dissipate-energy and the Restrict-vehicle pitching functions respectively. In Table 8-46, the components which have the greatest three (k_{Pareto}) frequencies for the design rework effort range from 776.09 to 738.91 hours, as mentioned earlier, so have the most likely opportunity to deliver design rework effort in this range compared with others. They are not necessary to form a component group together, but any component groups which have at least one of these components with the concerned functions would potentially provide the mentioned design rework effort. This interpretation is implemented to other clusters until the component prioritisation is achieved. The prioritised components based on the design rework effort are summarised and shown in Table 8-47. The recommended components to focus on in each cluster would reduce the major issues as suggested by with the Pareto Analysis.

Table 8-46: The frequencies counting from the optimisation results (Macpherson strut suspension)

Functions directly linked to components	Components	Clusters and ranges of design rework effort (hours)									
		776.09 to 738.91	738.91> to 701.85	504.61> to 664.72	664.72> to 627.60	627.60> to 590.48	590.48> to 553.36	553.36> to 516.23	516.23> to 479.11	479.11> to 441.99	441.99> to 404.86
Allow-rotational	Front hub	14	4	14	16	42	9	25	28	33	19
	Wheel bearing	14	14	13	10	47	28	35	24	30	24
	Hub seal	14	4	11	16	43	9	21	29	32	14
	Knuckle	24	8	15	44	31	33	32	38	20	16
Support-vertical disturbance	Front hub	11	2	17	8	44	12	28	26	21	17
	Wheel bearing	13	17	22	18	62	44	39	62	45	34
	Knuckle	17	8	15	79	27	11	15	17	11	7
	Strut	0	3	3	0	3	14	8	8	10	12
	Strut mount	2	1	4	2	17	2	1	13	21	7
	Strut bearing	2	1	4	2	17	2	1	11	17	13
	Coil spring	2	0	5	1	20	4	6	14	12	32
	Lower spring insulator	2	0	5	2	16	2	1	9	21	8
	Upper spring insulator	2	0	5	2	16	2	1	11	20	7
	Lower ball joint	2	4	3	5	20	13	41	27	34	19
	Lower control arm	42	26	18	9	12	34	35	20	24	53
Limit-vertical movement	Strut	13	22	34	30	66	94	56	94	156	15
	Coil spring	3	5	0	9	17	4	9	21	32	47
	Strut bumper	3	1	5	1	16	0	10	10	10	15
	Lower control arm	57	34	25	38	29	49	76	56	59	72
Dissipate-energy	Strut	134	6	17	74	334	16	35	11	16	51
Prevent-environmental hazard	Strut	31	33	31	71	63	84	70	139	19	23
	Lower spring insulator	6	2	7	6	34	3	7	15	26	19
	Dust shield	6	2	6	7	32	5	6	16	26	14
	Upper spring insulator	6	2	7	14	27	5	12	19	33	25
Maintain-sprung mass’s height	Strut	7	1	5	15	8	20	29	21	35	20
	Coil spring	6	9	8	14	38	29	22	34	49	33
Restrict-vehicle pitching	Strut	109	6	12	66	236	12	35	14	25	39
	Coil spring	21	47	52	48	54	70	92	60	67	47
	Stabiliser bar	60	62	126	51	42	67	98	68	100	21
Stabilise-vertical movement	Strut	2	0	6	6	5	10	28	7	6	14
	Coil spring	8	2	4	14	40	8	21	22	21	18
	Lower ball joint	8	4	11	13	37	27	24	27	27	17
	Lower control arm	22	23	52	27	48	29	30	46	75	82
	Stabiliser bar	14	3	8	16	39	20	19	26	29	22
Allow-steering control signal	Knuckle	46	16	36	30	28	12	22	16	18	31
	Strut	2	0	4	7	4	11	24	6	11	8
	Strut mount	6	0	4	12	38	7	13	26	19	8
	Strut bearing	6	0	4	13	43	5	14	25	22	8
	Lower ball joint	6	4	7	12	41	19	27	26	29	20
	Lower control arm	15	7	17	11	36	18	18	19	11	17
Optimise-toe angle	Front hub	4	4	6	8	21	14	19	18	20	23
	Wheel bearing	4	8	3	9	39	23	55	47	34	25
	Hub seal	4	0	2	4	26	2	12	12	9	1
	Knuckle	50	17	34	36	29	12	20	15	18	31
	Strut	2	0	5	6	4	11	27	5	9	8
	Lower ball joint	6	3	7	13	44	19	22	24	33	16
	Lower control arm	15	5	19	8	39	14	18	22	11	8
Optimise-caster angle	Front hub	4	2	4	1	26	9	8	12	16	12
	Knuckle	48	11	26	36	32	16	11	30	13	23
	Strut	2	0	7	4	4	12	26	5	9	10
	Strut mount	6	0	4	15	39	7	14	23	23	4
	Lower ball joint	6	3	7	13	39	18	24	27	30	21
	Lower control arm	14	5	9	19	33	9	17	19	23	8
Optimise-camber angle	Knuckle	56	32	49	27	31	32	20	16	22	6
	Strut	2	0	6	3	6	13	26	5	8	17
	Strut mount	6	0	2	13	40	6	13	23	25	4
	Lower ball joint	6	2	4	10	43	17	28	23	29	21
	Lower control arm	21	8	22	66	10	15	12	40	4	12

Table 8-46: (continued)

Functions directly linked to components	Components	Clusters and ranges of design rework effort (hours)								
		404.86 > to 367.74	367.74> to 330.62	330.62 > to 293.49	293.49 > to 256.37	256.37 > to 219.25	219.25 > to 182.12	182.12 > to 145.00	145.00 > to 107.88	107.88 > to 70.75
Allow-rotational	Front hub	27	24	36	9	27	54	59	67	101
	Wheel bearing	15	16	12	45	57	61	87	153	300
	Hub seal	28	15	21	10	34	65	67	70	126
	Knuckle	18	9	27	32	45	72	106	213	126
Support-vertical disturbance	Front hub	13	11	8	11	29	40	45	81	137
	Wheel bearing	77	147	165	10	12	17	3	9	16
	Knuckle	9	32	30	27	83	118	152	11	20
	Strut	16	4	13	11	18	28	47	77	106
	Strut mount	17	10	8	10	24	50	64	78	87
	Strut bearing	13	14	4	11	17	39	38	81	127
	Coil spring	21	30	18	18	24	34	26	57	95
	Lower spring insulator	7	22	7	11	16	43	41	81	117
	Upper spring insulator	10	21	9	9	20	44	67	80	102
	Lower ball joint	12	23	13	19	22	32	66	73	102
	Lower control arm	79	52	80	22	17	26	37	34	49
Limit-vertical movement	Strut	14	21	18	14	15	7	25	54	25
	Coil spring	31	24	27	38	49	69	104	161	162
	Strut bumper	28	28	28	19	70	98	63	86	175
	Lower control arm	93	52	17	33	37	34	31	62	60
Dissipate-energy	Strut	17	20	11	6	24	31	56	29	7
Prevent-environmental hazard	Strut	19	24	13	13	15	16	36	52	13
	Lower spring insulator	26	27	26	17	40	57	98	117	186
	Dust shield	30	26	32	18	60	79	64	85	149
	Upper spring insulator	22	22	34	43	78	90	119	180	148
Maintain-sprung mass's height	Strut	16	39	28	59	102	105	136	52	72
	Coil spring	40	30	34	48	79	116	145	124	116
Restrict-vehicle pitching	Strut	16	18	14	19	45	43	66	30	5
	Coil spring	114	100	17	31	24	53	57	60	19
	Stabiliser bar	38	49	40	57	91	33	65	69	32
Stabilise-vertical movement	Strut	19	20	25	12	20	42	53	74	107
	Coil spring	19	25	33	18	28	39	54	71	133
	Lower ball joint	28	22	16	21	44	62	76	124	116
	Lower control arm	73	49	72	39	32	33	19	50	61
	Stabiliser bar	23	19	14	10	37	51	124	151	215
Allow-steering control signal	Knuckle	19	23	6	21	38	35	75	87	158
	Strut	24	24	32	10	16	40	47	72	85
	Strut mount	18	20	36	13	16	57	76	77	110
	Strut bearing	12	26	38	10	12	53	61	83	143
	Lower ball joint	28	35	28	14	38	49	67	103	106
	Lower control arm	13	16	12	20	35	58	93	103	146
Optimise-toe angle	Front hub	48	60	60	38	40	79	103	127	82
	Wheel bearing	31	19	12	33	57	80	89	150	113
	Hub seal	11	20	30	13	15	55	73	101	116
	Knuckle	15	17	7	22	34	31	46	83	136
	Strut	25	21	33	7	14	40	44	46	86
	Lower ball joint	18	35	30	10	31	42	61	82	95
	Lower control arm	14	20	6	8	35	47	47	88	122
Optimise-caster angle	Front hub	19	45	37	45	42	70	51	50	120
	Knuckle	29	18	12	11	28	47	62	75	102
	Strut	25	26	29	9	20	40	50	81	92
	Strut mount	21	21	30	14	24	53	81	87	117
	Lower ball joint	17	36	28	20	23	42	67	86	108
	Lower control arm	12	14	20	3	18	41	49	75	106
Optimise-camber angle	Knuckle	19	22	24	55	74	102	125	58	61
	Strut	26	26	21	6	12	32	50	97	121
	Strut mount	23	17	34	13	18	31	80	85	116
	Lower ball joint	23	31	31	14	17	28	57	90	127
	Lower control arm	18	46	59	99	141	283	20	3	5

Table 8-47: The component prioritisation based on design rework effort and frequencies (Macpherson strut suspension)

Functions directly linked to components	Components	Design rework effort ranges (hours)	Frequencies
Dissipate-energy	Strut	776.09 to 738.91	134
Restrict-vehicle pitching	Strut		109
Restrict-vehicle pitching	Stabiliser bar		60
Limit-vertical movement	Lower control arm	738.91> to 701.85	34
Prevent-environmental hazard	Strut		33
Restrict-vehicle pitching	Coil spring		47
Stabilise-vertical movement	Lower control arm	504.61> to 664.72	52
Allow-steering control signal	Knuckle		36
Optimise-camber angle	Knuckle		49
Allow-rotational	Knuckle	664.72> to 627.60	44
Support-vertical disturbance	Knuckle		79
Optimise-camber angle	Lower control arm		66
Allow-rotational	Wheel bearing	627.60> to 590.48	47
Support-vertical disturbance	Wheel bearing		62
Limit-vertical movement	Strut		66
Support-vertical disturbance	Lower control arm	590.48> to 553.36	34
Maintain-sprung mass's height	Coil spring		29
Stabilise-vertical movement	Lower ball joint		27
Support-vertical disturbance	Lower ball joint	553.36> to 516.23	41
Maintain-sprung mass's height	Strut		29
Optimise-toe angle	Wheel bearing		55
Allow-rotational	Front hub	516.23> to 479.11	28
Allow-rotational	Hub seal		29
Optimise-caster angle	Knuckle		30
Limit-vertical movement	Coil spring	479.11> to 441.99	32
Prevent-environmental hazard	Upper spring insulator		33
Optimise-toe angle	Lower ball joint		33
Support-vertical disturbance	Coil spring	441.99> to 404.86	32
Optimise-toe angle	Front hub		23
Optimise-toe angle	Knuckle		31
Limit-vertical movement	Strut bumper	404.86> to 367.74	28
Prevent-environmental hazard	Dust shield		30
Allow-steering control signal	Lower ball joint		28
Optimise-caster angle	Front hub	367.74> to 330.62	45
Optimise-caster angle	Lower ball joint		36
Optimise-camber angle	Lower ball joint		31
Allow-steering control signal	Strut mount	330.62> to 293.49	36
Allow-steering control signal	Strut bearing		38
Optimise-camber angle	Strut mount		34
Stabilise-vertical movement	Coil spring	293.49> to 256.37	18
Allow-steering control signal	Lower control arm		20
Optimise-caster angle	Strut mount		14
Support-vertical disturbance	Front hub	256.37> to 219.25	29
Stabilise-vertical movement	Stabiliser bar		37
Optimise-toe angle	Lower control arm		35
Support-vertical disturbance	Strut mount	219.25> to 182.12	50
Support-vertical disturbance	Upper spring insulator		44
Optimise-toe angle	Hub seal		55
Stabilise-vertical movement	Strut	182.12> to 145.00	53
Optimise-caster angle	Strut		50
Optimise-camber angle	Strut		50
Support-vertical disturbance	Strut	145.00> to 107.88	77
Support-vertical disturbance	Strut bearing		81
Support-vertical disturbance	Lower spring insulator		81
Allow-steering control signal	Strut	107.88> to 70.75	85
Optimise-toe angle	Strut		86
Optimise-caster angle	Lower control arm		106

8.3 VALIDATION DEVELOPED METHODS BY VALIDATION SQUARE METHOD

The validation square method is implemented in this thesis and the rationales are in the adjacent sub-sections. Not only is a systematic method required to achieve reliable validation results, but also qualified experts for each case study are needed. Therefore, the experts who have experience of the agreed industrial cases are critical to this activity. The detailed introductory explanations of this section are as follows:

Rationale to select the validation square method

- This approach is developed for the research related to design methods as represented in Pedersen et al. (2000), which is quite similar to this research topic.
- The challenge in this chapter, raised earlier in sections 1.2 and 3.5.7, is that there is a limitation of participants to whom the statistical technique in the validation can be assigned. However, the validation square method is extended from the case study research method which is appropriate to the context of this thesis.

Elements in the validation square method

There are two criteria, structural validation and performance validation, used to test the developed method, as represented in section 3.9. In addition, each criterion requires three sub-criteria for validation. The earliest requirement from the structural validation is the acceptance construct's validity; however, this serves mainly to confirm the quality of references. Hence, it is always analysed at the beginning of each method's validation.

Later, two requirements from the structural validation and performance validation results are discussed together. Sections 8.3.1 to 8.3.3 represent the validation results for all criteria. The Likert-scale method represents the degree of acceptability of the score, while opinions from experts are recorded to support the scores. The experts from each case finish the scores separately and then the results are compared with one another. The interview results from each company are evaluated together. Later, the findings are concluded using a thematic analysis method. The questionnaire for method validations is provided in Appendix M.

Participants for method validation activities

The participants in the method validation activities are separately exhibited in chapter 5 as well as sections 8.1 and 8.2; thus, they are summarised explicitly in Table 8-48. The automotive water pump is the case for all method development.

Table 8-48: Participating experts in method validations

Industrial case studies	Total participants	Job title	Years of experience
Automotive water pump (Initial case for method developments)	2	CPPD Oil & Cooling	30
		Product Management Graduate	2
Turbocharger (Case 1)	2	IPSD Engineering Technical Steward	25
		Product Management Graduate	2
Macpherson strut suspension system (Case 2)	1	Product Engineer	5

Even though there are two experts involved in the development and validation activity, the expert with the more extensive experience is the main person contributing ideas, because the other is still in the company's training programme for new staff. The Product Management Graduate also participates in the turbocharger case, but agian he is not the main person sharing opinions. Lastly, there is one expert providing his opinion in the Macpherson strut suspension system case. Moreover, the experts in each case study are maintained throughout the method validations.

8.3.1 Develop templates for validation

The templates of method validations follow the requirements from the validation square method. The guidelines for developing the templates are as follows:

- There must be a template to collect the acceptance scores for each method.
- Each acceptance score is signified against the statement.
- Each statement is derived from the requirements of the validation square method.
- Opinions supporting the acceptance score must be asked for and recorded.

The templates to validate all methods are explicitly represented in Appendix M. Moreover, the templates were iteratively developed with the automotive water pump case, but each template shown in this thesis is the final version.

8.3.2 Validate the DRePOE method

The statements in column two of Table 8-50 are developed to comply with the requirements from the validation square method and they are represented against each degree of acceptance from the experts (columns four to eight). Subsequently, all statements are put into Table 8-51, column one, against the interview results from each case study's experts, as represented in columns two to four. The experts who participated in the DRePOE method validation are shown in Table 8-48.

The acceptance construct's validity is explicitly presented in the following sub-section, after that acceptance method consistency and performance validation are scored in Table 8-50 by each company's experts, while Table 8-51 collects all the qualitative answers to support the scoring results.

Structural validation

Acceptance of the construct's validity: This condition is focused on the quality of the literature and their validity for using each of them in the method development. The DRePOE method is evolved from the qualified literature, as is clearly shown in chapter 5. The selected methods to formulate this method are well developed and published, e.g. Saaty (2000). Therefore, the key inputs and techniques of the method are summarised in Table 8-49. There is one key input developed and one means applied to this method. The purpose of this table is to demonstrate the logic on how to combine the well-known approaches for method development.

Column one identifies the inputs or methods used in the method, while the purpose of each of them is shown in column two. The key developments are to explain the novelty claimed in this thesis, while the key applications show how the particular means support the achievement of the key development as reviewed in column three.

The key inputs, techniques, developments and applications are represented as I_n, M_n, D_n and Ap_n, respectively. The subscript n is ordered from this section all through section 8.3.3. The design rework drivers are extended from the literature by manipulating the case study-based method (Diverse case). All drivers captured are considered as the major development in this method. The AHP technique is to acquire a weighted average score for each driver.

Table 8-49: The summary of key inputs and techniques in the DRePOE method to comply with acceptance of the construct's validity

Key inputs (I_n)/methods (T_n) in the methods	Purpose of usage in the method	Key developments (D_n)/applications (Ap_n)
(I_1) Design rework drivers	They are used as drivers to be compared to each other as required by the analogy-based estimation method.	(D_1) They are evolved from factors related to design lead time or effort as captured from the literature and shown in Table 4-7.
(T_1) Analytical Hierarchy Process (AHP, Saaty, 2000)	It is selected as a method for giving scores to comply with the analogy-based estimation method.	(Im_1) It is a means of comparison among design rework drivers as well as the product being designed and its benchmarks.

Acceptance of the method's consistency: Statements DRe1 to DRe3 aim to achieve this validation. Questions about the acceptance of DRePOE method's assumptions, the validity of drivers to reduce design rework occurrence in the testing and refinement phase, and the application of applying AHP technique are asked. In summary, the experts from all companies agree or strongly agree with the statements as shown in Table 8-50.

From Table 8-51, there are two additional points raised from case studies one and three. The experts in case study one propose to evaluate the readiness of New Technology Introduction (NTI) or "Shelf Technology" which is in advance of the traditional Lesson Learnt. The traditional practice collects all previous activities and results in either success or failure, while the NTI is financially invested in so as to develop the new technologies and categorise them to be ready for use. In addition, this development must be independent from the New Product Introduction programme.

Another suggestion is from the supplier's point of view. The expert from company K mentions that there are many rework occurrences requested from OEMs, not because of market changes but due to OEMs' mistakes. Evidently, OEMs always ask for a reduction in the suspension weight when they cannot achieve the car's body weight target.

Acceptance of the example problem(s): All cases are supported by the participating companies. In addition, each of them confirms, through historical records or experts' confirmation, that there were design rework problems in the previous design projects. Hence, each company has accepted the example problems because they offer industrial case studies to develop the method.

Performance validation

Acceptance of the usefulness of the method outcome with respect to the initial purpose for some chosen example problem(s): All experts acknowledge the usefulness of the estimation result in their product design projects. Moreover, they concur that estimation enhances proactive action.

Acceptance of the linkage between the achieved usefulness and the method: The experts from all cases are satisfied with the estimation results. In addition, it is the consensus that the product being designed has some elements that are new to them. These new elements drive the estimation results closer to their expectation level.

Acceptance of the method's usefulness to apply beyond the case studies: Statements DRe 6 and 7 are meant to assure the usefulness beyond the case studies. All experts admit that the concept of the method is valid and useful. However, there are two concerns related to the company's context. This tool requires additional effort from the design team; hence, experts from case studies one and three express the key constraint as the official implementation. In addition, the norm in company K would be the major obstacle to this method of implementation, because the staff always prefer to solve emerging design problems rather than invest time in preventive actions.

Table 8-50: The level of acceptance scores for DRePOE method's validations from three case studies

Purposes in validation	Statements	Cases	Definitions: Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
			1	2	3	4	5
Structural validation							
Acceptance of the method's consistency	DRe1. All assumptions are valid.	Automotive water pump				✓	
		Turbocharger				✓	
		Macpherson strut suspension					✓
	DRe2. All drivers to reduce design rework probability of occurrence in the testing and refinement phase and Novelty Level are valid.	Automotive water pump				✓	
		Turbocharger				✓	
		Macpherson strut suspension					✓
	DRe3. The AHP technique is suitable to estimate design rework probability of occurrence.	Automotive water pump				✓	
		Turbocharger				✓	
		Macpherson strut suspension				✓	
Performance validation							
Acceptance of the usefulness of the method outcome with respect to the initial purpose for some chosen example problem(s)	DRe4. The estimated result is useful if the design team in this case realises the probability of design rework occurrences in the early phase of product design.	Automotive water pump					✓
		Turbocharger					✓
		Macpherson strut suspension				✓	
Acceptance of the linkage between the achieved usefulness and the method	DRe5. The estimated design rework probability of occurrence result is reasonable.	Automotive water pump					✓
		Turbocharger				✓	
		Macpherson strut suspension				✓	
Acceptance of the method's usefulness to be applied beyond the case studies	DRe6. The method to estimate design rework probability of occurrence is useful in the company's context.	Automotive water pump				✓	
		Turbocharger				✓	
		Macpherson strut suspension				✓	
	DRe7. The method is applicable in another company's product design projects.	Automotive water pump				✓	
		Turbocharger				✓	
		Macpherson strut suspension				✓	

Table 8-51: The interview results for supporting DRePOE method's validation from three case studies

Statements*	Cases		
	Automotive water pump	Turbocharger	Macpherson strut suspension system
DRe1	Yes, I agree with the assumptions.	I agree with the assumptions. Especially assumption one, which is all about new things, new competencies, new components, new features, new expectations and about some of the things we haven't got all the knowledge on. But again that is what we do.	I think all assumptions are valid.
DRe2	I agree with these drivers. In addition to lessons learnt, one of our suppliers actually puts money into learning technology. Some people call it "shelf technology", e.g., engine piston material at high temperature capability. We will pay them to develop the new piston and then we will run those new designs in the engine here. We will evaluate that new technology to gain all kinds of inertia benefits on that; and all that knowledge could be pulled together. Then you could call it NTI (New Technology Introduction). In our case, engine technology R&D is very important. The best place to put it would be lessons learnt which you learn before the NPI starts.	I think you cover all the various points in the design process. You catch the point regarding CAE and the way to describe it.	I think I agree on the validity of the drivers. However, there should be a factor describing the design change, because all of these drivers are related to design failure. But in reality, we have to rework because of the changes needed when the car body did not hit the weight target.
DRe3	AHP is a suitable tool. I think AHP is a good tool, providing it is properly used. I strongly agree with it.	We agree because we have used AHP. It is nothing new to us and we are used to it. And it is on MS-Excel, everybody uses it.	I think the method is valid, because it allows me to estimate design rework logically.
DRe4	Anything that prompts people to do things sooner is a good thing. So I would strongly agree with that.	I think I definitely agree with that. I think we need to inform the design team or the programme team to understand how to use the data coming up on the back of this and make them realise that it is more than a number, it helps them to plan the budget and resource allocation. Plan the design of work done as early as possible and try less fixing of work.	This method could help to team to proactively think about design issues based on the drivers. Previously, we just waited until problems occur then solved them. But this method helps us to evaluate the root cause beyond the technical issues.

*Statements are taken from Table 8-50 column two

Table 8-51: (continued)

Statements	Cases		
	Automotive water pump	Turbocharger	Macpherson strut suspension system
DRe5	Strongly agree. The impeller actually goes round and drives the liquid. If you make a very heavy impeller, such as a cast iron impeller, it has a lot of inertia and we don't want inertia because it causes torsional activity. So, we make a lighter impeller from composite. So, we change the inertia characteristics of the pump. It sounds like a tiny change, but you have to get the technology right to ensure the composite durability. There is a quantum leap in terms of confidence on the technology solution, and the inverse of that is how you think you are going to rework. If the confidence is high, the possibility of rework problems is low. Now Tier 4 is finished for design, and it is in validation so everything looks ok.	The estimation is fair. It is just a turbo, and there is not much change. If I say tier2 was one, Tier3 might be 3 in terms of Novelty Level, and this is the contribution to rework; so it adds up to 13%. So it is true, because this is the exact point as I said. If you have no change, you could have reduced the probability of rework because you have done more CAE work and you have captured more lessons learnt. But now new contents push us to have more rework.	I think the result makes sense, because the front suspension is relatively new to me.
DRe6	I think it is really useful. But the biggest problem for all of these is actually getting people to use them. We are very good at insisting that people use a whole raft of different tools, FMEA, QFD, etc. That is the other downside I can see, and that is a problem with the introduction of any new tool.	I think it is applicable to any system development, because it does not matter how you design. All those drivers exist for all systems. All those drivers are generic.	The concept is work. However, it requires time and internal review meetings. It requires the team to identify the key sub-systems or components that contribute to design rework probability in the whole product design. But, all these activities are considered to be boring. We prefer to solve emerging problems because they are challenging rather than spending time on preventive actions.
DRe7	The method is good, because everything is generic.	I think the process is applicable to other projects. However, if it is a totally new platform, I think this method is not valid. If the novelty goes above a certain level, it is not valid. It is a good process if your novelty is not too high, because what we are doing is extrapolation. If it becomes too many new, things, all your experience and supplier knowledge become less valid, e.g. changing from ICE to electric prime movers.	The method is useful because it visualises our working experiences. But we have never quantified them and this is a useful method to envision them. And it is very useful to record rework and enhance the company's continuous improvement.

8.3.3 Validate the DREE method

All statements in column two of Table 8-53 are developed to satisfy the requirements of the validation square method and they are represented against each degree of acceptance from the experts (columns four to eight). Subsequently, all statements are put into column one of Table 8-54 against the interview results from each case study's expert as presented in columns two to four. The participating experts in the DREE method validation are in Table 8-48.

Structural validation

Acceptance of the construct's validity: The developments of the DREE method as well as the related literature are detailed in chapter 6. The key inputs and techniques as well as their developments and applications are summarised in Table 8-52. There are five key inputs and five key means in this method. In addition, the key developments are claimed as a novelty in this thesis.

Acceptance of the method's consistency: Statements DR1 to DR7 in Table 8-53 aim to achieve this validation. Each of them focuses on the validity of each method's key developments. There is one reservation for the assumption of no change in the SOP deadline, the expert from company K, which is the Tier 1 supplier, mentions that sometimes the OEMs can call for a change in the SOP date, as represented in Table 8-54. However, this issue would be risky to OEMs to lose the opportunity to be a leader in markets; so it is regarded as less likely to happen. Therefore, this assumption is still considered to be valid.

Acceptance of the example problem(s): As mentioned earlier, all cases are supported by the participating companies. Especially in benchmark one from the automotive water pump case, where there was critical design rework effort to resolve design rework problems.

Performance validation

Acceptance of the usefulness of the method outcome with respect to the initial purpose for some chosen example problem(s): All experts acknowledge the usefulness of the estimation results. However, the expert from company E suggests the additional application point that this method will be useful to estimate the additional time required to resolve problems when APQP fails. But, it seems as if no one realises the problems until very late in the project. Nonetheless, this suggestion is beyond the intention of the method, because it is developed to estimate the design rework effort in the testing and refinement phase as early as possible.

Acceptance of the linkage between the achieved usefulness and the method: The experts from all cases satisfy the estimation results. The expert from company K makes the additional point that the knock-on effect for other components takes place under certain conditions in reality. One could be from wrong specifications specified from OEM. Another possibility is when the OEM ignores the component's test results which indicate risks of failure when they are integrated. Finally, it could be because the testing procedure is not correct or is obsolete. Therefore, the element in the testing list cannot capture all potential failures. As a result, the problems are not captured until late in the project. The worst-case scenario for the Macpherson strut case falls into this recent cause.

There is evidence from the water pump case that the worst case scenario was ball bearing failure. The information about torsional activity in the water pump had been specified since the beginning, but it seems that the supplier had no clue about how to deal with the problems until company E's team visited the supplier's manufacturing site to resolve the problem.

Acceptance of the method's usefulness to apply beyond the case studies: Statements DR 10 and 11 are to assure the usefulness beyond the case studies. All experts state that the concept of the method is applicable. However, there is one concern relating to the company's context and another is the application of the method to other projects.

Company K's expert mentions that OEMs force the company to follow their process; hence, there is little possibility of applying this method to work with OEMs on a daily basis. However, it has a high possibility to be implemented for internal usage.

Experts on the water pump and turbocharger express that the company's staff need to be convinced and educated because it is a new item. One possible way to achieve this is to test the method with more examples.

Table 8-52: The summary for key inputs and techniques in the DREE method to comply with the acceptance of the construct's validity

Key inputs (I_n)/methods (T_n) in the methods	Purpose of usage in the method	Key development (D_n)/applications (Ap_n)
(T_2) Function Analysis System Technique (FAST, Bytheway, 2007)	It is used for developing functional structure of the product being designed.	(Ap_2) It is applied as the initiative step for signifying the relationships between functions and components.
(I_2) Function-component relationship matrix	The matrix is for indicating the relationships among function and components.	(D_2) This is extended development from FAST by linking functions and components.
(T_3) AHP (Saaty, 2000)	It is used to acquire the relationship strength among functions and components.	(Ap_3) It is a means to attain the numeric values for the relationships instead of the direct assigning of "1" or "0" for relationships as used in Tumer and Stone (2003). But, the previous attempt cannot tell the difference in relationship strengths between two identical numeric values.
(I_3) The allocated design effort matrix.	It is the matrix filled with the design effort for each component.	(D_3) This matrix combines the AHP and function-component relationship matrix (from I_2) for getting the design effort for each component; which could not be achieved in Smith and Eppinger (1997).
(I_4) The component-component relationship matrix	It is for representing relationships' strength among components by using numeric values.	(D_4) This is the additional development from the matrix acquired in Tumer and Stone (2003) by combining I_2 and M_3.
(T_4) Zigzag technique (Suh, 2005)	It is used to capture components which induce failure in other components.	(Ap_4) The technique is modified in this thesis for capturing the linkages among component due to failures.
(I_5) The component failure relationships	They are for defining the failure root causes which happen from component interactions. All of them are filled in the matrix developed in I_4.	(D_5) It is claimed as an outcome of the extended development of the zigzag technique, because it is normally for designing products. Therefore, this is an early attempt to define the root causes of failure modes by applying the zigzag technique.
(T_5) Work Transfer Matrix (WTM, Smith and Eppinger, 1997)	It is the method for calculating design rework effort.	(Ap_5) This method is applied to estimate the design rework effort. There is no additional development within the method, and the only modification is the input vector. There is only initial design effort to resolve failure components filled in the vector.

Table 8-53: The level of acceptance scores for DREE method's validations from three case studies

Purposes in validation	Statements	Cases	Definitions				
			Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
			1	2	3	4	5
Structural validation							
Acceptance of the method's consistency	DR1. All assumptions are valid.	Automotive water pump				✓	
		Turbocharger				✓	
		Macpherson strut suspension				✓	
	DR2. The method to formulate relationships between functions and components is valid	Automotive water pump				✓	
		Turbocharger				✓	
		Macpherson strut suspension				✓	
	DR3. It is valid to assign the strength of relationships by AHP.	Automotive water pump				✓	
		Turbocharger				✓	
		Macpherson strut suspension				✓	
	DR4. It is valid to develop relationships among components by matrix operation.	Automotive water pump				✓	
		Turbocharger				✓	
		Macpherson strut suspension				✓	
	DR5. The method to capture "indirect" relationship is valid.	Automotive water pump				✓	
		Turbocharger				✓	
		Macpherson strut suspension				✓	
	DR6. The method to allocate design effort by AHP is valid.	Automotive water pump					✓
		Turbocharger				✓	
		Macpherson strut				✓	

		suspension					
	DR7. The method to estimate design rework effort with consideration of knock-on effects is valid.	Automotive water pump					✓
		Turbocharger				✓	
		Macpherson strut suspension				✓	

Table 8.53: (continued)

Purposes in validation	Statements	Cases	Definitions				
			Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
			1	2	3	4	5
Performance validation							
Acceptance of the the usefulness of the method outcome with respect to the initial purpose for some chosen example problem(s)	DR8. It is useful if the design team realises the design rework effort for each component in the early design phase.	Automotive water pump				✓	
		Turbocharger					✓
		Macpherson strut suspension				✓	
Acceptance of the the linkage between the achieved usefulness and the method	DR9. The estimated design rework effort result is reasonable.	Automotive water pump					✓
		Turbocharger				✓	
		Macpherson strut suspension				✓	
Acceptance of the method's usefulness to be applied beyond the case studies	DR10. The method is useful in the company's context.	Automotive water pump				✓	
		Turbocharger				✓	
		Macpherson strut suspension			✓		
	DR11. The method is applicable in other companies' design projects.	Automotive water pump					✓
		Turbocharger				✓	
		Macpherson strut suspension				✓	

Table 8-54: The interview results for supporting DREE method's validation from three case studies

Statements*	Cases		
	Automotive water pump	Turbocharger	Macpherson strut suspension system
DR1	In general, I agree with that.	All the assumptions are valid. I think the product functional structure is equivalent to our boundary diagram. You have got functions; you have got interactions, and how much it is interacted. SOP is the thing that you cannot change, because it is linked with a specific legislation launch date and those are fixed. Changing that will come up with big consequences in terms of your customers and everything. So normally it is fixed. For working in a CE environment, I think so, because people are always doing concurrent engineering. CE is well established and more complete now. The fact is because the development time is so short, so you cannot develop a programme in sequences. For whole engine development, all the different engineering teams work on their respective components concurrently, so everybody is moving as one. So the engine block team and air system team are working concurrently.	Yes, I think all of them are valid. However, sometimes the SOP is changed in our case, but it is called by the OEM.
DR2	It is valid. The matrix and scoring results are unique for that pump technology, but the tool is generic.	Yes. I think it is clearly visible. We are happy with the FAST methodology, so I agree with that one.	FAST is quite similar to what we use for design. The additional part is linking it with components, and I think this part is good.
DR3	So, these numbers are derived from what you and I actually talked about in the past, and you collected them with AHP. It makes perfect sense.	I'm very strongly agreed on that one.	I am an engineer, so I don't like to deal with subjectivity. But, this technique helps me get through easily.

*Statements are taken from Table 8-53 column two

Table8-54: (continued)

Statements	Cases		
	Automotive water pump	Turbocharger	Macpherson strut suspension system
DR4	I think it is valid. You can do it. You would have to mention that this matrix is unique for that pump technology and for that part of the component. The tool is generic, but by the time you get to that level it is specific to that certain pump and certain technology. So it is valid.	The relationship of the component concept is valid, but it very much depends on how we understand the relationships.	I am happy to see that all relationships are developed with strong foundations of mathematics.
DR5	Yes. I think it works, because we have seen how it is developed by the example of gear, ball bearing and impeller.	Relationship is valid but it is based on your past experience. But a new relationship is very difficult to predict.	This method is good for my company because there is no such clear guideline to develop failure modes. So, each one uses a different rationale to develop FMEA. But, this method, I think, still requires experienced engineers to develop.
DR6	Valid. You sub-divide from the start. You understand it from a local and global scale.	I think it is perfectly reasonable.	I think the method is ok, and it could be applicable in design for manufacturing. However, I would like to say that more examples make the higher confidence to me.
DR7	Yes. To come up with it you either use your original design or redesign. You still need to consider concurrent effects. If you have got strong relationships here with a high number, you could find the difference between these start to multiply quite quickly. The actual methodology I think looks fine.	Agree. I can show people that it is always more than they expected.	I think it is useful for giving a guideline for time speeding on design activities.
DR8	I can see the distinction between FMEA and this method. It's going to be used. This method will give people in terms of the overall view on what they are doing can interact with all those different things. But you can argue that a good designer will realise it anyway. But I think it is useful. It is good for completeness.	Anything would help you with planning and get better help with it in terms of the next requirements of the next task. I think it is useful.	It could be useful to estimate the cost of failed APQP. This situation occurs when a design release engineer does not follow the APQP strictly or the gateway fails. Unfortunately, we always realise this failure at a very late stage.

Table8-54: (continued)

Statements	Cases		
	Automotive water pump	Turbocharger	Macpherson strut suspension system
DR9	So, you basically calculate the Benchmark1 factor. It comes to about 1 month. Yes, it makes sense. I understand how you do it. I have just sat here and tried to remember back thinking about what was my estimation and how was my estimation time with that. Just the design corrective actions, not procurement and everything else, no validation. You are only interested in the design element. Design element is probably a month. Ok; yes; I think that is very good.	The worst-case lead time to resolve problems is 2.5 months including design testing. The design lead time estimated is one month plus, so I agree. Level of accuracy does not really matter; sometimes relative is more important to you. For example, this programme cost twice as much as the previous programme, I think that it is still valid. Maybe it gives an order of magnitude on how difficult it is.	I am surprised that the estimate result is close to what is actually happening. But I would like to emphasise how the knock-on effect happens as a worst-case scenario in my case. One could be from wrong specification given from the OEM. Another possibility is when the OEM is so stubborn and neglects the component's test results which indicate risk of failure when they are integrated. And it could be because the testing procedure is not correct. Let's say we are supposed to test joint integrity/stability. But the test procedure from OEM is from the 1970s, and it neglects certain things that could affect the joint (i.e., torque angle measurement, measurement of hoop stress, lack of thread tension measurement). Or doesn't have a test procedure of the joint at all. All these could affect the test result.
DR10	I agree because everything you do early on is good.	I think the more you can apply to the existing case studies, the more you can validate and have more confidence.	I think this is a good method; however, we are a supplier. So, we need the follow the OEMs' process. However, the difference is that OEMs have the action plan to resolve issues in terms of project management such as assigning a design release engineer. But from an engineering standpoint, it's not so clear. But a design release engineer would lead the problem solving and all the potential causes would be reviewed.
DR11	I think it is useful; however, I have some reservations there. It is another methodology and people may have to convince themselves that there is a huge benefit in it. You can only do this when you have an awful lot of historical data in a particular component or a system. You have to build that. You have to put in effort upfront to actually build all those relationships. The technique is actually exciting. It will be of benefit to me, but if I give it to some of my designers upstairs, you have to convince them. That is a kind of implementation herbal; it is not unique to your tool. We have the same thing with FMEA. Now people understand the value.	I can't see why not. It gets you to think about pitfalls and obstacles, potential of rework activities, and how long it is going to take to redesign the components. The obstacle would be trying to educate people to understand the method and limitations.	I think it could be for internal use rather than working with OEMs.

8.3.4 Validate the PriDDREB method

Every statement in column two of Table 8-56 is developed to satify the requirements from the validation square method and they are represented against each degree of acceptance from the experts (columns four to eight). Subsequently, each statement is placed into column one of Table 8-57 against the interview results from each case study's experts, as represented in columns two to four. The participating experts in PriDDREB method validation are detailed in Table 8-48.

Structural validation

Acceptance of the construct's validity: The developments of the PriDDREB method as well as the related literature are given in chapter 7. Thus, the key inputs and techniques as well as their developments and applications are summarised in Table 8-55. There are two key means and one key input for this method.

Table 8-55: Summary of key inputs and techniques in the PriDDREB method to comply with acceptance of the construct's validity

Key inputs (I_n)/Techniques (T_n) in the methods	Purpose of usage in the method	Key development (D_n)/applications (Ap_n)
(T_6) Pareto Analysis (Ebert and Baisch, 2001)	It gives the guideline for setting up the size of each component group.	(Ap_6) There are approximately 20% of total components in each group.
(I_6) Component groups for optimisation (G_{Opt})	The component groups are used as inputs for optimisation.	(D_6) The members of each component group are selected based on the guidelines which are extended from the Pareto Analysis.
(T_7) Linear programming (Venkataraman, 2002, pp. 93-104)	It is for finding the maximum design rework effort potentially in each component group.	(Ap_7) The maximum design rework effort for every component group is evaluated separately. Later, all of them are evaluated for frequency plotting.

Acceptance of the method's consistency: Statements PRi1 to PRi3 in Table 8-56 aim to achieve this validation. Each of them focuses on the validity of each method's key developments. All experts accept the validity of each statement. Moreover, they have the consensus that this method is different from the FMEA method, as represented in Table 8-57. In particular, company K's expert mentions that the scoring activity in FMEA is very subjective, but this method furnishes a clear visibility to address the components' criticality.

Acceptance of the example problem(s): Each case has critical components which cause additional effort to resolve their problems.

Performance validation

Acceptance of the usefulness of the method outcome with respect to the initial purpose for some chosen example problem(s): All experts acknowledge the usefulness of the prioritisation results, because it increases the proactive actions to prevent problems.

Acceptance of the linkage between the achieved usefulness and the method: The expert from company K appreciates the prioritisation; however, there are reservations to prioritisation by frequency counting. In cluster two, there is only one different frequency between the strut under the Prevent-environment function (33) and knuckle under the Optimise-camber angle function (32) but the knuckle is not selected as a critical component. Hence, the expert has signified the acceptance score as "*Neither agree nor Disagree*" for this statement. However, the experts from industrial cases one and two agree on the prioritisation result.

Acceptance of the method's usefulness to be applied beyond the case studies: Statements PRi 6 and 7 assure the usefulness beyond the case studies. All experts agree that the concept of the method is applicable. However, there is one concern related to the company's context and another one is to apply the method to other projects.

Experts on the automotive water pump express that it requires mutual agreement to implement the method, because there are many tools and means to follow in the design process already. In addition, they see the benefits of using this method in the later design stage rather than the early phase, because all techniques are to achieve the design-right-first-time concept. Once this principle fails, the PriDDREB is very supportive to bring the programme back on track and to earn financial benefit, while the company K expert emphasises the need to follow OEMs' working process, as mentioned in the DREE method.

Table 8-56: The level of acceptance scores for PriDDREB method's validations from three case studies

Purposes in validation	Statements	Cases	Definitions				
			Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
			1	2	3	4	5
Structural validation							
Acceptance of the method's consistency	Pri1. All assumptions are valid.	Automotive water pump				✓	
		Turbocharger				✓	
		Macpherson strut suspension				✓	
	Pri2. It is valid to implement the Pareto principle to address critical components due to design rework effort	Automotive water pump					✓
		Turbocharger				✓	
		Macpherson strut suspension				✓	
	Pri3. The method is different from the FMEA method.	Automotive water pump					✓
		Turbocharger				✓	
		Macpherson strut suspension					
Performance validation							
Acceptance of the usefulness of the method outcome with respect to the initial purpose for some chosen example problem(s)	Pri4. The recommendations are useful if the design team realises them in the early design phase.	Automotive water pump				✓	
		Turbocharger				✓	
		Macpherson strut suspension				✓	
Acceptance of the linkage between the achieved usefulness and the method	Pri5. The prioritisation results from the method are valid.	Automotive water pump				✓	
		Turbocharger				✓	
		Macpherson strut suspension			✓		
Acceptance of the method's usefulness to be applied beyond	Pri6. The method is useful in the company's context.	Automotive water pump				✓	
		Turbocharger				✓	

the case studies		Macpherson strut suspension			✓		
	Pri7. The method is applicable in other companies’ design projects.	Automotive water pump				✓	
		Turbocharger				✓	
		Macpherson strut suspension				✓	

Table 8-57: The interview results for supporting PriDDREB method's consistency from three case studies

Statements*	Cases		
	Automotive water pump	Turbocharger	Macpherson strut suspension system
PRi1	I agree overall. However, you could put technical issues 5% of total effort might pass to PV. You could say technical issues. I'm describing the issues rather than the size of the issue.	They make sense. That 5% we will have a pre-determined or pre-defined plan in place in order to let those 5% get through. For example, A, C, D problems will have a prescribed fixing plan, implementation dates, and they will be worked out and documented. So, 5% aren't let through blindly.	I am Ok with the assumptions.
PRi2	20% of components from the water pump; so you constrain the problem to be 5%. You could have said 3, you could have said 10. Plug in your optimisation. Yes, in general I agree.	Yes, it is true. For the example of an EGR cooler, six months ago, the problem of the gasket connected to the flange of the pipe expands to the big problem, and it delays the whole process.	I can see the value of applying the Pareto principle to identify the critical component groups, which is different from FMEA. In FMEA, the components likely to be failed are from designers' experience.
PRi3	Yes, it is different from FMEA. It has similarity in terms of function, but it has total differences. I strongly agree. Your work is a kind of duct tail/ joint in with FMEA, which is good.	So the FMEA will tell you what part you need to focus on during your design activity, and what test you need to implement. Your tool by the relationship link tells you again what part you need to focus on and also potentially you can underwrite what test you need to do on it. But your approach is from a different angle.	I think this method is different from FMEA. FMEA is very subjective to give the score.
PRi4	It helps because it is kind of a precaution. You get this wrong and this is the feeling you are going to get later on. So, you are doing it upfront, which is good.	It is useful, because the tool can give transparency. Yes, as long as people understand what the tool is going to do; how the number and how the end results will be interpreted. I think it is valid.	I think it is useful to know this information early, as I mentioned before, that we always realise the APQP fails at a very late stage.

*Statements are taken from Table 8-56 column two

Table 8-57: (continued)

Statements	Cases		
	Automotive water pump	Turbocharger	Macpherson strut suspension system
PRi5	This is now you have run the programme, with 946 combinations. And these now are the results for the water pump. And you are predicting the size of the problems. Yes. I appreciate that.	I think so, so you just say the critical components. Ok, so the optimisation tool will call off the critical components. Yes I agree. I think what would be helpful again is to link how these numbers arrive at that. So, when you put the instruction for implementation, you should say how these numbers are arrived at, and what has driven them. As long as people understand what underpins it; what makes it work, then yes, that it is good.	I can see the strong support from a mathematical point of view to get the prioritisation. But I think the weak point is how well you understand the product. For me, this is the first time for my company to design the front suspension system and it is not completed yet. So, I would like to wait and compare with the actual project. Another point I am curious is about frequency counting, because some of them are very close to each other, but you have not put into the sequence, such as in cluster two, the Strut under the Prevent-environment function (33) and knuckle under the Optimise-camber angle function (32). There is only one frequency difference, but the knuckle is not selected in this cluster.
PRi6	It is useful upfront, but it is difficult to implement it at the moment. You go through the time line that you originally had with design, product objectives, SD, DV, PV, SOP, and what we are talking about is all the inputs into that phase, aren't we? You have got FMEA; you have got design brief; you have got design reviews; you have got design procedures that you have to follow. And now you have got another one (this metric). I'm not saying that it is not useful; it is useful. Your designer has to sit down and he has got to understand all of these and he has got to understand yours as well. And I can't put yours on the top at the moment. I'm not saying it is not useful.	So, when you are doing your function relationships diagram at the very start you have specific linkages. Specific definitions for those linkages can be assigned for various components. It is a lot more constraining but a lot more helpful, because it's not such a broad method to approach the problems. Then you get the scenario, and you could come up with the percentage of design rework number, and then from that you could figure out the testing activities to implement. Ultimately, it will tell you how long it will take to develop a component or a system with potential for increasing lead time due to unforeseen activities. So, it is really helpful when you plan.	I think it is useful to implement within my company; however, we always work with OEM. So, I can see little room to fully implement it at the moment.

Table 8-57: (continued)

Statements	Cases		
	Automotive water pump	Turbocharger	Macpherson strut suspension system
PRi7	If I am in the later state and I am asking to redesign the very latest design phase, then your tool is a very useful tool for me to have, because when you sit down to revisit these you are not on the same level as the other metric. To me in this situation, yours goes up. Because on that point, I know I have got to change something, and your method is a really clear guide. You know, when you change this it will affect that. This is the rework, so the other tool in terms of technical risk; I think it has almost no use there. I appreciate that you are trying to do it upfront. That is the right thing to do. That is the primary. But the second advantage which you shouldn't ignore is that your metric is more useful in the later stage, because if things do go wrong, and unfortunately you are in this situation, your method becomes almost even more valuable, I think. In the early phase, it just gives you the visibility of where the potential problems could be and how big they are. It's just a whisper in the early phase, but in the later phase it is a megaphone. In terms of financial benefits, the maximum financial benefit comes here (late phase), but it is a lot smaller in the early phase, because you are estimating a lot late in the programme. We aim to design-right-first-time in the process. If the design-right-first-time fails, which is the story here, your method still has value in terms of picking through the redesign.	So, the way we would work is we pool up resources on the stand. We then divide to take the lead in each activity. We would make progress on all activities, so that each one of those will always be addressed. But the amount of people we have focused on that activity could vary. So we have more resources allocation to use by prioritisation. They will all get progress but in different ranks. So you can manage the resource upfront rather than let the problem occur.	I can see the whole logical flow. But to implement it as a standard practice in business, it needs more experiments first.

8.4 CROSS CASE STUDY ANALYSIS

The aim of this section is to address the generic aspects of all methods by comparing inputs and outputs from each one. In addition, the linkages among the methods are also concentrated on. All activities in this section are from the researcher's observations after gaining each developed method's inputs and output.

8.4.1 Analysis of the DRePOE method

Table 8-58 collects the required inputs for the method in columns two to four, while the estimated design rework probability of each product is in column five. Moreover, Table 8-59 represents the drivers for reducing the design rework probability of occurrence scores against each industrial case study.

It is explicitly shown that the estimated design rework probability of occurrence mathematically depends on the Novelty Level, weighted average scores of drivers for reducing design rework occurrence and probabilities of design rework occurrences from the benchmark products.

However, the significant observation regarding the method's generic aspect is that the Novelty Level and weighted average scores of drivers for reducing design rework occurrence are context dependent. The context in this case is the organisation's environment, acknowledged as customers, legislations, political constraints, economics and technological changes, all of which shape the individual's perspectives (Ivancevich et. al, 2011, pp. 9-10). Once Table 8-59 is evaluated, it is shown that the scores from the Automotive water pump and Turbocharger experts are quite close to one another in terms of numeric values and trends, even though they performed scoring separately. Though both cases are from company E, their suppliers are different. The automotive water pump case experience was with an under performing supplier, so the score in this item is significantly distinctive. The scores from Table 8-59 also contrast the viewpoints between OEMs and suppliers. Company K's expert presents the score related to CAE as the strongest, while both company E's experts do not. The interesting point is that company K is the supplier while the other is the OEM. However, this is not the focus of this thesis, but it is a good starting point to find out more about the future.

When the benchmark products are designed, they must also be constrained by the Novelty Level and the drivers for reducing design rework occurrence. Therefore, the estimated design rework occurrence is also context dependent.

Another key observation is made concerning the relationships among the method's inputs and the business context. Even though it is shown in Eq. 5-1 that the estimated probability has a linear relationship with the inputs, this method does not explain the relationship between business context to the Novelty Level and business context to the drivers for reducing design rework occurrence.

Table 8-58: The inputs and outputs from the DRePOE method

Cases	Novelty Level of the new product	Weighted averages of drivers for reducing design rework occurrence	Probability of design rework occurrences from benchmarks	Estimated probability of design rework occurrence (%)
Automotive water pump (Initial case)	2.44	*New product:* 0.57 *Benchmark1:* 0.09 *Benchmark2:* 0.34	*Benchmark1:* 13% *Benchmark2:* 3%	4.88%
Turbocharger (Case 1)	8.51	*New product:* 0.71 *Benchmark1:* 0.07 *Benchmark2:* 0.22	*Benchmark1:* 0 *Benchmark2:* 5 to 10%	6.56-13.15%
Macpherson strut suspension system (Case 2)	3	*New product:* 0.57 *Benchmark1:* 0.21 *Benchmark2:* 0.22	*Benchmark1:* 30% *Benchmark2:* 10%	22.33%

Table 8-59: Weighted average scores of drivers for reducing design rework occurrence

Cases	Exploita-tion of CAE Software	Coordina-tion across Team Members	Lessons Learnt	Supplier expertise	Clarity of specifica-tions	Open Communica-tion to Inform Design Time Issues
Automotive waterpump (Initial case)	0.08	0.09	0.29	0.11	0.35	0.08
Turbocharger (Case 1)	0.04	0.05	0.26	0.06	0.48	0.11
Macpherson strut suspension system (Case 2)	0.44	0.06	0.21	0.19	0.03	0.07

8.4.2 Analysis of the DREE method

Table 8-60 summarises the inputs and output of each case by applying the DREE method. It is emphasised that this method does not require benchmarks as discussed in chapter six. Mathematically, the functions directly connecting to components, total components and failure relationships, as represented in columns two to four, are the major characteristics controlling the estimated design rework effort. The combination of these factors manages the constant in the estimation, as represented in Eq. 6-5, because it is the property of the component-component relationship matrix. In addition, the total design rework effort given (Ef_{given}) is another factor constraining the estimation result. The other input of the method is the Expected design rework effort (Ef_{expected}) which is the "*optimistic*" design rework effort "*expected*" by the experts. Therefore, the estimated design rework effort shows the worst case or "*pessimistic result*" of the design issues. However, Ef_{expected} does not represent the characteristics of the product as other inputs do.

Table 8-60: Summaries for inputs and outputs for the DREE method

Cases	Total functions directly connecting to components	Total components	Total failure rerationships among components	Total design effort given (Ef_{given}, Hours)	Expected design rework effort (Ef_{expected}, Hours)	Estimated design rework effort ($Ef_{estimated}$, Hours)
Automotive waterpump (Initial case)	9	13	6	3,680	95.21	161.79
Turbocharger (Case 1)	19	11	2	9,200	82.27	200.45
Macpherson strut suspension system (Case 2)	12	15	12	13,800	14.42	156.30

The first three factors in Table 8-60, columns two to four, depend on the experts' experience, while the Ef_{given} relies on the company's context. It is significantly revealed that the Macpherson strut suspension system case delivers high $Ef_{estimated}$ with very low Ef_{expected} which is increased approximately 12 ($156.30/14.42$) times because of the knock-on effect. Compared with the Automotive water pump case ($Ef_{given}/Ef_{Estimated} \approx 2.44$), the knock-on effect is considerably less. Even though the functions directly connecting to components are insignificant numbers, the total failure relationships and Ef_{given} are distinct.

When the Turbocharger case is considered, it has the greatest total number of functions connecting to components, but it has minimal components as well as failure relationships. Even though its Ef_{given} is approximately in the middle between the automotive water pump and the Macpherson strut suspension system, the design rework effort due to the knock-on effect is close to the results from the Initial case. Therefore, the sensitivity of inputs to outputs is still not covered in this section.

8.4.3 Analysis for the PriDDREB method

Table 8-61 summarises the input characteristics and outputs of the PriDDREB method. It is noted that this method is an additional development from the DREE method; hence, most inputs are taken from what was completed in the previous endeavour. One input required for this method is obtained from the method to allocate components into groups to comply with the Pareto Analysis. The characteristics of this method are represented as k_{Pareto} in column one. It is interesting to note that every industrial case has the k_{Pareto} equal to 3; the method to come up with this value has been explicitly described in section 7.2.1.

Table 8-61: Summaries for inputs and outputs for the PriDDREB method

Cases	k_{Pareto}	nf	G_{Opt}	Cl	Possible design rework effort (Hours)	
					Maximum	Minimum
Automotive waterpump (Initial case)	3	22	641	7	222.51 (12.12% of Ef_{ideal})	94.67 (5.16% of Ef_{ideal})
Turbocharger (Case 1)	3	29	2,174	9	568.56 (14.63% of Ef_{ideal})	217.78 (5.43% of Ef_{ideal})
Macpherson strut suspension system (Case 2)	3	58	17,320	19	776 (54.85% of Ef_{ideal})	70.75 (9.12% of Ef_{ideal})

Another input that is important in terms of product characteristics is nf which represents the total number of linkages among functions and components. In addition, this factor presents the visibility on how the components in the product interact with each other. It is fascinating to see that the greater nf value is the result of the larger range of possible design rework effort obtained with optimisation, as shown in columns six and seven. This finding might answer the open issue concerning the sensitive factor raised in section 8.4.2. However, this hypothesis cannot be achieved at the moment because there are few industrial cases to confirm it statistically. Moreover, nf also triggers the G_{Opt} and *Cl*, as shown in columns four and five respectively.

8.4.4 Key Observations

The key observations related to general aspects of the developed methods are as follows:

- All methods are context dependent.
- The sensitivity analysis of the inputs and the estimated output of the DRePOE method are not covered in this thesis.
- The criticality of drivers for reducing design rework probability is not similar from one company to another.
- What influences the estimated result from the DREE method has not been answered in this thesis. Nonetheless, nf would be possible to answer this issue when the PriDDREB method is analysed in section 8.4.4, but more cases are necessary to confirm this finding. In addition, the finding would lead to a new definition of "*Product Complexity*". It is interesting that the higher nf value presents the wider possible design rework effort range; furthermore, it represents the interaction among components.

8.5 KEY OBSERVATIONS FROM VALIDATION

8.5.1 Key observations from the DRePOE method validation

- All experts have accepted the Structural and Performance validities of the DRePOE method.
- There have been two suggestions in the drivers. Company E's experts have proposed including the effects of new technology introduction, which is the investment within the company and independent from the product being developed. Company K's expert has suggested embracing the estimation of the probability of design failure originated from the OEM, because it causes design rework to suppliers.
- The inputs from this method depend on the context of each company.

8.5.2 Key observations from the DREE method validation

- All experts have not refuted the Structural and Performance validities of the DREE method. However, there has been one comment from company K that this method would be difficult to implement at the moment, because the company's design teams have to follow the OEMs' design process as a benefit of cooperation. Even though the method could not have been used externally with the OEM, it could have been used internally in the organisation.
- Company K's expert has supported that the DREE method has provided the worst case design rework effort estimation; however, the worst case takes place within specific situations which are composed of wrong specifications prearranged from the OEM, the OEM being unaware of risks from part integrations, and incorrect or obsolete test procedures.
- Company E's experts have a shared comment that this method is difficult to implement unless the company convinces its staff to use it, because it is new to them.
- Company K's expert has raised an issue related to the organisation's culture that could prevent the method implementation, because staff always prefer the challenges of solving emerging problems rather than investing time in preventive actions.
- The inputs from this method are constrained by the company's context.
- The sensitivity of the estimated design rework effort has not been covered in this thesis.

8.5.3 Key observations from the PriDDREB method validation

- All experts have not repudiated the Structural and Performance validities of the PriDDREB method. However, company K's expert has questioned the method to prioritise components when it seems there are insignificant frequencies of differences among components, and this is the reason to support the acceptance score on the validity of results as "Neither agree nor disagree".
- Company K's expert has insisted that the method is useful and applicable for internal usage, but to implement it as a standard working method to cooperate with OEMs would not have been achievable recently.

- Company E's experts from the automotive water pump case have approved this method higher in the later stage than in the early design stage, because of the existence of the right-first-time principle. Therefore, this method will provide financial benefit when the company cannot maintain this principle.

8.6 CHAPTER SUMMARY

This chapter fulfils research question five and achieves research objective five by implementing three developed methods into one initial case study as well as other two industrial case studies. All cases are applied into the Validation Square method in order to validate all methods.

All experts from the three industrial case studies have accepted the logic and consistency of all methods which are validated with the Structural validity principle. In addition, this principle includes the validity of references which are used in the method and the selection of case studies are explicitly revealed in sections 8.4.1 to 8.4.3.

All experts have not refuted the Performance validity of all three methods; however, there have been the concerns about DREE and PRiDDREB method applications in the company K's context, because this company has been the supplier to many OEMs; hence, they force the company to follow their design process and tools during the development programme as a benefit of coordination. However, all methods have had the potential to be implemented for the company's internal usage. In addition, this company has provided a neutral opinion on the validity of the PriDDREB method because the frequencies of the components are sometimes insignificantly different.

There have been suggestions to test the three methods further in order to sustain the implementation. All key observations are considered within the thesis discussions and conclusions in chapter 9.

CHAPTER 9
DISCUSSIONS AND CONCLUSIONS

The research discussions and conclusions are combinations of the researcher's observations (section 9.1) as well as the analysis of all key observations from chapter 8. The challenges in terms of conducting the research are described in section 9.1.1. Moreover, the quality of research is discussed in section 9.1.2. The required resources to implement all developed methods are considered in section 9.1.3, because they are built up from the assumptions of the methods. In section 9.1.4, the inferences of the business benefits as a result of each method are reviewed.

Later, the key observations from chapter 8 are used to identify the thesis limitations, recommendations and conclusions in sections 9.2, 9.3 and 9.4, respectively. The evidence supporting the method validity is reported against each research objective, while the concerns and suggestions are formulated as limitations of and recommendations for future works.

9.1 RESEARCHER' S KEY OBSERVATIONS

9.1.1 Key challenges during conducting the research

The elements during the observations were collected from the researcher's point of view throughout every activity. The academic's viewpoints reveal the solutions to resolve challenges while the industry's viewpoints disclose the constraints that shape the research direction. In addition, an alternative research direction is also discussed.

Chapter 1: Introduction

Academic's viewpoints: Design is composed of activities to convert the subjective requirements into physical entities. Once it is combined with the cost of design issue, the research topic becomes increasingly more challenging. Hence, the researcher is in the unenviable situation of dealing with the subjective issues.

Industry's viewpoints: For any industry, design is one of each company's key competitive advantages; therefore, it has been a real challenge even to acquire cooperation from companies. In addition, this project has not been funded by any UK enterprise, thus this is another significant challenge in this research. One solution for this challenge is by proposing an unambiguously clear topic which fully benefits industry as well as being valuable from an academic point of view; however, the researcher has more experience in academia than in the industrial sector. Therefore, finding the research focus required significant iterations at the beginning until the researcher discovered that the design rework issue, especially in the testing and refinement phase, is harmful to companies' start-of-production date. As a result of Along with this focus, several aerospace and automotive companies accepted this idea.

Chapter 2: State-of-the-art in the Design Rework Effort Estimation

Academic's viewpoints: This is another iterative activity. The researcher directly searches for the state-of-the-art in design rework effort estimation literature at the beginning; yet most of the literature estimates the design lead time or effort, both of which are embedded with design rework. The aim in each literature is to achieve higher estimation accuracy rather than focus on the design rework effort itself. Even though each literature source provides different contributions, there are several repetitions. The probability of upstream design changes and downstream design sensitivity are obvious. Another key observation is that DSM is a self-explainable tool by assigning the numeric values to the relationships among design tasks; however, the method to define them is not clearly visible. Optimisation techniques are widely used in estimation, while some literature incorporates risk analysis principles in estimation. All these observations constrained the direction to search for the fundamental knowledge that would help the researcher to better understand the state-of-the-art literature, all of which play a major role to establish the research questions. As a final point, the factors captured have been prepared for data analysis as shown in chapter 4.

Industry's viewpoints: The major challenge is that there is insufficient literature that describes the design rework issues in the testing and refinement phase. So, the researcher decided to extend the factors captured from the existing literature to analyse the data collected from the participating companies.

Chapter 3: Research Protocol Design

Academic's viewpoints: The key challenges to designing the research protocol are from the research questions, because they lead to the selection of the most appropriate type of research, research strategy and research method, as shown in sections 3.3 to 3.5.

Design rework is incompleted from the prior studies. Therefore, research question one, which is to find the design rework drivers in the testing and refinement phase, is a Descriptive research rather than Exploratory.

Once the design rework drivers on the probability of occurrence in the testing and refinement phase are developed, their relationships are analysed and validated. Therefore, research question two is in accordance with Explanatory and Emancipatory researches.

For research question three, the literature does not focus on the testing and refinement phase. Hence, developing drivers to estimate the design rework effort for this phase is necessary. In addition, developing the relationships among the drivers and effort as well as validating them requires the use of every research type. Research question four is closely linked to research question three; however, it needs additional guidelines in order to develop a warning approach based on the design rework effort. Nonetheless, it requires validation and is clearly an Emancipatory type of research. Later, all developed methods have to be validated; therefore, research question five is purely regarding Emancipatory research.

A flexible research strategy is selected for this thesis, because it is easier to alter the data collection method due to unforeseen situations when compared with a fixed research strategy. Then, the case study research method is chosen because it requires only a low sample amount compared with other methods.

Based on the case study research method, multi-data sources are collected in order to formulate the understanding of each case; each participating company is treated as one case. Documentation, interviews and direct observation are three major methods in collecting data, while thematic analysis is the method used to analyse those data.

Industry's viewpoints: The research methodology is constrained by the limited number of participating companies. Hence, testing the hypotheses using statistical methods is not a practical choice in this thesis. However, there is a concern on the repetitiveness of the data collection results, because the context of each company is unique. So, the research protocol must be able to extract the generic phenomena among companies.

Chapter 4: Industrial Field Studies

Academic's viewpoints: The interview questions are set to collect the design rework phenomena in the testing and refinement phase broadly at the beginning. There are five questions to the interviews during the preliminary data collection. The factors captured from the literature, as represented in Table 2-8, are not put into the questions at this stage in order to avoid bias, but they are helpful in analysing the interview results. It is exciting to find that the thematic analysis method fits very well with the classification of data into content and context themes. This classification is very important because the context theme is composed of statements which are generic for companies. However, each company has no control over context. . Content theme is a fact which is able to be manipulated by companies. All themes are synthesised with the factors from Table 2-8; moreover, they are designed to develop the drivers to reduce the design rework probability of occurrence, as illustrated in Table 4-7.

Industry's viewpoints: The content and context themes are developed regardless of cultures and geographic locations of the participating companies. There is a crucial finding in the context theme that the design lead time or design effort is either driven from the market's point of view or arranged by an agreement between the management and customers. Therefore, achieving the higher estimation accuracy has a minimal value for industry.

Chapter 5: The Development of the Design Rework Probability Estimation Method

Academic's viewpoints: Chapters 4 and 5 are extended from the principle of the risk assessment concept which requires the probability and impact from the product being evaluated. The DRePOE method assesses the probability of design rework occurrence, while the DREE method in chapter 5 estimates the impact in terms of effort from the captured issues. So, there are two main tasks in chapter 4: developing drivers and formulating the estimation procedure.

Once drivers are developed in chapter 4, they are validated with other companies in chapter 5. There are two purposes of this activity: one is to confirm that they are generic, while the other is to comprehensively collect all possible drivers. Several sub-drivers are captured. In addition, the researcher has more confidence to use them to estimate the probability of design rework occurrence.

An analogy-based estimation is applied in this method. The probability of design rework occurrence in the testing and refinement phase is focused on but it has to be evaluated in the early design phase; hence, parametric and analogy methods are the only two candidates. If the parametric method is selected, the researcher would be faced with the challenge concerning insufficient samples to confirm the estimation accuracy, but not with the analogy method. Therefore, the analogy-based estimation method is selected.

In principle, this estimation method is a means to acquire scores for the new element relative to the benchmarks, and this is the key challenge in the estimation. Apart from the AHP technique, the other method provides the score with the assumption that there is an absolute origin to be referred to. However, all of the captured drivers are subjective; so, this assumption on absolute origin is questionable. The reference is necessary to interpret the numeric value. If it does not exist, the numeric value has no meaning. Nonetheless, the AHP method provides the relative reference rather than the absolute origin; therefore, it is selected in this thesis.

Industry's viewpoints: During the testing of the method with company E, experts discussed previous projects beyond those evaluated in the method. One of the feedbacks is that this method enhances more visibility on how it works than the parametric method, but it has a trade-off with time spent. Nonetheless, this issue can be managed by using the incomplete comparison technique to reduce the comparison effort.

Chapter 6: Development of the Design Rework Effort Estimation Method

Academic's viewpoints: The DREE method is a hybrid of combining analogy and analytical principles. The WTM itself is an analytical method, while this research implements the analogy method to formulate it more comprehensively and meaningfully. The achievement of this method is from the finding that "*the design lead time is assigned by the management*", as revealed in the content theme. In addition to the industrial field study, the knock-on effect due to design failure from one component could cause extensive design rework effort needed for other components, and fortunately the WTM can model this phenomenon very well.

The WTM method is selected for two reasons. Currently, it is applied to estimate the design lead time with the consideration of design rework under concurrent design tasks, but it has never been used to estimate design rework in the testing and refinement phase before. Another point is that there are potential gaps for development. The method to obtain relationships among elements is questionable; moreover, the description for each numeric value in the matrix is not explicitly defined. Thus, there are two tasks to complete before performing estimations: building up the relationship matrix among components and the input vector.

Obtaining the relationship matrix among components is completed by an indirect method rather than a direct approach. To overcome this challenge, a function hierarchy of a considered product is attained by FAST and then functions in the lowest level are linked to the components by judgements as a result of a function-component relationship matrix. Later, the AHP technique is applied to examine how each component contributes to a particular function. After this activity, the function-component relationship matrix becomes a numeric matrix, and then it is converted to become a component-component relationship matrix. Another numerical group in the matrix is failure relationship which is defined as the associations among components that lead to failure. Again, this is a novel step to identify a malfunction due to mechanical loads interactions, as identified in Table 6-7. Once both relationships are placed, the matrix is achieved. Even though this method is lengthier, compared with previous attempts, higher visibility to develop the relationship as well as being more meaningful on numerical values are its prominent advantages.

Before generating the input vector, it is necessary to identify the amount of design effort for each component; however, the design effort is allocated from the AHP scoring activity, as revealed in section 6.2.4. In addition, the design effort allocated is to generate the input vector, as requested by the method. The key success is that the total score in the AHP technique is always equal to one, so each score is inferred as a percentage of the design effort. If the total design effort is acknowledged, it is effortless to calculate the design effort for each component. Coincidentally, the design lead time and effort are prearranged, as mentioned earlier, so the design effort allocated to each component is easily achieved. Again this is a novel step which cannot be achieved from the existing literature.

To set up the input vector, the issues are captured from experts by asking them to address the highest likelihood problems. There are three elements to making decisions on each issue. One is that the main component contributes to the issue and then the function which the component works for must be identified. The final decision is the estimated percentage in terms of the original design effort required to resolve the considered problem. These three decisions must be made for all expected design issues. Once everything is achieved, the input vector is generated and is ready to estimate. This is another novelty that has never been stated in other literature.

Industry's viewpoints: Obtaining the relationship matrix by asking the experts directly about the relationship among components is a real challenge. Therefore, the researcher decided to find other alternatives in order to attain the relationship matrix. Once the indirect method to acquire the relationships among components is tested with company E, the activity goes more smoothly than with the direct method. However, it requires investing a great deal of time to generate the component-component relationship matrix.

Chapter 7: Development of the Prioritisation Design by the Design Rework Effort Method

Academic's viewpoints: The key challenge in this chapter is evolved from the previous chapter. The DREE method is particularly vigorous, if users can pick up on the components likely to deliver issues precisely. Therefore, the challenge is that the users have difficulty in selecting which components to estimate. Another challenge is how to help designers to cover as many issues as possible. Currently, FMEA is a best practice to identify high risk issues. The important activity is capturing failure modes; however, this relies heavily on the expert's experience. Therefore, these challenges prompted the researcher to develop a method to address the critical components. The intention of the PriDDREB method is not to try to challenge the well established FMEA, but to identify the components that could potentially create high design rework efforts.

The challenge becomes "*how*" to do it. At present, DREE reactively works by assigning the expected issues in order to create the input vector. Therefore, there should be an additional module to create the worst case scenario. In fact, it is possible that there is more than one issue happening in the testing and refinement phase; but it is a challenge to address a group of them. Moreover, addressing the percentage of design rework effort in developing the input vector for the DREE method is another difficulty to consider. Hence, the researcher proposes the optimisation technique to evaluate the component group that could deliver significant design rework effort by looking at all possible component combinations. However, making a decision on a number from each component group is inevitable. Thus, the Pareto Analysis is proposed to set up the component groups that could cause a critical design rework effort; therefore, the components in each group are set to be 20% of a total component at a time. If designers can capture the component group that could deliver considerable design rework effort earlier, they would be carefully evaluated and managed before the design reaches the testing and refinement phase. Once the group that could trigger maximum design rework effort is evaluated, the less critical group is addressed and continued in order to cover every component.

However, each component can deliver more than one function, so the computer program counts all possible combinations exhaustively, as represented in section 7.2.1. To assign a percentage of the initial design rework effort to the input vector, the researcher proposes that the aggregate design rework effort from each component must be equal to or more than 5% of the total design effort. The researcher develops this method as an automated process after the DREE method is finished, and it is achieved because of the existing Pareto Analysis.

Industry's viewpoints: This method is effortless compared with previous methods. During testing with the water pump project from company E, the experts were impressed by the strong logic supporting this method, especially the Pareto Analysis. There was some discussion about assigning 5% to the optimisation constraints, but finally they understood that the proposed number is simply an indicator to evaluate criticality.

Chapter 8: Validation of Three Developed Methods

Academic's viewpoints: The validation square method is selected as a means in confirmation activity, because it is conceived to validate research related to design methodology. Its requirements are explicitly illustrated, so it causes the validation activity to be completed systematically.

Industry's viewpoints: All developed methods are validated with other two cases. In addition, there are no negative responses from any of the experts.

9.1.2 Quality of research

The quality of research is defined into three areas: quality of literature, quality of collected data, and quality of the method development, and they are involved in every step of this thesis.

Quality of the literature

In the quality of literature, all methods are developed from well-documented publications. In addition, the methods used during the development are well-established in academia and industry, as discussed in each chapter. Especially within the academic literature, each method must at least be cited in journal publications.

Quality of the collected data

Bias is identified as a risk from the data collection. As defined in section 3.5.6, it is from the belief that the elements being studied are representative of the population concerned, even though actually they are not. In this thesis, the highest risk is located during developing drivers to reduce the probability of design rework. However, the bias risk can be lessened following the concrete research protocol. The case study research approach is applied in the initial and comprehensive data collection, as represented in chapters 4 and 5. Each company is defined as a case. In principle, this research approach helps to extract the context and phenomena within a case by using multi-data sources. Direct observations, Archival records and Interviews are selected as means in the data collection. The Interview as an open-ended response technique is implemented in the initial data collection, because asking too stratified questions would lead to bias.

Quality of the method development

Once the qualified literature is addressed, as well as confirmation of the quality of the data, the method development can be conducted smoothly to serve each research objective. The assumptions of the method are very important in order to make sure that the method is valid under predefined situations. It is a discipline in this thesis that all assumptions must be at least be inferred from the context theme developed in sections 4.4 and 4.5. Therefore, all assumptions are based on industrial reality. As mentioned in the quality of literature, all methods are additional developments from the qualified literature. There are five key developments claimed in this thesis: developing drivers, providing assumptions, formulating each means together to be the developed methods in this thesis, presenting guidelines to prepare inputs, and applying the developed methods to other cases, and these are explicitly defined in chapters 4, 5, 6 and 7. However, all development outcomes are validated with three industry case studies by following the validation square method. Hence, the additional development in this thesis is validated, as disclosed in chapter 8.

9.1.3 Required resources for implementing methods

The DRePOE method

The critical resource in this method is that of human resources. It requires at least a team member who used to be a member of the previous product design team; because the fundamental point of this method is analogy. If all members are new, comparing the product level (alternative level) is a very difficult task to attain the score accurately. In addition, the experienced team member contributes by reviewing the estimated result, whether it is reasonable or not. Another required resource is a set of benchmark products; otherwise the comparison with the new product cannot be achieved.

An important resource is the historical evidence of the probability of design rework occurrence. Most benchmark products in this thesis have no historical records, so the numbers used in estimation rely on the expert's memory.

The DREE method

Even though the previous product designs are kept within the participating companies, each of them is obviously not in a functional structure. So, at least one experienced engineer must be available, otherwise there is nobody to develop the component-component relationship matrix, to score the effort spent in each function and component, as well as issue the expected design problems. Again, experienced team members are necessary to evaluate the estimated result.

The PriDDREB method

The experienced engineers are the sole required resource, because this method is automatically performed after the DREE is completed. They need to review the prioritisation results and plan to manage the critical components.

9.1.4 Business benefits

The researcher categorises the business benefits into the following: the confidence of estimation transparency, enhancement of the cooperation among team members, enrichment of historical records, and prevention of the design issues in the testing and refinement phase. They are explicitly represented as follows:

Confidence of estimation transparency

From observation, the experts, especially from company E, express their preferences on transparency. They hesitate to make decisions on a multi-million GBP project when they do not know how the estimated number is provided.

Applying the AHP technique into the DRePOE and DREE methods allows perfect transparency on how each number is developed. In particular, during scoring activities in both methods, the AHP supports experts to discuss before making decisions on scores. In addition, the concrete procedures and guidelines accommodate the user to understand clearly how the method performs. Therefore, all methods are validated smoothly in every industrial case study.

Enhancement of the cooperation among team members

The value in this point of view is from the fact that the experts can discuss freely, and then they need to make decisions on the score mutually, both of which are captured during the the validation session especially for the DRePOE and DREE methods. In addition, all methods could be a means to reduce the learning curve when there are new team members.

Enrichment of historical records

The DRePOE and DREE methods provide clear formats for the collection of data. The scoring results from the design rework drivers as well as the projects in the DRePOE method allow companies to record a snapshot situation in their contexts. The scoring in each driver and project can be changed with time, so it is a good source from which to evaluate the previous design team's operational capability. In addition, the functional structures of sub-systems, systems and products, as completed in the DREE method, can be kept for future products. Moreover, the scores of the effort spent on functions can be recorded for benachmarks in the future

Prevention of the design issues in the testing and refinement phase

All developed methods in this thesis prevent late design issues, especially in the testing and refinement phase. The DRePOE method foresees the probability of design rework occurrence from the drivers, all of which are confirmed as good practice to reduce design rework probability in the testing and refinement phase. In the DREE method, the designers can evaluate the unconfident design and this method has the capability to model the worst-case scenario if problems appear during the testing and refinement phase. With this prediction capability, the design team can plan either technically or managerially to resolve the problems early on.

If the design team has limited experience in the product being designed, addressing the critical components leading to high design rework effort in the testing and refinement phase is the challenge. The PriDDREB method is a useful approach to provide guidelines on what the critical components in terms of design rework effort are. Hence, the design team can focus their attention as early as possible.

9.2 RESEARCH LIMITATIONS

The characteristics of each method and the recommendations captured during validation are summarised for thesis limitations as follows:

- The DRePOE method is not to generalise the criticality sequence of design rework drivers, because each individual organisation has a dissimilar business context. So, the criticality in each company is not similar.
- The design rework drivers in the DRePOE method are generic but independent from the business environment, so the best practice on how much the probability of design rework occurrence should be is not answered in this thesis.
- Experts on the turbocharger mentioned that the Novelty level can prevent the implementation of DRePOE when there are no benchmark products with which to compare.
- The design rework effort obtained by the DREE method is specific for each organisation's business environment, hence the best practice on how much design rework effort there should be is not obtained in this thesis.

- The sensitivity analysis for the DREE method's inputs is not covered in this thesis.
- The PriDDREB method cannot provide the failure modes and recommendations to resolve problems to a particular component.
- All methods developed in this thesis will be useful only if staff in design activities use them. It is very difficult to implement them if the organisation's culture does not acknowledge the value of proactive actions to prevent problems, as occurred in company K.

9.3 RECOMMENDATIONS FOR FUTURE WORKS

The thesis limitations, characteristics of the developed method and recommendations captured in the method validation are summarised as recommendations for future works as follows:

- The design rework drivers should be the initiatial step to develop the standard key awareness specific to each industry sector.
- The DRePOE method could be the standard tool to define the industry's best practice based on the design rework probability of occurrence.
- The DRePOE method should be improved to estimate the design rework probability of occurrence even though there are no benchmark products.
- The DREE method could be the standard tool to identify the industry's best practice based on design rework effort.
- Enhance the PriDDREB method to provide the potential failure modes and recommendations to resolve problems concerning a particular component.
- Use all methods in the research related to organisational development, specifically in design activities.
- Apply all methods using further industry case studies in order to increase confidence within industries.
- Developing FAST to be a more automated activity is a potential key improvement.
- Capturing component failure relationships with the zigzag method still relies heavily on experience, so the method should be a more self-identifying process.

- The amount of design rework effort is based on three factors: the sequence of components and functions in the function-component relationship matrix, component relationship scores and the number of functions satisfied by one component. There is no answer to the question of which one has the highest sensitivity to the design rework effort, so this is another potential research opportunity.
- Develop concrete guidelines for decision making when the frequencies of components are not significantly different.

9.4 THESIS CONCLUSIONS

There are six key developments which are claimed as novelties in this thesis as summarised in section 8.3. All of them are supported by the achievement of three methods in this thesis. The thesis conclusions are summarised in Table 9-1 against the research objectives.

Table 9-1: The summary of the research objectives and the developments in this thesis

Research objectives	A specific development to answer the research question	Evidences for achievements
1. To identify the key drivers for the probability of occurrence of design rework in the testing and refinement phase.	Drivers to reduce design rework probability of occurrence and Novelty Level.	All experts agree about their validity as represented in Table 8-50.
2. To develop an estimation method for the design rework probability of occurrence at the early design phase.	DRePOE method	All experts accept the Structural and Performance validities of the method as represented in section 8.3.1.
3. To develop a methodology to estimate the design rework effort with consideration of the knock-on effect at the early design phase.	DREE method	All experts agree on the Structural validity of the method. In general, the Performance validity of the method is accepted.
4. To extend the methodology in the third objective to provide a warning about the components which would require extensive design rework effort to resolve.	PriDDREB method	All experts concur on the Structural validity of the method. In broad view, the Performance validity of the method is accepted.
5. To validate each individual method with industrial experts and case studies.	Applying Validation square method to validate all methods	Successful validations by obtaining all required validation results.

Research objective 1: All drivers to reduce design rework probability of occurrence and Novelty are valid in the experts' opinions. However, this objective requires the achievement of the DRePOE method in order to fully answer this research objective.

Research objective 2: All experts agree on the validity of the DRePOE method; therefore, research objective two is successfully achieved and its logical flow and usefulness confirmed. As a consequence, research objective one and two is completely answered.

Research objective 3: All experts concur on the logic supporting the DREE method through the Structural validity, even though there is one concern about implementing the method in the company during working with OEMs which was raised by the supplier (company K). But company E answers from the OEM viewpoint that it is a useful method and can be applied in their company. However, companies E and K are not in the same business sector, but it is a high possibility that the DREE method can be considered as one standard tool in the design process. So, it is reasonable to declare the accomplishment of this research objective.

Research objective 4: All experts are of the same opinion about the logical flow of the PriDDREB method by accepting the Structural validity. However, there are two concerns from company K. Implementation of the method with OEMs is a key concern; however, company E supports the usefulness of the method. Another concern is how to prioritise when components have insignificantly different frequencies. However, the expert does not deny the prioritisation result. Therefore, it is realistic enough to affirm the achievement of this research objective.

Research objective 5: The validation square method overcomes the challenge of the insufficient number of industrial case studies to be validated by statistics. All useful validation results are captured throughout the validation session. So, this research question is fully completed.

In conclusion, the design rework probability and effort in the testing and refinement phase can be structurally assessed early in the design phase by DRePOE and DREE methods respectively. The DREE and PriDDREB fit very well under the worst case scenario, which is supported by the company K scenario when the design failures are from the following: wrong specifications, neglecting the potential risk of failure of components integration and obsolete testing procedures. Moreover, the components that potentially lead to significant design rework effort in the late design phase can be structurally addressed early on with the PriDDREB method.

The acceptance of all methods verifies three hypotheses. Hypothesis two: the relationships among design rework drivers developed in chapters 4 and 5 are confirmed and they can be used to estimate probability of design rework occurrence in the testing and refinement phase. Hypothesis three: it is authenticated that the design rework effort in the testing and refinement phase can be assessed in the early design phase. Finally hypothesis four: it is confirmed that a group of components seems to deliver small technical issues but they potentially create greater design rework effort than expected. The endorsement of these hypotheses is knowledge affirmed in this thesis. Hence, the conclusion of this thesis is as follows:

“The aim of this thesis is accomplished systematically with the DRePOE, DREE and PriDDREB methods.”

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APPENDICES

APPENDIX A

QUESTIONS FOR INTERVIEW DURING INITIAL DATA COLLECTIONS

Cranfield UNIVERSITY

Date :

Candidate Name :

Position :

Job Function :

Year of Relevance Experience :

Contacts :

Cranfield UNIVERSITY

Interview Questions

Capturing the Design Process and Design Rework issues

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Objectives

1. Identify AS-IS model of design process in Company.
2. Capture current practice in estimation PD effort and lead time.
3. Capture sources of design rework in practice.
4. Capture impacts of design rework to the whole design activities.
5. Identify metrics to evaluate success of PD

Questions

- Would you please explain the product development processes used in your organisation?

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- Please explain the product architectural design and integration methods. Are there any software tools supported for this activity?

- Who should be involved in PD team? How do you structure PD team?

- Please explain the project planning methods implemented in design project. Is there any software tools used?

- Please explain how to estimate time and effort required in each design activity.

APPENDIX B
SECONDARY DATA COLLECTIONS

B. 1 COMPANY C

The interview lasted for 3 hours with a senior engineer from engineering support & the V3P promotion project. The interviewee is currently working on automotive V3P. It is a new project launch within company C, while it has been a common procedure for vehicle development projects in Japan. This project is trying to enhance more CAE and CAD tools for vehicle development projects in terms of consultancy and training support. The ambition is to deploy fully 3D digital modelling for vehicle development in Europe. Even though the interviewee is not a designer, he has 11 years of experience in car body design and development in company C.

From the initial findings about evaluating design rework through component interactions, the Design Structure Matrix (DSM) is initially implemented in this case to capture the components’ interactions in the car grille’s improvement project. There are only two data collection types in this case; documentation and interviews. Even though the interview was conducted in company C, it was in a meeting room which is completely disconnected from the staff working area. Hence, direct observation cannot be conducted. The detailed data collection from company C is shown in section B.1. 1.

B.1. 1 Documentations

During the interviews, the interviewee used company C’s design and development process to explain; however, reproduction of the document was not allowed. Nonetheless, a hand drawing was accepted by the interviewee as shown in Figure B-1, and the detailed discussion is in section B.1. 1.

In addition, there is an Engineering Manual as a guideline for car body part design and Engineering Standards for the collection of all knowledge of Company C, both of which are used as a starting point in designing for new product design projects.

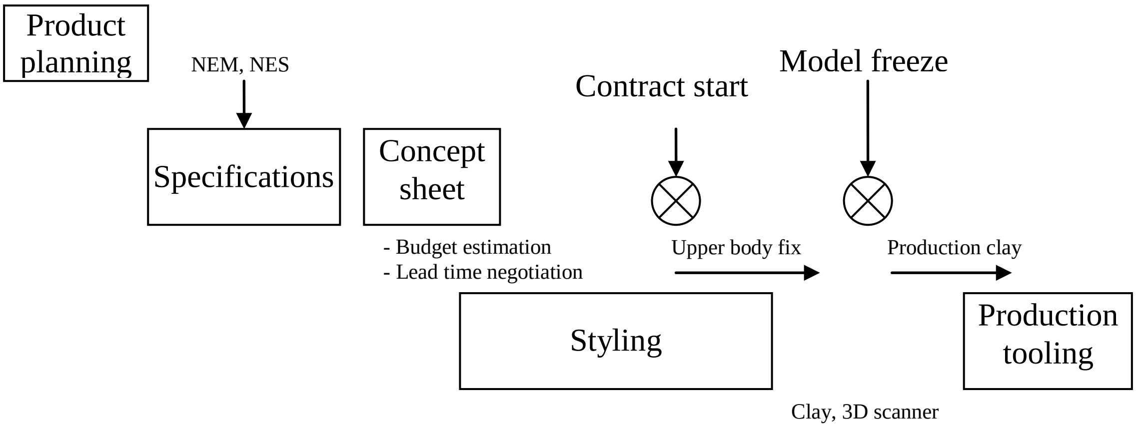

Figure B-1: Car body design and development process from Company C, partially captured by hand drawing

B.1. 2 Interviews

Car body design and development process from Company C

The interviewee was very much involved in the car body design, while the Japanese team in Japan is strongly involved in the platform design. There are two types of vehicle development project:

- *Face lift project:* This is a minor change vehicle project, i.e. small appearances changes to an existing vehicle.
- *Body in white:* This refers to body structure. It is considered to be a major modification of a vehicle or major change to a vehicle model from concept to finish.

The example of the Face lift project on a vehicle grille was used during the interview. Even though this is a minor change project it still helps to explain Figure B-1 very well.

Product planning: In principle, this is analysing what the customers want. From company C's point of view, trying to achieve a design for customers with the minimum of changes to a previous design is an ideal achievement, because every modification has to be paid for. Company C's engineers try to reuse parts from previous design as much as possible to cut development and testing costs.

Specifications: Once a customer's wants are clearly defined, specifications and a concept sheet are developed iteratively. The Project Development Management department (PDM) prepares a reasonable schedule for a project and defines the scope of the project. The project scope starts from the target setting activity which is defining the further development of the vehicle, e.g. fuel economy, acceleration etc. These mentioned scopes are converted into technical specifications numerically. The related components and design sequence to deliver new specifications are from design team experience.

The sub-process which helps to achieve the activity is Digital Planning (DPl). Car body performances such as durability, weight, stiffness, crash performance or noise vibration characteristics are checked by CAE software.

Concept sheet: Once the specifications are defined, a concept sheet is generated. The designer will then realise what individual engineers need to do with the new specifications. This document gives direction to the designer to have a plan to deliver the specification. The concept sheet is later used for budget estimation and negotiation. Once the concept is decided, this document is passed to the chief vehicle engineer. Cost for and benefit to the customers are also agreed to be a part of the project.

Specifically, the PDM department initially specifies the amount of workload. This estimation goes into the initial document in what they call the product concept letter. It contains the schedule and list of items being designed. This document is for everybody to study and provide feedback on regarding manpower or lead time requirements. Obviously the senior engineer or engineers give feedback to the project from their experience. The PDM department always asks for manpower reduction for savings in the budget. Eventually there will be an agreement between the planned manpower and budget between the PDM and design department. The design department is the key player for feedback on budget planning. So, estimated time and effort are from the experience of the PDM and feedback is from the design department. There are three iterations to update the concept sheet and three iterations for updating the budget. These iterations lead to the formulation of the contract for vehicle development. There is in-house software available to collect data and understand the cost for individual components.

Everybody builds in buffer time by looking at the project schedule list; however, the budget will always force team members to agree to less. It seems that the design team has to accept the budget constraint. Then, the accumulative cost is obtained as planned cost. But, the actual cost is usually rather more than the planned cost.

The PDM department use Microsoft Project software for planning, while feedbacks are done by spreadsheet. The project will not continue until they achieve agreement. Then the design team starts the initial study requirements. The design department separates the panel hood, front doors and back doors, exterior trim, headlamp, dash board and seat into sub-systems. The seat sub-system is responsible for safety systems such as air bags. There is generally one design engineer per part.

Styling: Once the concept is accepted by the chief engineer and financial department, the designer starts styling by using a clay model in parallel with a concept sheet generation. Actually, styling has been done with some overlap with a concept sheet generation. Normally, there are two styling models in competition between the UK and Japanese teams.

One styling model is chosen from the brainstorming of the top executive and design team, which is to fix a vehicle body milestone or, as shown in Figure B-1, the upper body fix. Then the product engineer will go for the chosen model and engineering activity. The clay model is scanned and checked by the engineers, for legislation, visibility, rear view mirrors and all of access. Body panel data are generated from clay by styling software called Ellious.

After scanning the chosen styling, all surfaces have to be designed in detail, for example, a full door panel with mechanisms, and then all parts have to be analysised digitally. This activity has to be iteratively working with the styling activity. The clay model is still important for styling during this stage. The sub-process for this activity is Digital Development (DD). The design team brings in a lot of trim parts such as headlamp, bumper, seat, cockpit module and then checks whether they are feasible for assembly within the available target lead time or not. Performance for large trim parts such as the bumper is studied and digitally tested in CAE. Furthermore, parts are checked for manufacturability. As many major issues as possible for production are eliminated by the design team.

Production tooling: Once vehicle body has been analysed enough, then the design team freezes it. So, theoretically, no more styling changes are allowed beyond this point. This is another important milestone, as shown in Figure B-1. Potentially, there are some modifications to the model in reality, however, after the model freeze. After the model freeze, the design team prepare final production surface data digitally from the production clay, and all data are checked out for final engineering evaluation; the sub-process for this activity is Digital Confirmation (DC). DC is for the selection suppliers.

Once the suppliers have been selected, they start working on detailing component shapes and provide feedback to the design team. The design team can complete digital prototypes, and there are obviously four of them in CAD. The sub-process support for this activity is Digital Production Vehicle (DPV).

The digital prototypes are confirmed by performances, production requirements and assembly. Then, they are in the design release phase to suppliers for making tools. Later, the first physical vehicle prototype is built. In brief, designing a vehicle is done in the digital world and then the digital definition is used for constructing tools.

Although the first car is for testing, all parts are from production tools. At this stage, the opportunity for design change is very small because it is very close to the start of making the production tools. However, it costs a great deal of money to change the production tool.

In terms of timing for production tool development, the design team releases a long lead time here in terms of tool development, such as bumper, headlamps, and body. It is the design team's responsibility to manage the schedule to get the product tools on time. However, the design team are aware that there will be design rework before confirmation for production tool release. So, this is the strong supporting rationale for using digital vehicles for evaluation before physical prototype building. There are many concerns here; however, the target for getting to this stage is to reduce concerns as much as possible. There should be only minor concerns, which should be corrected just in time before the production tool release.

Classification of design change happening in car body design and development

Generally changes happening at the end point of design and development are responded to seriously. The start of production needs to be maintained, even though there is a delay in something due to a big style change, for example bumper change. So, there are many special activities required to complete the design before its release for production tooling. The classification of changes is captured from interview as follows:

Process driven change: This change happens from the early stage of design until model freeze and is acceptable as an informal change through conversations or emails. There are styling changes, packaging concerns, production issues, Proceed Quality (PQ) feedback, supplier change due to less capability to make parts at target costs, etc. Performance or durability problems seem to be the main causes of change. Before the model freeze, suppliers pay for modifications, but after this milestone company C has to pay for them. Also change requests become formal. In other words, this type of change is an iterative one.

Physical testing driven changes: The model freeze milestone means that there should be no styling change, and then a physical test has to be conducted. If, for example, the cooling system does not agree with the CAE simulation, changing the cooling design would need a car body styling change. That is certainly an abnormal change because it has gone passed scheduling where the design team can manage it as a progressive drive change. Therefore, special actions recall keeping it back.

This change is driven by test failure, so it would need to be re-designed or reworked. This type of change is a serious issue because it happens close to the SOP and making the production tool has already started which is expensive to change. In addition, it breaks company C’s philosophy which gauges the right-first-time of the production tool. The estimation for this type of change is at least 20%.

If there is a physical issue, the first thing that needs to be checked is the ability to achieve tooling because this affects the SOP. Delaying the SOP will lead to huge costs in terms of opportunity lost. Then special actions, such as obtaining more resources, are necessary to maintain the SOP.

Classifying design fault and failure is possible to be done by detailed design analysis through a Failure Mode and Effect (FMEA) study in the early design phase.

Over-written changes: The example for this type of change is the headlamp. Its model is frozen, but this is overwritten by the executive because they do not like it. It is considered that this change has originated from outside the design team so it is difficult to control.

Understanding the consequences of change is necessary. The easy issue could be contained within that one part and easier to manage than those impacted on many other parts, because generally the design team has to look at other parts in order to change a design. So, somebody else's mistake or something else changes means that team members have to go out of their way to change their design. Limiting the change as much as possible is highly preferable, but there are no concrete, written down procedures. Normally, a team gathers data from the facts, the time, the cost and decides the best solution.

Tools, knowledge and other supported systems in company C

This section is developed by extracting details from interview. Hence, the results enhance company's C design process in more details.

Clay: Clay has been an important tool for vehicle development since the project started. It is the main tool for the styling design.

Software tools: All CAD data originate from 3D scanning of the clay model, for which there is a styling software call Ellious. CAE software is for testing parts using a computer, for example LS-DYNA is the software for crash simulation. Furthermore, the interviewee agreed that CAE helps the design team by reducing design rework.

IT tool for supporting coordination: This is very much 3D CAD data used in terms of defining the shape of the parts and interaction between the parts. There are some 2D drawings generated as well. CAD data management is the core of the design process. Team members have to put every design into the system so everybody can see the updated parts. If nobody can see it, then they look at the old version. Hence, CAD data management is the key contribution for the prevention of using obsolete data. If data are not managed properly, this can cause unnecessary change.

However, the workload is the main barrier to preventing a designer from keeping updated. So it is a discipline for design engineers to make the CAD data right in the first place either from their own CAD or from the suppliers. Thus, updating a design seems to be a low priority workload.

The other concern happens from cultural point of view. Japanese teams do not like to put data into a product data management system until the level of completeness satisfies them or the milestones have been reached. They do not put in something wrong or incorrect. This behaviour is totally different from the company C team; as a consequence, company C has no time to correct and evaluate the data given by Japanese team.

Lessons Learnt for beginning new design: Designing parts starts from the best practice of historical data in order to prevent concerns in manufacturing and assembly. The architecture designs are from what company C used for their design before, so the new design is not entirely from scratch. There are books which contain the master sections. The Engineering Manual shows the ideal body part section that designers should use to give strength to the provided area. Another book is the Engineering Standard. This book collects all company C's knowledge on every car system, so these are the starting points for designers. As a result, company C's team never starts from scratch. Everything is built from the current knowledge available.

Supplier role in the design and development of a car body

This finding emerged during interviews; therefore, the researcher has separated it from the last sub-section. The supplier is critical to the design team because suppliers will finalise detailed designs or provide some data to complete a part design, since they are experts on a particular part. For example in grille design, designers will tell suppliers the size and the output as well as its connection to other parts as required. Then the suppliers will design the grille and come back to the designers. So, the suppliers are important to the team because they give information after the vehicle body design has been started. So, each supplier's input is crucial to the part design for design engineers.

Methods to evaluate design

The methods used to evaluate design also came out during interviews, so the author devised additional questions to cover them. The first captured method is Proceed Quality (PQ). This is actually validating the quality of the part by looking at the vehicle from the customer's point of view. Then the design is judged on whether it appears to be a good quality product, e.g. feeling good, or feeling the sense of quality when touching the materials, and deciding if the gaps between the bumper and the grille are too big or not which may make the customers feel it is of poor quality.

In terms of CAE feedback, this is performance evaluation. This evaluation is carried out during the design phase by using digital data, while physical tests are performed at the end, such as the crash test. There is a group responsible for specific tests, such as expansion due to thermal change. There are also a different number of tests. Experienced test engineers are also involved in the early design phase to ensure that parts successfully pass every test.

Another evaluation is the integration of parts by checking for any interferences among parts to make sure that they physically fit together; this is the responsibility of the Layout department. The main task of this department is giving recommendations for package space within a vehicle. So, engineers in this department are always using CAD to run collision tests for confirming integration. Feedback on interferences is given to the designer in order to change a part's shape. Obviously this is a checking activity rather than collaboration, i.e. check and feedback problems then fix them.

On top of checking, meetings and agreement between design and production engineering are required. So there are many sub-processes in place to make sure this happens throughout rather than just between production and the design engineer by getting the team together and building in the development process.

B.1. 3. Key observations captured from Company C

The data analysis used in the previous two cases is still used in this case. Full transcriptions from tape recordings are implemented and the key observations from this case are summarised as follows:

- Design effort or man power is driven by budget.

- New vehicle design project start from clearly define what customer wants.
- Lesson learnt, such as Engineering Manual and Engineering Standard, is helpful for design new vehicle.
- The related components and design sequence to deliver new specifications are from design team experience.
- There are three types of changes realise from interviewee; process driven changes, physical testing driven changes, over-written changes.
- CE is implemented either in vertical or horizontal point of view.
- Designers have to make sure that everybody part is integrated to perform vehicle required functions.
- Vehicle body architectures are evolved from previous design, so designers have the starting point to design a new one.
- Designing a new vehicle body required a group of people from different disciplines working together through out the project.
- Clay is the important tool for body vehicle design.
- CAD and CAE are very important for car body design.
- IT technology supports coordination is very helpful, only if designers use it.
- Work load is the barrier preventing designer to update their design.
- FMEA is a tool capable to capture design failures in testing phase and it has been used since the design begins.
- Knock-on effect from design change from one part to others is not desirable.
- SOP is relatively fixed. If changes occur, special activity such as increase resources is needed to maintain SOP.
- Considering design rework effort required are done reactively after event happen.
- Suppliers have a vital role to feedback the potential concerns to the design team.

From key observations above, research put more intention to FMEA because it seems to be a powerful assessment tool for capturing design failure issues. Furthermore, it is implemented in the early design phase. This point makes researcher investigate more in FMEA related literature; moreover, it evolve issues to be looking for in the next data collection.

B. 2 COMPANY D

Company D is one of the biggest local suppliers for the Thai automotive industry located in the eastern part of Bangkok. Automotive seat and interior trim parts are designed and manufactured for the OEMs in Thailand either for internal consumers or export. The interviews were conducted with the design engineer for a total of six hours. His experience in seat design spans 10 years.

The interview focused on the front seat which is the first full project undertaken by company D engineers, while previous projects were jointly developed with OEMs' vehicle development team. The ambition for this project is to generalise this sporty looking seat to a wide range of cars produced in Thailand. Company D hopes that this seat model will receive contracts easily from OEMs because they will not need to pay for seat development as before.

Most of the time spent in the interviews was for capturing the dependency of seat components by using Design Structure Matrix (DSM) method. This is an early attempt to develop a method to estimate design rework effort from a horizontal point of view, as will be explained in section B.2. 4.

B.2. 1 Direct observations

Data collection is conducted in Company D's R&D facilities within the assembly site. The testing facility is located next to the meeting room area, and there are many test beds close to the meeting room filled with human dummies. However, there was no opportunity to observe the test facility closely because it is in a restricted area. So, observation from a distance was the only chance. The seat is considered to be a safety part in a car. Every seat must not break if a car is involved in an accident, and this is the main purpose of all test facilities.

B.2. 2 Documentations

Schematic drawings

Front seat schematic drawings were asked for, as shown in Figure B-2 for capturing component dependency in section B.2. 4.

FMEA document

FMEA was regarded by Company C as an assessment tool to identify design failures as mentioned in Key Observations 10; therefore the researcher asked the interviewee to show a document from a historical project which had already been launched on the market.

In Company D, Design FMAE (DFMEA) is always conducted or provided in the early design phase by OEMs. In principle, all failure modes are considered when a car has an accident and parts looked for that could injure passengers. Corrective actions are derived based on scores given to failure modes: high scores require immediate actions, compared with the low score which are dealt with later.

B.2. 3 Interviews

Capturing the seat design process in Company D

Seat designers usually team up with the OEM. Company D has close relationships with a Japanese automotive OEM, and normally the design activity is conducted in Japan. Design and development lead times result from negotiations between company D's management and customers. In the negotiation period, company D management has to evaluate staff capability, especially for prototype building and equipment for manufacturing. These two criteria help company D plan their budget. If requirements from OEMs exceed the company's capability, company D has to look for Tier 2 suppliers as a result of cost increases. Therefore, requirements, seat styling, and knowledge are assigned by the OEM. For company D itself, the knowledge is kept in a drawing format and embedded with designers, but there is no such a system for retrieving previous knowledge. One reason is that designing is always with the OEMs; however, all drawings are kept at company D in order to work with part suppliers in Thailand. For the front seat one engineer is required per seat, and this interview is therefore focused on the front seat only.

Even though the sporty style of seat is the stand alone project in company D, generic requirements have to be studied by the company D team before conducting any design. Obviously requirements are provided by the OEM, but in the current project the interviewee has to study the dimension of the seat produced in Thailand and determine the average size. This task can be achieved because company D dominates the auto seat industry in Thailand.

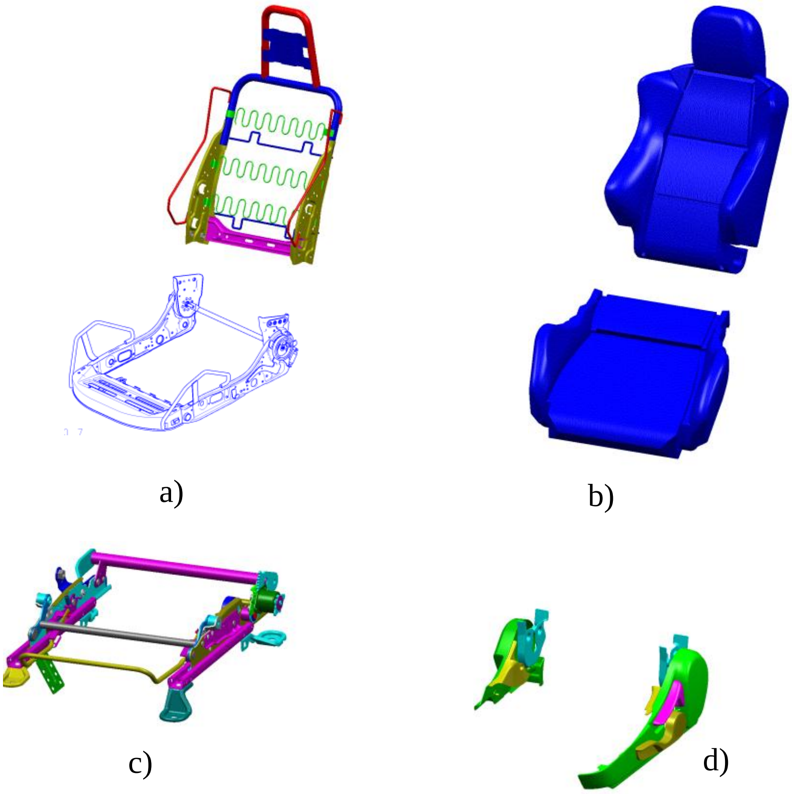

Figure B-2: Major automotive seat subsystems a) Cushion and Back frames b) Pad and Covering for cushion and back c) Height adjuster d) Belt e) Plastic cover (Source: Company D)

Each front seat is divided into three sub-assemblies; back, cushion, and height adjuster as shown in Figure B-2a, b and c. However, the seat is a safety system, so there is a metal frame structure within a seat as shown in Figure B-2a. Figure B-2d is the plastic cover to decorate height adjuster. The example for unit design cost for a front seat system with one Japanese OEM is shown in Table B-1. Column 4 represents cost but the interviewee has removed all cost items for reasons of confidentiality.

There are gateways between design stages; moreover, designers on other seat projects help by reviewing the design. Designing is concurrently conducted among components to obtain the conceptual layout up to the detailed design. Normally, the layout part of the conceptual design and DFMEA is given by OEMs, but for this sporty looking seat, project company D has to do both of these on its own. From the designer’s point of view during the detailed design, obviously the cushion is the starting point because it connects to a height adjuster which is integrated within the vehicle body and then the other sub-assembly refers to the cushion during design. However, the design is iteratively performed and it is very difficult to explicitly define during iteration. To do a detailed design, designers have to check previous designs and reuse previous parts as much as they can in order to reduce testing costs. Also from the designer's point of view, the metal frame structure is critical, so retrieving previous designs will help to guarantee the successfulness of seat design and development. If the design of a previous structure cannot comply with the new styling at all, then clearly some modifications will be necessary.

A detailed part design is prepared to be a 3D and 2D prototype part data. Company D has recently implemented a CAE program but it has not been implemented for this project. Therefore, testing the seat is based on physical testing. Testing simulates seats under accident conditions and parts must not break although deformation within certain limits is regarded as acceptable. In the testing phase, many testing criteria are required; however, in principle, testing has to be done in a bare structure frame test and full assembly seat system.

Company D has a high capability to design and manufacture, as well as assemble seats. Only the height adjuster system, as shown in Figure B-2c, requires the supplier to develop it because the OEMs still have no confidence to develop this system.

Table B-1: Example of unit design effort for front seat system

No.	Activities	Unit (hrs)	Remarks
1.	Receive and collect CAD data -Specifications -Benchmark	8	Reviewing CAD and comparing new specifications with historical parts. (Concept design)
2.	Layout part concept design -Part conceptual design	8	Integration design
3.	3D/2D data -3D data prototype -2D data prototype	240	Preparing for prototype
4.	DFMEA	56	
5.	Reviewing for manufacturability	16	
6.	Prototyping -Material ordered -Prototype built	480	
7.	3D/2D data -3D data release for approval -2D data release for approval	56	Release to manufacturing department and customers.
	Total	864	

Capturing design changes in Company D

The main sources of change are from OEMs, because there have been many changes requested on the attachment point of the height adjuster to the vehicle body. Therefore, there is much design rework required for the height adjuster.

As stated earlier, a seat is designed by one engineer, so design change is obviously progressive changes and changes due to failures found when testing the prototypes. Once the design failures happen designers have to evaluate root causes, alternative methods to correct the problems and economic concerns; furthermore, every criterion has to be evaluated with durability performance.

B.2. 4 Capturing seat component dependency by DSM

Capturing the dependency of the seat system is an additional study in this case. The initiative of this study is because of Key Observations nine and eleven from Companies B and C respectively. Therefore, the researcher has tried to implement DSM to capture dependency among components. The researcher was under developing a method to estimate design rework probability and effort required. This was the most time consuming during the interviews. The direct method to obtain relationships among components was conducted with the interviewee. During capturing relationships, the researcher asked whether each pair of components in the rows and column headings have any relationship or not; if so, the researcher put "×" in the cell where both headings joined each other.

Top management had assigned full responsibility to the interviewee for the design of the front seat. Therefore, the author is confident that the interviewee is qualified to complete DSM. From previous experience, the interviewee realised that two objectives need to be achieved. A car seat has to deliver comfort to drivers and styling to attract OEMs, while safety features are compulsory to be met. A front seat system can be decomposed into cushion and back frames, cushion and back pads, covering, height adjuster.

The designer selects frames from previous projects. Therefore, it could be reasonably assumed that the frames have already passed the safety requirements. The frame was selected by modelling various frames and a model pad and covering. Later, the distances between pad and frame were checked for safety legislations.

The DSM output is shown in Figure B-3. The DSM is a square matrix which is identical in row and column headings. The matrix obtained from this interview is non-symmetric. The lower diagonal relationships show the dependencies of the parts in the row headings to the parts in the column headings, while the upper diagonal relationships are considered as feedbacks from the column headings to the row headings. In principle, if there are many feedbacks, it is considered to have a high complexity (Browning, 2001).

Components		Cf	Bf	Cp	Bp	Pc	B	Ha	C
Cushion frame	Cf		×	×					
Back frame	Bf	×		×					×
Cushion pad	Cp	×			×		×		×
Back pad	Bp	×	×	×					×
Plastic cover	Pc	×		×	×		×	×	
Belt	B			×	×			×	
Height adjuster	Ha	×	×						
Covering	C	×	×	×	×	×	×	×	

Figure B-3: Decomposition and design sequence of automotive seat systems

B.2. 5 Key observations captured from Company D

An additional activity is capturing components' dependencies. This is the only data collection from a supplier's point of view. The key observations found in this data collection are as follows:

- FMEA analysis is available since product design start.
- Design lead time is given from negotiation with company D management and OEMs.
- Specification is either clearly given from OEMs or developed by company D's team.

- OEM treat seat as dependent system to car floor panel on which seat design have to rely.
- Qualified staff members and equipment capability are criterions to negotiate cost with OEMs.
- Designing new products always begin with previous design to assure that design will comply with safety requirements, and it also reducing testing cost.
- The components for seat are designed concurrently.
- In detailed design, every seat component is designed iteratively in order to achieve the design.
- In seat itself, design change happens from progressively design, feedback from testing. But there are a lot of changes requested from OEM due to changing the connecting point between seat and car floor.
- OEM treat seat as dependent system to car floor panel on which seat design have to rely.
- Reactions to failures are evaluated from the difficulty to resolve the problems, alternatives to solve problems, economics aspect; furthermore, they have to be assessed with requested performances.
- It is very time consuming to implement direct method to capture component relationships.

B. 3 COMPANY E

Company E is one of the leading OEMs for engine manufacture. The interviews were conducted for three hours with the cooling team leader who has been responsible for the design and development of the cooling team for three years. Furthermore, there were nine hours of interviews with specialists in the lubrication and cooling systems of diesel engines for 30 years. In addition, there was one interview focused in DFMEA with the Validation leader, again with 30 years of experience, on the 9th of March 2009 for three hours. Company E gave access to two water pump projects. All interviews were recorded by taking notes.

Company E outsourced the first water pump design and development project with a foreigner supplier starting from 2002. Previously, their water pumps were supplied by another company, but the management decided to change supplier. There were many problems on this project due to failures in the testing and refinement phases which were very close to the SOP. So, there had been many failed water pumps, until Company E decided to send two members of staff to help solve the problems with supplier in 2006. Later, Company E intended to change their supplier in order to eliminate the problem permanently, so a second project began in 2007. The second project was treated as a stand alone, and independent from the engine development programme; it took approximately one year to design.

This data collection is focused on finding the root causes of failure problems by treating each water pump project as one unit of analysis and Company E itself is considered as one case; therefore, it is a single-case multi-unit of analysis.

There are many document available, especially email communications, between company E and their suppliers. Therefore, the interviews are based on trying to capture issues and understand the context of design and development conducted with both suppliers, rather than just capturing design processes as in previous data collections. Nonetheless, key observations have been analysed and prompted to develop themes in section B.3. 4.

At the end of the data collections, the author did try to implement DSM to capture dependency among water pump components by direct method, but the cooling team leader found it very difficult to manipulate the matrix. So, the author decided to go back to the literature and search for alternative methods to obtain the relationships.

B.3. 1 Direct observations

The data collections were conducted in Company E's manufacturing site in the Midlands, UK. The office is based in the design and development centre. There are many notice boards urging staff to develop engines to achieve innovative product. Furthermore, there were several leaflets available advertising training courses such as CAE training.

Engine testing facility centre is also on the same site. In addition, the manufacturing and assembly sites are in the same area; therefore, the co-location of the design and development teams provide is economically viable.

B.3. 2 Documentations

Many document have been given to author, as stated above. Most of them are from the first project. A summary of the document for both projects is shown in Table B-2. The *Purposes* column provides a summary for each document. The author gained access to all of these documents; however, not all details can be shown in this thesis because of the confidentiality agreement. The specifications of the water pump evolved during the progression of the project.

Table B-2: Summary of documentation provided in company E case study

Documents	Projects		Purposes
	1st	2nd	
Email communications with supplier	✓		They represent when issues start and give their resolutions.
Drawings	✓		They show detailed drawing of the water pumps in order to understand the design failures.
Schematic drawing (3D)		✓	It represents the overall arrangement of the water pump.
Technical specifications	✓	✓	They show the technical specifications of both water pumps.
Failure mode analysis (FMA)	✓		It represents failure issues found in the verification and validation phase. Reactive actions are also shown for any issues found.
Failure mode and effects analysis (FMEA)		✓	It identifies potential failure modes in the 2nd project. Proactive actions to reduce risk are shown in the document.
Progressive presentation		✓	It represents progress of the project.

B.3. 3 Interviews

Company E development process

The generic design process for company E is captured from interviews, as shown in Figure B-4, and is called the New Product Introduction (NPI) process in company E. To keep it, generic terminology for every case, design and development process is used for discussion.

There are many detailed activities within this process. The water pump project is one sub-system of an engine development project. Company E implements Six Sigma for managing the design and development process. There is an Advance Product Quality Planning (APQP) team controlling the design and development for the engine project, while the cooling team known as the Concurrent Product and Process Development

(CPPD) team is the cascaded team focused on engine cooling and lubrication sub-system design and development. In addition, there are several CE principles implemented either in a vertical or horizontal direction, and there are official meetings among teams on a weekly basis to confirm the integrity of the sub-system to the whole engine.

Company E's main product is an off-highway diesel engine for a wide range of applications such as in agriculture, power generation etc., and the USA has the biggest markets.

Requirements for the engine are driven by emissions legislation launched by government authority. Company E follows USA regulations which forces OEMs to reduce emissions. The engine class is defined by "Tier". The 1st and 2nd projects studied in this case are for a Tier 3 engine; furthermore, Tier 4 was implemented in 2011. In each Tier, the emission allowance is based on power output, which is dependent on engine fuel efficiency driven by the engine's operating temperature. Therefore, a new water pump design and development is required in order to circulate engine coolant for removing excess heat by that engine coolant. New engine design and development is needed for each milestone to comply with the new legislation, otherwise company E cannot sell its engines in the USA market. In addition, similar regulations are applied in the same direction throughout the world.

A schematic 3D drawing for the automotive water pump is shown in Figure B-5; there are 13 components. The conceptual design of the water pump originated from company E and its suppliers, and then supplier has full authority for a detailed design. Suppliers should have enough expertise to design and eliminate any problems from the assigned product. After a prototype water pump has been built, the supplier has to ship it to company E and put it into the developing engine for validation, as shown in Figure B-4 (Design Verification and Validation (V&V) block). If everything is fine, the design can be frozen and signed off for the V&V process. If there are problems in the Design V&V which require design rework to resolve the issues, company E needs to spend extra resources to fix any problems and maintain the SOP. It would be a high risk to let the problem continue until closer to the SOP.

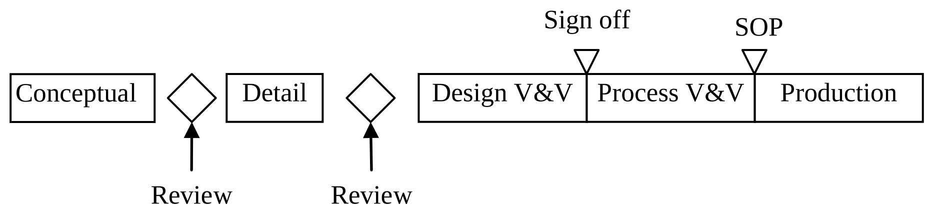

Figure B-4: Generic design and development process for Company E, captured from interviews

For the first project, there were many water pump failures during the design V&V, especially with ball bearing problems due to torsional activity. So, there was a huge amount of cost incurred associated with those problems. To resolve the torsional activity problems, company E had to re-analyse not only the ball bearings but also the impeller and gear because both of these create tangential forces which could damage the ball bearings.

After deliberating, company E decided to launch the second project aiming to replace the first supplier. The later project needed to finish the second project as quickly as possible, having replaced the first supplier, by increasing resources and working closely with the new supplier, otherwise correct costings for the water pump problems in field would be enormous. The progressive presentation showed that the second supplier worked very well even though the schedule was tight.

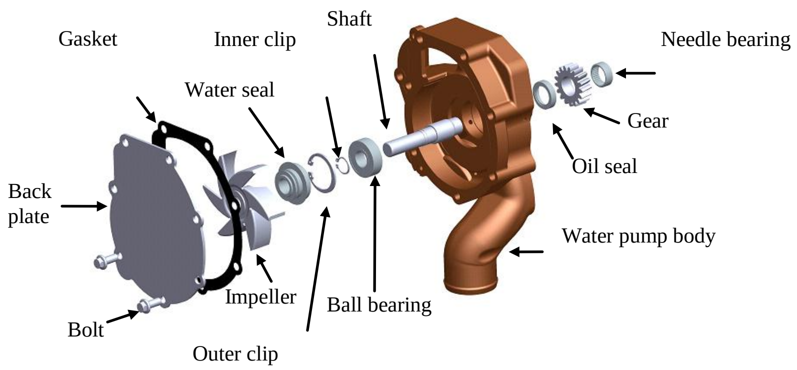

Figure B-5: Schematic 3D drawing of an automotive water pump

The different costs incurred between these two projects are shown in Table B-3. It is clearly shown that the second project spent much effort and costs on meetings and CAE analysis, compared with the first project; as a result, the first project had considerable penalty costs to resolve the issues in the Design V&V phase. The CAE analysis for the water pump is the AMESim software which is for analysing operational condition characteristics for the water pump, such as flow rate, temperature etc., while Tomahawk is for analysing dynamics forces in components and it is this latter program that helped to reduce failures due to torsional activity in the second project.

Table B-3: Comparative cost incurred between the first and second project.

Phases	Cost incurred		1st Project	2nd Project	Unit
Conceptual Design	APQP/CPPD meetings	Number of meetings	5	10	meetings
		Total Meeting cost	150	300	£
	Analysis cost	CAE software implementation			
		AMESim		35,000	£
		Tomahawk		10,000	£
		Total Analysis cost		45,000	
	Design Administration		10,000	10,000	hours
	Total Conceptual design cost		10,150	55,300	£
Detail Design	APQP/CPPD meetings	Number of meetings	15	6	meetings
		Total Meeting cost	1,800	720	£
	Prototype cost	Tooling cost	12,000	50,000	£
		Prototype part cost	55,000	30,000	£
		Total Prototype cost	67,000	80,000	£
	Total Detail design cost		68,800	80,720	£
Design V&V	Meeting cost	Number of meetings	15	6	meetings
		Total Meeting cost	450	180	£
	Sign off Validation cost	CAE softwares for sign-off validations			
		Number of cases required in Tomahawk	5	1	cases
		Total CAE cost for sign-off validations	12,000	4,400	£
	Swapping Cost		100,000		£
	Redevelopment Cost		15,000		£
	Courier cost to Supplier	Returned items	67		items
		Total courier cost	6,365		£
	Total Design V& V cost		133,365	4,400	£
Total cost			225,315	140,420	£

Implementation of FMEA in Company E

FMEA continuously evolves from the product start until sign off. FMEA helps to reduce reworks by using a fail safe principle. The design team has to look at the parts' functionalities and their failure modes. In addition, the root causes are also studied. If failure modes exist, the design team has to eliminate them. This is the proactive

action. Obviously, the validation team has to work with the designer from the early design phase to develop FMEA. Therefore, the high potential failure modes would be removed in the early design phase. In addition, company E's validation plan is derived from FMEA.
The potential failure modes are assessed by a Criticality index which is the combination of severity and occurrence of the issues. Severity refers to how harmful the failure mode is to the system while occurrence gives the probability of the issue occurrence. Both of them have scores from 1 to 9. The higher the score, the more undesirable it will be. The FMEA begins from the engine level and is derived for system, sub-system and components. Some of failure modes are taken from a previous Tier. The historical information on failures is from such items as warranty failures, in-house classed problem products, etc. Once the FMEA for engine and component levels are developed, the high criticality systems will be given to the responsible CPPD team in order to resolve the failure modes. So, the task for each CPPD team is finding the failure modes and fixing them. Furthermore, the validation list is created from the high criticality failure modes.

If a failure mode is captured, as predicted in the test, the detection score is very low, which means the design team is very confident about finding the problems in the product. The detection score from testing and the occurrence score are used to generate a Dealer Repair Frequency (DFR); the lower the detection score with a longer operating period means the DFR is low. Ultimately, DFR helps to predict product reliability in the field, because company E does not want any components to fail in the field during their expected life. Company E is looking for any failure reported in service and this information helps to calibrate the FMEA generated.

In Design V&V phase, company E classifies the severity of issues found to be A, B and C risks: A means cannot go to production because of extreme customer dissatisfaction; B implies moderate customer dissatisfaction and problems should be resolved by certain activities before going into production; C denotes minor customer dissatisfaction and therefore can go into production regardless of the issues. Severity in this last phase means risk to the business if the problems recur.

Company E implements 8D to resolve the issues found in Design V&V. 8D is composed of Define the team, Define the problem, Determine the immediate corrective actions, Determine root causes, Identify solutions, Validate solutions, Congratulate success, Celebrate success. There are no standard procedures to estimate efforts to resolve the problems at the moment.

B.3. 4 Key observations captured from Company E

The key observations from Company E are analysed from multiple data sources as follows:

- Design and development lead time is set due to legislation milestone in Company E.
- CE principle is implemented either in horizontal and vertical direction in Company E.
- APQP and CPPD teams have to meet weekly based and make sure that every sub-system can be integrated together to achieve engine design.
- Exploitation of CAE Software is potentially a key to reduce design rework in Design V&V phase as shown in Table B-3.
- More coordination through meeting is potentially helping to reduce design rework in Design V&V as shown in Table B-3.
- The level of specification clarity is potentially decrease design rework in Design V&V phase.
- Water pump performances are depended on engine requirements and the supplier has to achieve them.
- Supplier should have enough expertise to design and eliminate any problems from the assigned product.
- Previous knowledge is helpful to generate FMEA in the early design phase.
- FMEA begins in the early design phase.
- FMEA consider failure modes which might happen in the field.
- Resolution is necessary if the there are issues found in Design V&V phase. Design rework in V&V is happened due to design failures.
- There are no standard procedures to estimate design rework effort.

APPENDIX C
SKIMMED VERSION OF FMA DOCUMENT FOR AUTOMOTIVE WATER PUMP

Sub component failure mode	Failure Date	Root Cause	Action Taken
Gear	02/03/2006	Helix Angle out by 20'	
	09/05/2006	Helix Angle out by 20'	
	15/09/2006	Helix Angle out by 20'	
Ball Bearing	11/2005	Fatigue due to torsional activity	Analyse by in house software
	06/02/2006	Fatigue due to torsional activity	Analyse by in house software
	21/03/2006	Fatigue due to torsional activity	Validation/CAE work underway
	01/04/2006	Fatigue due to torsional activity	
	12/05/2006	Fatigue due to torsional activity	Analyse by in house software
	12/05/2006	Fatigue due to torsional activity	
	12/05/2006	Fatigue due to torsional activity	
	15/05/2006	Fatigue due to torsional activity	
	11/07/2006	Fatigue due to torsional activity	Analyse by in house software
	21/07/2006	Fatigue due to torsional activity	Awaiting report from supplier
	27/07/2006	Fatigue due to torsional activity	
	01/08/2006	Fatigue due to torsional activity	Awaiting report from supplier
	13/09/2006	Fatigue due to torsional activity	
	21/09/2006	Fatigue due to torsional activity	
	17/10/2006	Fatigue due to torsional activity	
	20/10/2006	Fatigue due to torsional activity	
Water Seal	30/08/2006	Wear/Poor materials used in seal (Hard carbon rather than SiC)	PCA to have SiC
	29/08/2006		PCA to have SiC
Impeller	11/11/05	Surface fatigue/manufacturing	Alternate tolerance designed
	21/03/2006	High torsional crank activity	Redesign to improve strength
	23/03/2006	Fatigue	Validating plastic impeller
	28/03/2006	Fatigue	Validating plastic impeller
	15/05/2006	Fatigue	Validating plastic impeller
Fixings - pump to engine	21/02/2006	Rusty	

Noted: Painted cells are design rework issues in the testing and refinement phase.

APPENDIX D
SCORING RESULTS FOR DESIGN REWORK DRIVERS FROM AUTOMOTIVE WATER PUMP CASE

Table D- 1: Drivers for reducing design rework probability of occurrence

Drivers	Exploitation of CAE Software	Coordination across team members	Lessons learnt	Supplier expertises	Clarity of Specifications	Open communication to inform design time issues	Weighted average scores
Exploitation of CAE Software	1	1			1		0.08
Coordination across team members	1	1	1/3				0.09
Lessons learnt		3	1	3			0.29
Supplier expertises			1/3	1	1/3		0.11
Clarity of Specifications				3	1	5	0.35
Open communication to inform design time issues	1				1/5	1	0.08
Level of consistency (*LOC*) (Target *LOC* = 88.90)							91.84%

Table D- 2: Sub-drivers within Exploitation of CAE Software

Sub-functions	Benchmark CAE results	Fundamental knowledge of product being design	Fundamental knowledge of mathematics behind CAE tools	Weighted average scores
Benchmark CAE results	1	1/7	1	0.12
Fundamental knowledge of product being design	7	1	5	0.75
Fundamental knowledge of mathematics behind CAE tools	1	1/5	1	0.13
CR				1.09%

Table D- 3: Product being compared under Benchmark CAE results

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	9	5	0.70
Benchmark 1	1/9	1	1/7	0.06
Benchmark 2	1/5	7	1	0.24
CR				18.67%

Table D- 4: Product being compared under Fundamental knowledge of product being design

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	8	3	0.64
Benchmark 1	1/8	1	1/7	0.06
Benchmark 2	1/3	7	1	0.30
CR				9.31%

Table D- 5: Product being compared under Fundamental knowledge of mathematics behind CAE tools

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	7	3	0.67
Benchmark 1	1/7	1	1/3	0.09
Benchmark 2	1/3	3	1	0.24
CR				0.61%

Table D- 6: Sub-drivers within Coordination across Team Members

Sub-functions	Sufficient number of qualified team members	Procedure to inform update to design team members	Procedure to make decision on conflict design issues	Weighted average scores
Sufficient number of qualified team members	1	1	1	0.33
Procedure to inform update to design team members	1	1	1	0.33
Procedure to make decision on conflict design issues	1	1	1	0.33
CR				0.00%

Table D- 7: Product being compared underSufficient number of qualified team members

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	7	3	0.62
Benchmark 1	1/7	1	1/7	0.07
Benchmark 2	1/3	7	1	0.31
CR				11.90%

Table D- 8: Product being compared under Procedure to inform update to design team members

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	3	1	0.43
Benchmark 1	1/3	1	1/3	0.14
Benchmark 2	1	3	1	0.43
CR				0.00%

Table D- 9: Product being compared under Procedure to make decision on conflict design issues

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	3	1	0.45
Benchmark 1	1/3	1	1	0.23
Benchmark 2	1	1	1	0.32
CR				11.74%

Table D- 10: Sub-drivers within Lessons Learnt

Sub-functions	Availability of lessons learnt	Discipline to implement lessons learnt for new design projects	Weighted average scores
Availability of lessons learnt	1	1/5	0.167
Discipline to implement lessons learnt for new design projects	5	1	0.833

Table D- 11: Product being compared under Availability of lessons learnt

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	9	3	0.65
Benchmark 1	1/9	1	1/7	0.06
Benchmark 2	1/3	7	1	0.29
CR				7.01%

Table D- 12: Product being compared under Discipline to implement lessons learnt for new design projects

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	5	1	0.48
Benchmark 1	1/5	1	1/3	0.11
Benchmark 2	1	3	1	0.41
CR				2.51%

Table D- 13: Sub-drivers within Supplier expertises

Sub-functions	Supplier's technical expertise	Supplier's internal management	Weighted average scores
Supplier's technical expertise	1	5	0.833
Supplier's internal management	1/5	1	0.167

Table D- 14: Product being compared under Supplier's technical expertise

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	9	3	0.63
Benchmark 1	1/9	1	1/9	0.05
Benchmark 2	1/3	9	1	0.32
CR				11.91%

Table D- 15: Product being compared under Supplier's internal management

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	7	1	0.47
Benchmark 1	1/7	1	1/7	0.07
Benchmark 2	1	7	1	0.47
CR				0.00%

Table D- 16: Product being compared under Clarity of Specifications

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	3	1	1
Benchmark 1	1/3	1	1/3	1/3
Benchmark 2	1	3	1	1
CR				0.00%

Table D- 17: Product being compared under Open Communication to Inform Design Time Issues

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	5	3	0.66
Benchmark 1	1/5	1	1	0.16
Benchmark 2	1/3	1	1	0.19
CR				2.52%

APPENDIX E
SCORING RESULTS FOR FUNCTION AND COMPONENT RELATIONSHIP STRENGTHS FROM AUTOMOTIVE WATER PUMP CASE

Table E- 1: Functions within Deliver-coolant function

Functions	Input coolant	Contain coolant	Increase velocity	Decrease velocity	Output coolant	Weigthed Average score
Input coolant	1	1/3	1/7	1	1	0.08
Contain coolant	3	1	1/7	1	1/2	0.11
Increase velocity	7	7	1	5	7	0.60
Decrease velocity	1	1	1/5	1	1	0.10
Output coolant	1	2	1/7	1	1	0.11
CR						7%

Table E- 2: Sub-functions within the Contain-coolant function

Sub-functions	Prevent-coolant	Store-coolant	Weighted average scores
Prevent-coolant	1	5	0.83
Store-coolant	1/5	1	0.17

Table E- 3: Components within Increase-velocity function

Sub-functions	Accelerate-coolant	Transfer-rotational	Support-rotational	Receive-rotational	Weighted average scores
Accelerate-coolant	1	3	1/3	3	0.28
Transfer-rotational	1/3	1	1/3	1	0.12
Support-rotational	3	3	1	3	0.47
Receive-rotational	1/3	1	1/3	1	0.12
CR					6%

Table E- 4: Components within Prevent-coolant function

Components	Functions	Water pump body	Water seal	Oil seal	Outer clip	Gasket	Back plate	Weighted average scores
Water pump body	1	1/5	3	1	1	1	3	0.14
Water seal	5	1	3	5	1	1	5	0.28
Oil seal	1/3	1/3	1	3	1	1	5	0.14
Outer clip	1	1/5	1/3	1	1/5	1/3	1	0.05
Gasket	1	1	1	5	1	1	3	0.17
Back plate	1	1	1	3	1	1	5	0.17
Bolt	1/3	1/5	1/5	1	1/3	1/5	1	0.04
CR								9%

Table E- 5: Components within the Store-coolant function

Components	Water pump body	Gasket	Back plate	Bolt	Weighted average scores
Water pump body	1	1	1	5	0.32
Gasket	1	1	1	5	0.32
Back plate	1	1	1	3	0.28
Bolt	1/5	1/5	1/3	1	0.07
CR					1%

Table E- 6: Components within the Accelerate-coolant function

Components	Impeller	Water pump body	Weighted average scores
Impeller	1	1	0.5
Water pump body	1	1	0.5

Table E- 7: Components within the Store-coolant function

Components	Water pump body	Ball bearing	Needle bearing	Inner clip	Weighted average scores
Water pump body	1	1	3	7	0.42
Ball bearing	1	1	1	5	0.30
Needle bearing	1/3	1	1	5	0.23
Inner clip	1/7	1/5	1/5	1	0.05
CR					4%

APPENDIX F

FAILURE TAXONOMY

(ADAPTED FROM COLLINS ET AL., 1976)

Primary identifiers	Failure modes
Buckling (High and/or point load geometric configuration)	Buckling
Corrosion (Material deterioration due to chemical or electrochemical interaction with environment)	Biological corrosion
	Cavitation erosion
	Corrosion fatigue
	Crevice corrosion
	Direct chemical attach
	Erosion corrosion
	Galvanic corrosion
	Hydrogen damage
	Inter granular corrosion
	Pitting corrosion
	Selective leaching
	Stress corrosion
Creep (Plastic deformation)	Creep
	Creep buckling
	Stress rupture
	Thermal/Stress relaxation
Ductile deformation (Ductile material)	Brinelling
	Force induced elastic deformation
	Yielding
Fatigue (Fluctuating loads or deformation)	High cycle fatigue
	Low cycle fatigue
	Surface fatigue
	Thermal fatigue
Fretting (Small amplitude fluctuating loads or deformations at joints not intended to move)	Fretting corrosion
	Fretting fatigue
	Fretting wear
Galling& Seizure (Sliding surfaces)	Galling
	Seizure
Impact (Impact load of large magnitude)	Impact deformation
	Impact fracture
	Impact fretting
Radiation (Nuclear radiation)	Radiation damage
Rupture (Separation into two or more parts)	Brittle fracture
	Ductile rupture
Spalling (Particle spontaneously dislodged from surface)	Spalling
Wear (Undesired change in dimension)	Abrasive wear
	Adhesive wear
	Corrosive wear
	Deformation wear/Impact wear
	Surface fatigue wear

APPENDIX G
OPTIMISED RESULTS FOR AUTOMOTIVE WATER PUMP

No.	Design rework effort (hours)	No.	Design rework effort (hours)	No.	Design rework effort (hours)	No.	Design rework effort (hours)	No.	Design rework effort (hours)
6	222.5054	72	222.5054	165	158.676	234	171.2471	285	187.2851
7	222.5054	73	222.5054	179	171.6735	235	169.2444	286	153.1218
8	222.5054	75	222.5054	181	169.0174	236	140.9455	287	149.2544
10	222.5054	76	222.5054	183	135.7498	237	181.9096	288	127.7913
11	222.5054	77	222.5054	185	176.7168	238	152.0088	289	169.1929
12	222.5054	79	181.9096	187	173.2148	239	149.2544	290	135.0296
14	222.5054	80	154.5895	188	188.6095	240	115.3669	291	118.6764
15	222.5054	81	140.3031	189	171.8904	241	140.1904	292	107.8688
16	222.5054	82	175.1219	190	187.2851	242	152.0088	294	144.7666
19	222.5054	83	172.9094	191	153.7982	243	149.2544	295	140.9607
20	222.5054	84	138.2567	192	169.1929	244	112.2818	296	101.4647
22	222.5054	101	196.4365	193	145.046	245	114.5577	297	170.248
24	222.5054	103	196.0373	195	162.5763	246	152.0088	298	153.2234
26	222.5054	105	193.682	196	170.248	247	149.2544	299	152.0088
27	222.5054	108	222.5054	197	160.5345	248	110.9031	301	168.2062
31	208.2484	109	222.5054	198	168.2062	249	175.1219	302	151.1816
33	200.5253	110	222.5054	199	131.4332	251	149.5501	303	149.2544
35	195.9016	116	222.5054	200	139.1048	252	114.0656	305	139.1048
37	202.5753	117	222.5054	201	124.0369	253	172.9094	306	122.0803
39	202.4291	118	222.5054	203	156.2074	254	149.5872	307	113.931
41	195.2393	120	222.5054	204	159.2554	256	113.9451	310	119.1339
44	222.5054	121	222.5054	205	153.7361	257	120.1148	311	115.328
45	222.5054	122	222.5054	206	156.7841	258	115.7824	313	159.2554
46	222.5054	124	222.5054	207	118.5121	259	114.921	314	152.4914
47	222.5054	125	222.5054	208	121.5601	266	171.8144	315	152.0088
48	222.5054	126	222.5054	209	173.9185	267	171.2471	317	156.7841
49	222.5054	128	160.5271	213	163.8446	268	119.0202	318	150.0201
55	222.5054	129	157.1193	214	173.5663	270	170.0442	319	149.2544
56	222.5054	130	133.4447	215	138.3347	271	169.2444	321	121.5601
57	222.5054	139	222.5054	216	148.0563	272	116.8264	322	114.7961
59	222.5054	142	222.5054	217	172.185	274	142.0035	323	111.5584
60	222.5054	143	222.5054	219	163.6668	275	141.1235	326	175.6891
61	222.5054	144	222.5054	220	173.2423	276	96.9039	327	175.1219
63	222.5054	149	222.5054	223	137.8493	278	184.1605	328	131.25
64	222.5054	156	222.5054	224	147.4248	279	181.9096	333	173.5663
65	222.5054	157	222.5054	225	130.2563	280	162.8077	334	151.9924
67	222.5054	158	222.5054	227	121.738	281	188.6095	335	149.5501
68	222.5054	159	222.5054	228	124.1237	282	154.4462	336	94.6719
69	222.5054	163	222.5054	229	120.8767	283	152.0088	337	148.0563
71	222.5054	164	222.5054	230	123.2624	284	129.9851	338	126.4824

Appendix G (Continued)

No.	Design rework effort (hours)	No.	Design rework effort (hours)	No.	Design rework effort (hours)	No.	Design rework effort (hours)	No.	Design rework effort (hours)
339	116.1555	408	169.1929	480	175.472	532	222.5054	594	121.8781
342	173.8095	410	170.248	481	166.5148	533	192.8536	595	119.3439
343	172.9094	411	168.2062	482	166.5148	534	222.5054	596	105.0954
344	129.3177	412	139.1048	484	190.8667	535	192.8536	597	222.5054
345	173.2423	414	159.2554	485	181.9096	536	222.5054	598	138.0743
346	151.9927	415	156.7841	486	181.9096	537	192.8536	599	121.9497
347	149.5872	416	121.5601	487	222.5054	538	222.5054	600	120.0701
348	96.2211	419	173.5663	488	166.0563	539	192.8536	601	152.0088
353	147.4248	420	148.0563	489	142.7077	540	222.5054	602	149.2544
354	126.1752	422	173.2423	490	131.4548	543	222.5054	603	119.8009
355	116.0036	424	147.4248	492	173.7279	545	222.5054	605	181.9096
358	124.691	426	124.1237	493	150.3794	547	222.5054	606	145.654
359	120.885	427	123.2624	494	139.1264	549	222.5054	607	129.488
361	124.1237	434	188.6095	495	222.5054	551	222.5054	608	175.1219
362	118.8295	435	187.2851	496	160.4194	553	222.5054	609	172.9094
363	116.2953	436	169.1929	497	132.1593	557	222.5054	610	127.1724
365	123.2624	438	170.248	498	109.5774	559	222.5054	612	181.9096
366	117.9681	439	168.2062	500	163.4674	561	222.5054	613	145.654
367	115.4339	440	139.1048	501	135.2073	563	222.5054	614	129.488
374	160.5271	442	159.2554	502	112.6254	565	222.5054	615	175.1219
375	157.1193	443	156.7841	503	222.5054	567	222.5054	616	172.9094
376	118.8388	444	121.5601	504	168.5556	570	174.6606	617	127.1724
377	148.2763	447	173.5663	505	165.4002	571	151.7584	619	222.5054
378	152.0088	448	148.0563	506	146.5471	572	147.1235	620	222.5054
379	149.2544	450	173.2423	508	178.2773	573	181.9096	621	145.965
380	121.6251	452	147.4248	509	175.1219	574	147.7462	622	222.5054
381	129.0133	454	124.1237	510	156.2688	575	138.0743	623	156.7034
382	152.0088	455	123.2624	511	222.5054	576	138.0743	624	138.0743
383	149.2544	457	222.5054	512	168.3774	577	145.654	625	127.7421
384	115.4005	459	166.5148	513	163.334	578	128.6295	626	222.5054
385	117.667	460	181.9096	514	145.2583	579	120.4803	627	156.7034
386	152.0088	461	137.9824	516	177.9529	580	112.3034	628	126.675
387	149.2544	462	145.654	517	172.9094	581	129.488	629	111.4215
388	112.1422	463	126.44	518	154.8338	582	122.724	630	222.5054
389	160.5271	464	129.488	519	222.5054	583	119.4863	631	156.7034
391	149.5501	465	165.4002	520	159.6119	584	101.9684	632	125.7894
392	118.0176	466	175.1219	521	130.6484	585	175.1219	633	103.9736
393	158.1055	467	163.334	522	111.0511	586	153.548	634	222.5054
394	149.5872	468	172.9094	524	161.9976	587	152.0088	635	156.7034
396	117.8377	469	124.7867	525	133.0341	588	122.278	636	152.0088
397	125.2705	470	127.1724	526	113.4368	589	172.9094	637	152.0088
398	116.7522	472	222.5054	527	222.5054	590	151.6599	638	222.5054
399	115.8908	473	222.5054	529	192.8536	591	149.2544	639	156.7034
406	188.6095	474	222.5054	530	222.5054	592	121.3541	640	149.2544
407	187.2851	479	222.5054	531	192.8536	593	127.1724	641	149.2544

Appendix G (Continued)

No.	Design rework effort (hours)	No.	Design rework effort (hours)	No.	Design rework effort (hours)	No.	Design rework effort (hours)	No.	Design rework effort (hours)
642	222.5054	708	222.5054	777	222.5054	830	110.5784	900	201.8478
643	156.7034	710	222.5054	781	222.5054	836	164.6544	906	222.5054
644	125.6626	711	222.5054	783	222.5054	837	160.5271	907	222.5054
645	111.6756	712	222.5054	785	222.5054	838	160.5271	908	201.8478
651	190.8667	713	222.5054	788	164.6544	840	163.7685	913	222.5054
652	181.9096	714	222.5054	789	136.9625	841	157.1193	915	222.5054
653	175.3098	715	222.5054	790	131.3582	842	157.1193	919	222.5054
655	173.7279	723	222.5054	791	160.5271	844	158.5416	920	156.7034
656	150.3794	725	156.9442	792	152.5761	845	127.9238	921	130.8851
657	135.1259	726	160.5271	793	152.0088	846	113.1379	922	130.8851
659	163.4674	727	153.9356	794	118.5638	852	164.6544	924	222.5054
660	135.2073	728	157.1193	795	157.1193	853	160.5271	925	222.5054
661	113.3916	729	120.8989	796	150.0542	854	160.5271	926	222.5054
663	178.2773	730	121.7273	797	149.2544	856	163.7685	928	222.5054
664	175.1219	732	222.5054	798	117.4868	857	157.1193	929	222.5054
665	175.1219	733	222.5054	799	121.7273	858	157.1193	930	222.5054
667	177.9529	734	222.5054	800	119.889	860	158.5416	931	222.5054
668	172.9094	739	222.5054	768	222.5054	861	127.9238	932	222.5054
669	172.9094	740	161.0715	769	192.8536	862	113.1379	935	222.5054
671	161.9976	741	156.9442	801	119.0091	864	222.5054	936	222.5054
672	133.0341	742	127.5081	802	104.1532	865	222.5054	937	222.5054
673	119.0471	744	164.6544	803	222.5054	866	222.5054	939	222.5054
679	190.8667	745	160.5271	804	152.0088	868	222.5054	940	222.5054
680	181.9096	746	131.091	805	149.2544	869	222.5054	941	222.5054
681	175.3098	747	222.5054	806	119.1678	870	222.5054		
683	173.7279	748	160.5848	808	160.5271	875	222.5054		
684	150.3794	749	153.9356	809	157.1193	876	192.8536		
685	135.1259	750	125.4345	810	121.7273	877	192.8536		
687	163.4674	752	163.7685	812	160.5271	878	192.8536		
688	135.2073	753	157.1193	813	157.1193	880	222.5054		
689	113.3916	754	128.6182	814	121.7273	881	222.5054		
691	178.2773	755	222.5054	816	222.5054	882	222.5054		
692	175.1219	756	157.7133	817	222.5054	883	192.8536		
693	175.1219	757	127.0954	818	141.4038	884	222.5054		
695	177.9529	758	106.2211	819	222.5054	885	222.5054		
696	172.9094	760	158.5416	820	156.7034	887	222.5054		
697	172.9094	761	127.9238	821	152.0088	889	222.5054		
699	161.9976	762	107.0494	822	152.0088	890	192.8536		
700	133.0341	763	222.5054	823	222.5054	891	192.8536		
701	119.0471	765	192.8536	824	156.7034	892	149.6819		
703	222.5054	766	222.5054	825	149.2544	894	222.5054		
704	222.5054	767	192.8536	826	149.2544	895	222.5054		
705	222.5054	770	222.5054	827	222.5054	896	158.676		
706	222.5054	773	222.5054	828	156.7034	898	222.5054		
707	222.5054	775	222.5054	829	125.3643	899	222.5054		

APPENDIX H

MATLAB PROGRAMMING FOR PriDDREB METHOD

```
clear all
clc
tic%start clock
counting=1;
%1. Effort allocation matrix
newzm_function={['Input-coolant'],['Prevent-coolant'],['Store-
coolant'],['Accelerate-coolant'],['Transfer-rotational'],...
                ['Support-rotational'],['Receive-
rotational'],['Decrease-velocity'],['Output-coolant']};
Function_amount=length(newzm_function);
component_all={['Gear'],['Impeller'],['Water    pump    body'],['Ball
bearing'],['Needle bearing'],['Shaft'],...
               ['Water   seal'],['Oil   seal'],['Outer   clip'],['Inner
clip'],['Gasket'],['Back plate'],['Bolt']}';
Component_amount=length(component_all);
Input_eff=xlsread('Allocation1_13_07_11','Allocation','BO22:BW34');
Effort=Input_eff;
Effort2=Input_eff;
for find_function=1:1:Function_amount
    for find_component=1:1:Component_amount
        if Effort2(find_component,find_function)>0
           Effort2(find_component,find_function)=1;
        end
    end

Component_for_each_function(find_function)=sum(Effort2(:,find_functio
n));
end
Effort2;
total_effort=sum(sum(Effort)');% Calculate total design effort
%5. Input relationship matrix
relationships=xlsread('Allocation1_13_07_11','Allocation','BO41:CA53'
)
[m4,n4]=size(relationships);
%2.  Implement  Pareto  statement  "80%  of  problems  come  from  20%  of
causes"
[m1,n1]=size(Effort);                      %m1=amount of components
```

```
[ms,ns]=size(find(Effort));                %ms=amount of vectors and
each vector has effort for a particular component
%2.1 Calculate 20% of components from total
Paret_o=ceil(0.2*m1);%Pareto is approximately closest integer
zm=zeros(m1,ms);%zm=single component's effort vector representation
cm  =  nchoosek(1:1:n1,Paret_o);%cm=Combination  of  functions  by
selecting  from total function n1
%2.2 Put function for cm
[m11,n11]=size(cm);
for cm_f=1:1:m11
    for cm_pos=1:1:n11
        cm_each{cm_f,cm_pos}=newzm_function(1,cm(cm_f,cm_pos));
    end
end
%3. Create combination matrix
i1=1;
i11=1;
m2=1;
for i11=1:1:n1
     [m2,n2]=size(find(Effort(:,i11)));
     [i2,j2,k2]=find(Effort(:,i11));
     if i1>1
        l=i1+m2-1;
     else l=i1;
     end
     i3=1;
     for j1=i1:1:l
         zm(i2(i3,1),j1)=k2(i3,1);
         i3=i3+1;
     end
newzm{i11}=zm(:,i1:l);                        %newzm=single component
matrix for each function
i1=i1+m2;
end
%4. Create input vector
[m3,n3]=size(cm);                              %m3=Amount of function
combinations from combination cm
i9=1;
for i6=1:1:m3
%4.1 Loop for total combination
    [v_1,u_1,w_1]=find(cm(i6,:));
```

```
    u1_1=length(u_1);
    q1_1=zeros(u1_1,1);
    tot_1=1;
    for i6_1=1:1:u1_1
        [q_1,r_1]=size(find(Effort(:,w_1(1,i6_1))));
        q1_1(i6_1,1)=q_1;
        tot_1=tot_1*q1_1(i6_1,1);
    end
    tot(i6)=tot_1;
    i10=i9;
    Each(i6)=tot(1,i6);
    [v_2,u_2,w_2]=find(cm(i6,:));%Focus at a particular function
    YY=length(w_2);%YY=number on commbination at cm(i_7,:)
    for i_77=1:1:YY%Find amount of component in each function
        [num_func,num_comp]=size(newzm{1,w_2(1,i_77)});
              %w_2(1,i_77)
        if i_77==1
           num_comp_1=zeros(1,num_comp);
        end
        num_comp_1(1,i_77)=num_comp;
    end
    XX=num_comp_1(1,i_77);
    num_each=ones(1,YY);
    begin=num_each(1,YY);
    while num_each(1,1)<=num_comp_1(1,1)
          for begin=1:1:XX% Looping last component first
              for fix=1:1:YY-1
                  com(:,i9)=newzm{1,w_2(1,fix)}(:,num_each(1,fix));
                  i9=i9+1;
              end
              com(:,i9)=newzm{1,w_2(1,YY)}(:,begin);
              i9=i9+1;
          end
          if begin==XX
             num_each(1,YY-1)=num_each(1,YY-1)+1;
          end
          for forward_incremental=YY-1:1:2
              if
num_each(1,forward_incremental)>num_comp_1(1,forward_incremental)
                   num_each(1,forward_incremental-
1)=num_each(1,forward_incremental-1)+1;
```

```
                num_each(1,forward_incremental)=1;
            end
        end
    end
% % %4.2 Grouping components for each function combination
  function_component_comb{i6}=com(:,i10:i9-1);
  function_component_comb{i6}(:,:);
end
%find size of zm
[component_zm,size_zm]=size(zm);
%Set postion of function for newzm
newzm_position=zeros(1,length(newzm_function));
for newzm_assign_function=1:1:length(newzm_function)
    [s1_newzm,s2_newzm]=size(newzm{:,newzm_assign_function});
    if newzm_assign_function>1

newzm_position(newzm_assign_function)=newzm_position(newzm_assign_fun
ction-1)+s2_newzm;
    else newzm_position(newzm_assign_function)=s2_newzm;
    end
end
total_comp=sum(sum(Each)');
%Calculate combinationa amount base on two rules
[FC1,FC2]=size(cm);%Developing size of each combination
Yahoo=0;
for FC3=1:1:FC1
    [Amount1,Amount2]=size(function_component_comb{:,FC3});
    A_special=Amount2/Paret_o;
    for Lo=1:1:A_special
        func{:,FC3}(:,1+(Lo-
1)*Paret_o:Lo*Paret_o)=function_component_comb{:,FC3}(:,1+(Lo-
1)*Paret_o:Lo*Paret_o);
        Yahoo=Yahoo+1;
        func_retrive{:,Yahoo}=func{:,FC3}(:,1+(Lo-
1)*Paret_o:Lo*Paret_o);
        [position_i,position_j]=find(sum(func_retrive{:,Yahoo}')');
        if sum(position_j')<Paret_o
           counting_combination(Yahoo)=0;
        else counting_combination(Yahoo)=1;
        end
        XY1(1,Yahoo)=FC3;
```

```
        %XY2(1,Yahoo)=Lo;
    end
    Amount(1,FC3)=Amount2;
end
combination_amount=sum(counting_combination);
%End calculate combination amount
%6. Calculate constant for design rework calculations
[S,Lamda] = eig(relationships);                 %Calculate eigenvalue and eigenvector for relationship matrix
U_const=S*(eye(m4)-Lamda)^-1*S^-1;                  %Calculate constant value for design rework effort
Effort_5_percent=0.05*total_effort;           %Calculate 5% of total effort
%7. Optimization by linear programming
%Goal : Find range of design rework for each components combination
%Objeactives
%%1.Find Max rework for each combination of components
%%2.Find Min rework for each combination of components
%Note :   Combination of component are calculated from Pareto's Principle
i13=1;
i15=1;
i17=1;
i18=1;
ii18=0;
ii19=0;
ii20=0;
iii13=1;
iiii13=1;
   for i11=1:1:m3%m3
%Loop for getting input
   [m5,n5]=size(function_component_comb{1,i11}(:,:));  %  n5=Size  of each combination for function combination i11
       for i12=1:Paret_o:n5  %n5 Loop  for  each  function  combination (This loop need to be generallise for the other size of matrix)
           for i16=1:1:Paret_o
             if i16==1
                Input_op=zeros(m1,1);
                up=zeros(Paret_o,1); %Upper bound constraint-Invalid
                lb=zeros(Paret_o,1); %Lower bound constraint-Invalid
                ii16=i12;
```

```
                Bound_less_Paret=zeros(m1,1);
             end

[Xi11,Xj11,X11]=find(function_component_comb{1,i11}(:,ii16));
             A_comp1=function_component_comb{1,i11}(:,ii16);
             A_comp_for_sequence{:,i13}(:,i16)=A_comp1;
%for finding Upper and Lower bound for inputs equal to paret_o
%The value is varied from 5% to 100% of the ideal design effort
             up(i16,1)=X11;
             lb(i16,1)=0.0000000001*X11;
%end
%for finding Upper and Lower bound for inputs less than Paret_o
             Bound_less_Paret=Bound_less_Paret+A_comp1;
             %end
             A_comp1(Xi11,Xj11)=1;
             Input_op=Input_op+A_comp1;
             ii16=ii16+1;
          end
          [Number1,Number2]=size(find(Input_op));%Number1    is    the
number of components being optimised
%Assign upper and lower bound if 0<Number1<Paret_o
%Start
          if  Number1==Paret_o  %Assign  Constraints%  The  constraints
are assigned for the amount of component equal to Pareto number only
             Aeq=ones(1,Paret_o);      %Constraint  equation  (Equality
constraint)-Invalid if Number1<Paret_o
          end
%end
%Every case constraint
%Start
          beq=[Effort_5_percent]; %Constant in constrain equation
          %end
          if Number1==Paret_o%Perform optimisation only the component
group equals to Pareto size
               exitflag=[];
               f_max_available=0;
               [locatei,locatej,Vij]=find(Input_op);
               for i14=1:1:Paret_o %Create input for optimization
Input_for_op(i14,1)=sum(Input_op(locatei(i14,1),1)*U_const(:,locatei(
i14,1)));
               end
```

```
%f_min_input=Input_for_op;
               f_max_input=(-1)*Input_for_op;
%Optimisation
%Finding Maximization
%if  sum(up)>=Effort_5_percent%  This  criteria  is  for  preventing
conflict  constraint.  If  the  summation  of  up  less  than
Effort_5_percent, the constraint is conflicted.
     [x_max,f_max,exitflag]=linprog(f_max_input,Aeq,beq,[],[],lb,up);
                  exit_criterion{:,i13}=exitflag;
                  f_max_available=1;
               if exitflag==[]
                  location_exit1(iii13)=i13;
                  iii13=iii13+1;
               end
               if f_max_available==1
                  f_max_results(1,i13)=abs(f_max);
                  if f_max_results(1,i13)<Effort_5_percent
                     f_max_results(1,i13)=0;
                  end
                  x_max_results{:,i13}=x_max;
               end
               i15=i15+1;
         end
    if i13<total_comp
    i13=i13+1;
    end
   end
 end
 i13;
 i15;
 i17;
 i18;
f_max_results_backup=f_max_results;
%Find index for every combination
for ind=1:1:m11
   [Amount_comp,size_comb]=size(function_component_comb{:,ind}(:,:));
    index_comb(:,ind)=size_comb/Paret_o;
    if ind>1
       index_func(:,ind)=index_func(:,ind-1)+index_comb(:,ind);
    else index_func(:,1)=index_comb(1,1);
    end
```

```
end
%8. Sequencing component
%8.1 Checking for amount of loops
[L1,L2]=size(zm);
Loops_sequence=L2/Paret_o; %calculate loop for sequencing design
if (length(zm)/Paret_o-round(length(zm)/Paret_o))~=0
   Loops_sequence2=floor(Loops_sequence);
end
%Algorithm 1 Find Range
%find min but more than 0
[f_mi,f_mj,f_mk]=find(f_max_results);
find_range=(max(f_max_results)-min(f_mk))/Loops_sequence2;
f_max_op=max(f_max_results);
%Algorithm 2 Find Level
f_max_results2=f_max_results;
zm2=zm;
zm_position=1;%For defining location of maximum frequency
count_more_than_one=0;
for level=1:1:Loops_sequence2
   levelx{:,level}=find(f_max_results2-(f_max_op-
level*find_range)>0);
   num_f_max=length(levelx{:,level});%Number of expected function in
each level
   num_f_max_history(level)=num_f_max;
%num_comp=num_f_max*Paret_o;%Number of expected component in each
level
%This loop is for creating matrix combine matrix for plotting
   for level_func=1:1:num_f_max %Checking for every member in the
level
       Pos_f=levelx{:,level}(:,level_func);%Show postion of
f_max_results
       combine1{:,level}(:,(Paret_o*(level_func-
1)+1):Paret_o*level_func)=func_retrive{:,Pos_f};%Combine the input of
f_max_results together,func_retrive is constant. Do not delete.
   end
   [cb1,cb2]=size(combine1{:,level}(:,:));%find size of every
possible component
   cb2_history(level)=cb2;
%This loop is checking for frequency
   frequenc1=zeros(1,size_zm);
   for frequenc=1:1:size_zm
```

```
        for ffind=1:1:cb2
            if zm2(:,frequenc)==combine1{:,level}(:,ffind);
               frequenc1(:,frequenc)=frequenc1(:,frequenc)+1;
            end
        end
    end
    frequenc1_overall{level,:}=frequenc1;
    f_max_results2(find(f_max_results2-(f_max_op-
level*find_range)>0))=0;
end
Show_combination{:,:}
iiii13;
[Row_position,Position_for_results,Optimisation_results]=find(f_max_r
esults>0);
toc
```

APPENDIX I

SCORING RESULTS FOR DESIGN REWORK DRIVERS FROM TURBOCHARGER CASE

Table I- 1: Drivers for reducing design rework probability of occurrence

Drivers	Exploitation of CAE Software	Coordination across team members	Lessons learnt	Supplier expertises	Clarity of Specifications	Open communication to inform design time issues	Weighted average scores
Exploitation of CAE Software	1	1				1/3	0.04
Coordination across team members	1	1	1/5				0.05
Lessons learnt		5	1	5			0.26
Supplier expertises			1/5	1	1/7		0.06
Clarity of Specifications				7	1	5	0.48
Open communication to inform design time issues	3				1/5	1	0.11
Level of consistency (*LOC*) (Target *LOC* = 88.90)							88.07%

Table I- 2: Sub-drivers within Exploitation of CAE Software

Sub-functions	Benchmark CAE results	Fundamental knowledge of product being design	Fundamental knowledge of mathematicsbehind CAE tools	Weighted average scores
Benchmark CAE results	1	1/7	1	0.12
Fundamental knowledge of product being design	7	1	5	0.75
Fundamental knowledge of mathematics behind CAE tools	1	1/5	1	0.13
CR				1.09%

Table I- 3: Product being compared under Benchmark CAE results

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	7	5	0.70
Benchmark 1	1/7	1	1/5	0.07
Benchmark 2	1/5	5	1	0.23
CR				16.29%

Table I- 4: Product being compared under Fundamental knowledge of product being design

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	8	6	0.73
Benchmark 1	1/8	1	1/5	0.07
Benchmark 2	1/6	5	1	0.21
CR				17.73%

Table I- 5: Product being compared under Fundamental knowledge of mathematics behind CAE tools

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	7	6	0.72
Benchmark 1	1/7	1	1/4	0.08
Benchmark 2	1/6	4	1	0.20
CR				15.30%

Table I- 6: Sub-drivers within Coordination across Team Members

Sub-functions	Sufficient number of qualified team members	Procedure to inform update to design team members	Procedure to make decision on conflict design issues	Weighted average scores
Sufficient number of qualified team members	1	1/5	1/7	0.08
Procedure to inform update to design team members	5	1	1	0.44
Procedure to make decision on conflict design issues	7	1	1	0.49
CR				1.09%

Table I- 7: Product being compared underSufficient number of qualified team members

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	7	5	0.71
Benchmark 1	1/7	1	1/4	0.08
Benchmark 2	1/5	4	1	0.21
CR				10.93%

Table I- 8: Product being compared under Procedure to inform update to design team members

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	8	6	0.73
Benchmark 1	1/8	1	1/5	0.07
Benchmark 2	1/6	5	1	0.20
CR				17.73%

Table I- 9: Product being compared under Procedure to make decision on conflict design issues

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	8	6	0.73
Benchmark 1	1/8	1	1/5	0.07
Benchmark 2	1/6	5	1	0.20
CR				17.73%

Table I- 10: Sub-drivers within Lessons Learnt

Sub-functions	Availability of lessons learnt	Discipline to implement lessons learnt for new design projects	Weighted average scores
Availability of lessons learnt	1	1/5	0.17
Discipline to implement lessons learnt for new design projects	5	1	0.83

Table I- 11: Product being compared under Availability of lessons learnt

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	8	6	0.73
Benchmark 1	1/8	1	1/5	0.07
Benchmark 2	1/6	5	1	0.20
CR				17.73%

Table I- 12: Product being compared under Discipline to implement lessons learnt for new design projects

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	7	6	0.72
Benchmark 1	1/7	1	1/4	0.08
Benchmark 2	1/6	4	1	0.20
CR				15.30%

Table I- 13: Sub-drivers within Supplier expertises

Sub-functions	Supplier's technical expertise	Supplier's internal management	Weighted average scores
Supplier's technical expertise	1	1	0.5
Supplier's internal management	1	1	0.5

Table I- 14: Product being compared under Supplier's technical expertise

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	8	5	0.71
Benchmark 1	1/8	1	1/5	0.07
Benchmark 2	1/5	5	1	0.22
CR				12.95%

Table I- 15: Product being compared under Supplier's internal management

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	7	5	0.70
Benchmark 1	1/7	1	1/5	0.07
Benchmark 2	1/5	5	1	0.23
CR				16.29%

Table I- 16: Product being compared under Clarity of Specifications

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	7	5	0.70
Benchmark 1	1/7	1	1/5	0.07
Benchmark 2	1/5	5	1	0.23
CR				16.29%

Table I- 17: Product being compared under Open Communication to Inform Design Time Issues

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	7	5	0.72
Benchmark 1	1/7	1	1/3	0.08
Benchmark 2	1/5	3	1	0.19
CR				5.67%

APPENDIX J
SCORING RESULTS FOR FUNCTION AND COMPONENT RELATIONSHIP STRENGTHS FROM TURBOCHARGER CASE

Table J- 1: Functions under the Provide-ride comfort function

Functions	Compress-working fluid	Drive-compressor	Support-rotational	Weighted average scores
Compress-working fluid	1	1	1	0.33
Drive-compressor	1	1	1	0.33
Support-rotational	1	1	1	0.33
CR				0.00%

Table J- 2: Sub-functions within Convert-energy function (from compressor side)

Sub-functions	Input-working fluid	Prevent-working fluid	Increase-velocity	Reduce-velocity	Maintain-pressure	Output-working fluid	Weighted average scores
Input-working fluid	1	1/4				1	0.044
Prevent-working fluid	4	1	½				0.157
Increase-velocity		2	1	1			0.279
Reduce-velocity			1	1	1		0.249
Maintain-pressure				1	1	4	0.222
Output-working fluid	1				1/4	1	0.049
Level of consistency (*LOC*) (Target *LOC* = 88.90)							89.09%

Table J- 3: Sub-functions within the Increase-velocity function

Sub-functions	Accelerate-working fluid	Receive-rotational	Weighted average scores
Accelerate-working fluid	1	1	0.5
Receive-rotational	1	1	0.5

Table J- 4: Sub-functions within the Maintain-pressure function

Sub-functions	Measure-pressure	Actuate-control system	Weighted average scores
Measure-pressure	1	1/5	0.167
Actuate-control system	5	1	0.833

Table J- 5: Components within Prevent-working fluid function

Components	Compressor housing	Compressor housing seal	Weighted average scores
Compressor housing	1	1	0.5
Compressor housing seal	1	1	0.5

Table J- 6: Components within the Accelerate-working fluid function

Components	Compressor wheel	Compressor housing seal	Weighted average scores
Compressor wheel	1	9	0.9
Compressor housing seal	1/9	1	0.1

Table J- 7: Components within the Actuate-control system function

Components	Actuator	Wastegate	Weighted average scores
Actuator	1	1	0.5
Wastegate	1	1	0.5

Table J- 8: Sub-functions within Drive-compressor function

Components	Input-working fluid	Prevent-working fluid	Distribute-working fluid	Reduce-enthalpy	Output-working fluid	Weighted average scores
Input-working fluid	1	½			1	0.080
Prevent-working fluid	2	1	3			0.173
Distribute-working fluid		1/3	1	1/9		0.063
Reduce-enthalpy			9	1	9	0.611
Output-working fluid	1			1/9	1	0.074
Level of consistency (*LOC*) (Target *LOC* = 86.40)						92.21%

Table J- 9: Sub-functions within Reduce-enthalpy function

Sub-functions	Drive-turbine	Control-rotational	Provide-rotational	Weighted average scores
Drive-turbine	1	2	8	0.58
Control-rotational	½	1	8	0.37
Provide-rotational	1/8	1/8	1	0.06
CR				4.65%

Table J- 10: Components within the Drive-turbine function

Components	Tubine housing	Turbine wheel	Weighted average scores
Tubine housing	1	1	0.5
Turbine wheel	1	1	0.5

Table J- 11: Components within the Prevent-working fluid function (from turbine side)

Components	Tubine housing	Turbine housing seal	Weighted average scores
Tubine housing	1	1	0.5
Turbine housing seal	1	1	0.5

Table J- 12: Components within the Control-rotational function (from turbine side)

Components	Tubine housing	Waste gate	Weighted average scores
Tubine housing	1	1	0.5
Waste gate	1	1	0.5

Table J- 13: Sub-function for Support-rotational function

Sub-functions	Provide-lubrication	Allow-rotational	Position-rotational	Weighted average scores
Provide-lubrication	1	¼	1/4	0.11
Allow-rotational	4	1	1	0.44
Position-rotational	4	1	1	0.44
CR				0.00%

Table J- 14: Sub-function for Provide-lubricant function

Sub-functions	Provide-lubricant	Transfer-heat	Weighted average scores
Provide-lubricant	1	5	0.833
Transfer-heat	1/5	1	0.167

Table J- 15: Components for Provide-lubricant function

Components	Bearing housing	Oil seal	Weighted average scores
Bearing housing	1	1	0.5
Oil seal	1	1	0.5

Table J- 16: Components for Allow-rotational function

Components	Turbocharger shaft	Bearing housing	Weighted average scores
Turbocharger shaft	1	1	0.5
Bearing housing	1	1	0.5

APPENDIX K
SCORING RESULTS FOR DESIGN REWORK DRIVERS FROM MACPHERSON STRUT SUSPENSION SYSTEM CASE

Table K- 1: Drivers for reducing design rework probability of occurrence

Drivers	Exploitation of CAE Software	Coordination across team members	Lessons learnt	Supplier expertises	Clarity of Specifications	Open communication to inform design time issues	Weighted average scores
Exploitation of CAE Software	1	7			7		0.443
Coordination across team members	1/7	1	1/4				0.058
Lessons learnt		4	1	1			0.212
Supplier expertises			1	1	7		0.193
Clarity of Specifications				1/7	1	1/3	0.025
Open communication to inform design time issues	1/7				3	1	0.069
Level of consistency (*LOC*) (Target *LOC* = 88.90)							91.41%

Table K- 2: Sub-drivers within Exploitation of CAE Software

Sub-functions	Benchmark CAE results	Fundamental knowledge of product being design	Fundamental knowledge of mathematics behind CAE tools	Weighted average scores
Benchmark CAE results	1	1	1	0.33
Fundamental knowledge of product being design	1	1	1	0.33
Fundamental knowledge of mathematics behind CAE tools	1	1	1	0.33
CR				0.00%

Table K- 3: Product being compared under Benchmark CAE results

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	7	5	0.70
Benchmark 1	1/7	1	1/5	0.07
Benchmark 2	1/5	5	1	0.23
CR				16.29%

Table K- 4: Product being compared under Fundamental knowledge of product being design

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	7	5	0.70
Benchmark 1	1/7	1	1/5	0.07
Benchmark 2	1/5	5	1	0.23
CR				*CR*

Table K- 5: Product being compared under Fundamental knowledge of mathematics behind CAE tools

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	1	1	0.33
Benchmark 1	1	1	1	0.33
Benchmark 2	1	1	1	0.33
CR				0.00%

Table K- 6: Sub-drivers within Coordination across Team Members

Sub-functions	Sufficient number of qualified team members	Procedure to inform update to design team members	Procedure to make decision on conflict design issues	Weighted average scores
Sufficient number of qualified team members	1	5	7	0.70
Procedure to inform update to design team members	1/5	1	5	0.23
Procedure to make decision on conflict design issues	1/7	1/5	1	0.07
CR				16.29%

Table K- 7: Product being compared underSufficient number of qualified team members

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	5	5	0.71
Benchmark 1	1/5	1	1	0.14
Benchmark 2	1/5	1	1	0.14
CR				0.00%

Table K- 8: Product being compared under Procedure to inform update to design team members

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	4	1	0.48
Benchmark 1	¼	1	1	0.20
Benchmark 2	1	1	1	0.31
CR				18.94%

Table K- 9: Product being compared under Procedure to make decision on conflict design issues

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	4	1	0.48
Benchmark 1	¼	1	1	0.20
Benchmark 2	1	1	1	0.31
CR				18.94%

Table K- 10: Sub-drivers within Lessons Learnt

Sub-functions	Availability of lessons learnt	Discipline to implement lessons learnt for new design projects	Weighted average scores
Availability of lessons learnt	1	1	0.5
Discipline to implement lessons learnt for new design projects	1	1	0.5

Table K- 11: Product being compared under Availability of lessons learnt

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	5	3	0.62
Benchmark 1	1/5	1	1/4	0.10
Benchmark 2	1/3	4	1	0.28
CR				7.47%

Table K- 12: Product being compared under Discipline to implement lessons learnt for new design projects

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	4	3	0.63
Benchmark 1	¼	1	1	0.17
Benchmark 2	1/3	1	1	0.19
CR				0.79%

Table K- 13: Sub-drivers within Supplier expertises

Sub-functions	Supplier's technical expertise	Supplier's internal management	Weighted average scores
Supplier's technical expertise	1	7	0.875
Supplier's internal management	1/7	1	0.125

Table K- 14: Product being compared under Supplier's technical expertise

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	1	8	0.47
Benchmark 1	1	1	8	0.47
Benchmark 2	1/8	1/8	1	0.06
CR				0.00%

Table K- 15: Product being compared under Supplier's internal management

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	1	8	0.47
Benchmark 1	1	1	8	0.47
Benchmark 2	1/8	1/8	1	0.06
CR				0.00%

Table K- 16: Product being compared under Clarity of Specifications

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	1/3	1/3	0.14
Benchmark 1	3	1	1	0.43
Benchmark 2	3	1	1	0.43
CR				0.00%

Table K- 17: Product being compared under Open Communication to Inform Design Time Issues

Products	New product	Benchmark 1	Benchmark 2	Weighted average scores
New product	1	5	5	0.71
Benchmark 1	1/5	1	1	0.14
Benchmark 2	1/5	1	1	0.14
CR				0.00%

APPENDIX L

SCORING RESULTS FOR FUNCTION AND COMPONENT RELATIONSHIP STRENGTHS FROM MACPHERSON STRUT SUSPENSION SYSTEM CASE

Table L- 1: Functions under the Provide-ride comfort function

Functions	Isolate-road imperfection	Maintain-tyre contact	Control-traction	Weighted average scores
Isolate-road imperfection	1	5	7	0.70
Maintain-tyre contact	1/5	1	5	0.23
Control-traction	1/7	1/5	1	0.07
CR				16.29%

Table L- 2: Sub-functions within the Isolate-road imperfection function

Sub-functions	Receive-road disturbance	Control-road disturbance	Weighted average scores
Receive-road disturbance	1	1/7	0.125
Control-road disturbance	7	1	0.875

Table L- 3: Sub-functions within the Receive-road disturbance function

Sub-functions	Allow-rotational	Support-vertical disturbance	Weighted average scores
Allow-rotational	1	1/5	0.167
Support-vertical disturbance	5	1	0.833

Table L- 4: Sub-functions within the Control-road disturbance function

Sub-functions	Limit-vertical movement	Absorb-road disturbance	Weighted average scores
Limit-vertical movement	1	1/7	0.125
Absorb-road disturbance	7	1	0.875

Table L- 5: Components within Allow-rotational function

Components	Front hub	Wheel bearings	Hub seals	Knuckle	Weighted average scores
Front hub	1	1/5		1/7	0.0736
Wheel bearings	5	1	9		0.4265
Hub seals		1/9	1	1/7	0.0549
Knuckle	7			1	0.4450
Level of consistency (*LOC*) (Target *LOC* = 81.90)					86.33%

Table L- 6: Components within Support- vertical disturbance function

Components	Frontt hub	Wheel bearings	Knuckle	Strut	Strut mount	Strut bearing	Coil spring	Lower spring insulator	Dust shield	Upper spring insulator	Lower ball joint	Weight average scores
Front hub	1	1/8									1/7	0.0487
Wheel bearings	8	1	3									0.4016
Knuckle		1/3	1	5								0.1381
Strut			1/5	1	9							0.0285
Strut mount				1/9	1	3						0.0033
Strut bearing					1/3	1	1/7					0.0011
Coil spring						7	1	9				0.0081
Lower spring insulator							1/9	1	1/4			0.0009
Dust shield								4	1	1/9		0.0038
Upper spring insulator									9	1	1/9	0.0356
Lower ball joint	7									9	1	0.3303
Level of consistency (LOC) (Target LOC >=93.80%)												96.95%

Table L- 7: Components within Limit- vertical movement function

Components	Strut	Coil spring	Strut bumper	Lower control arm	Weighted average scores
Strut	1	6		1	0.4722
Coil spring	1/6	1	3		0.0936
Strut bumper		1/3	1	1/9	0.0371
Lower control arm	1			1	0.3971
Level of consistency (*LOC*) (Target *LOC* = 81.90)					84.09%

Table L- 8: Sub-functions within the Dampen-vertical movement function

Sub-functions	Dissipate-energy	Prevent-environment	Weighted average scores
Dissipate-energy	1	9	0.9
Prevent-environment	1/9	1	0.1

Table L- 9: Components within the Prevent-environment function

Components	Strut	Lower spring insulator	Dust shield	Upper spring insulator	Weighted average scores
Strut	1	9		5	0.7317
Lower spring insulator	1/9	1	2		0.0749
Dust shield		1/2	1	1/5	0.0345
Upper spring insulator	1/5			1	0.1589
Level of consistency (*LOC*) (Target *LOC* = 81.90)					92.12%

Table L- 10: Sub-functions within the Maintain-tyre contact function

Sub-functions	Restrict-longitudinal load transderred	Restrict-rolling load transderred	Weighted average scores
Restrict-longitudinal load transderred	1	5	0.833
Restrict-rolling load transderred	1/5	1	0.167

Table L- 11: Sub-functions within the Restrict-vehicle height function

Sub-functions	Maintain-static riding height	Restrict-vehicle pitching	Weighted average scores
Maintain-static riding height	1	1/7	0.125
Restrict-vehicle pitching	7	1	0.875

Table L- 12: Components within the Maintain-sprung mass height function

Components	Strut	Coil spring	Weighted average scores
Strut	1	1	0.5
Coil spring	1	1	0.5

Table L- 13: Components within the Restrict-vehicle pitching function

Components	Strut	Coil spring	Stabiliser bar	Weighted average scores
Strut	1	2	2	0.50
Coil spring	½	1	1	0.25
Stabiliser bar	½	1	1	0.25
CR				0.00%

Table L- 14: Components within the Stabilise-vertical movement function

Components	Strut	Coil spring	Lower ball joint	Lower control arm	Stabiliser bar	Weighted average scores
Strut	1	1			1/4	0.042
Coil spring	1	1	1/2			0.049
Lower ball joint		2	1	1/5		0.113
Lower control arm			5	1	5	0.647
Stabiliser bar	4			1/5	1	0.149
Level of consistency (*LOC*) (Target *LOC* = 86.40)						87.06%

Table L- 15: Sub-functions within the Control-traction function

Sub-functions	Maintain-longitudinal direction	Provide-steering ability	Weighted average scores
Maintain-longitudinal direction	1	1/7	0.125
Provide-steering ability	7	1	0.875

Table L- 16: Sub-functions under the Maintain-logitudinal function

Sub-functions	Optimise-toe angle	Optimise-caster angle	Optimise-camber angle	Weighted average scores
Optimise-toe angle	1	6	1	0.462
Optimise-caster angle	1/6	1	1/6	0.077
Optimise-camber angle	1	6	1	0.461
CR				0.00%

Table L- 17: Components within Allow-steering control signal function

Components	Knuckle	Strut	Strut mount	Strut bearing	Lower ball joint	Lower control arm	Weighted average scores
Knuckle	1	7				1	0.331
Strut	1/7	1	7				0.053
Strut mount		1/7	1	1/5			0.009
Strut bearing			5	1	1/5		0.047
Lower ball joint				5	1	1	0.265
Lower control arm	1				1	1	0.296
Level of consistency (*LOC*) (Target *LOC* = 88.90)							89.39%

Table L- 18: Components within Optimise-toe angle function

Components	Front hub	Wheel bearings	Hub seals	Knuckle	Strut	Lower ball joint	Lower control arm	Weighted average scores
Front hub	1	1					4	0.3260
Wheel bearings	1	1	9					0.3015
Hub seals		1/9	1	1/5				0.0310
Knuckle			5	1	9			0.1433
Strut				1/9	1	1/7		0.0147
Lower ball joint					7	1	1	0.0953
Lower control arm	¼					1	1	0.0881
Level of consistency (*LOC*) (Target *LOC* = 90.40)								92.48%

Table L- 19: Components within Optimise-caster angle function

Components	Front hub	Knuckle	Strut	Strut mount	Lower ball joint	Lower control arm	Weighted average scores
Front hub	1	1/7				2	0.062
Knuckle	7	1	6				0.403
Strut		1/6	1	1/2			0.062
Strut mount			2	1	1/3		0.116
Lower ball joint				3	1	9	0.323
Lower control arm	1/2				1/9	1	0.033
Level of consistency (*LOC*) (Target *LOC* = 88.90)							93.90%

Table L- 20: Components within Optimise-cmber angle function

Components	Knuckle	Strut	Strut mount	Lower ball joint	Lower control arm	Weighted average scores
Knuckle	1	7			1	0.429
Strut	1/7	1	3			0.061
Strut mount		1/3	1	1/3		0.020
Lower ball joint			3	1	1/7	0.061
Lower control arm	1				1	0.429
Level of consistency (*LOC*) (Target *LOC* = 86.40)						100%

APPENDIX M

QUESTIONNAIRE FOR METHOD VALIDATIONS

Cranfield UNIVERSITY

Questionnaire for validation design rework estimation method

Introduction

This questionnaire is developed in order to validate design rework estimation methods. There are three sections. The section one is the validation for Design rework probability of occurrence estimation (DRePOE) method. The section two is for Design rework effort estimation (DREE) method and the last section is for Prioritization design by design rework effort based (PriDDREB) method

Instructions

1. Please × to express you opinion.
2. Score 5 means strongly agree while 1 means strongly disagree.

Section 1 Design rework probability of occurrence estimation (DRePOE) method.

Statements	Definitions				
	Strongly disagree	Disagre e	Neither agree nor disagre e	Agree	Strongl y agree
	1	2	3	4	5
DRe1. All assumptions are valid.					
DRe2. All drivers to reduce design rework probability of occurrence in design the testing and refinement phase and Novelty Level are valid.					
DRe3. The AHP technique is suitable to estimate design rework probability of occurrence.					
DRe4. The estimated result is useful if the design team in this case realise the probability of design rework occurrences in the early phase of product design.					
DRe5. The estimated design rework probability of occurrence result is reasonable.					
DRe6. The method to estimate design rework probability of occurrence is useful in the company's context.					
DRe7. The method is applicable in another company's product design projects.					

<u>Section 2</u> Design rework effort estimation (DREE) method.

Statements	Definitions				
	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
	1	2	3	4	5
DR1. All assumptions are valid.					
DR2. The method to formulate relationships between functions and components is valid					
DR3. It is valid to assign the strength of relationships by AHP.					
DR4. It is valid to develop relationships among components by matrix operation.					
DR5. The method to capture "indirect" relationship is valid.					
DR6. The method to allocate design effort by AHP is valid.					
DR7. The method to estimate design rework effort with consideration of knock-on effects is valid.					
DR8. It is useful if design team realise the design rework effort for each component in the early design phase.					
DR9. The estimated design rework effort result is reasonable.					
DR10. The method is useful in the company's context.					
DR11. The method is applicable in other company's design projects.					

<u>Section 3</u> Prioritisation design by design rework effort based (PriDDREB) method.

Statements	Definitions				
	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
	1	2	3	4	5
Pri1. All assumptions are valid.					
Pri2. It is valid to implement Pareto's principle to address critical components due to design rework effort					
Pri3. The method different from FMEA method.					
Pri4. The recommendations are useful if the design team realise them in the early design phase.					
Pri5. The prioritisation results from the method are valid.					
Pri6. The method is useful in the company's context.					
Pri7. The method is applicable in other company's design projects.					