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Investigating and Managing Design Margins throughout the Product Development Process

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Investigating and Managing Design Margins throughout the Product Development Process

Safaa Lebjioui

A thesis submitted for the degree of Doctor of Philosophy

2018

……To my parents

Declaration

Except where otherwise stated, this thesis is the result of my own research.

This thesis has not been submitted in whole or in part for consideration for any other degree qualification at this University or any other institution.

This thesis contains 52 figures, and less than 48 000 words.

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July 2018

Abstract

The automotive industry, like other sectors, faces a number of technological challenges in terms of meeting different legislations and developing products highly customised with a short lead time. They also have to manage the trade-offs between the price for the customer and the overall cost of the product development.

This thesis argues that design margins are a decisive factor with regard to many trade-offs that engineers may wish to make. These margins represent room for manoeuvre in the developing design. On the other hand, design margins allow engineers to accommodate new requirements without leading to costly engineering changes. If a change becomes necessary, the engineers might modify parameters where there are still margins with respect to the new requirements. Therefore engineers can avoid major redesigns to their existing components and systems. Ultimately this has the potential to enable control of the resulting development time and cost.

While margins are an intuitive concept, no clear and consistent definitions exist. The concept is relatively under-investigated area of design research. A comprehensive literature review and an empirical study at Volvo Global Truck Technology, emphasised the main issues and showed that there is a strong industrial need for support with margins, especially to understand how margins shape the design process. The concept of design margins, consisting of buffer and excess is developed. The key to managing product development is the transition from buffer to excess throughout the design process. This gives designers and engineers a rich way to express and communicate information about the forthcoming design to other team members, other teams and suppliers.

The thesis proposes a conceptual framework to investigate and capture design margins. The overall model indicates that a clear elicitation and an explicit documentation of design margins

can help decision makers implement more efficiently the necessary changes involved in product development: design margins are seen as a critical aspect of product design and development.

Acknowledgments

"If I have seen far, it is because I have stood on the shoulders of giants."
— Isaac Newton

The completion of this thesis could not be possible without the academic and moral support of many people.

First and foremost, I wish to express my sincere gratitude to my supervisors, Prof. Claudia Eckert and Prof. Chris Earl, for their continuous academic support throughout the course of my PhD. Thank you for your valuable insights and comments and always taking time to discuss ideas and for our countless interactions over the past four years. I would also like to thank my supervisor Prof. Ola Isaksson from GKN for his helpful comments and discussions on the topic of product development. Special thanks to Dr. Iestyn Jowers for listening to me, especially when I needed to complain about academic life. Thank you for your support and encouragement.

Many other people have assisted with contributions of an academic or technical nature; Stefan Edlund (senior manager, Volvo GTT), Dr. Catic Amer (Knowledge management leader, Volvo GTT), Dr. Peter Lindroth (Chassis and vehicle dynamics, Volvo GTT), Katarina Jemt (Cooling system Engineer, Volvo GTT) and Dr. Peter Gulberg (Cooling system Engineer, Volvo GTT). I also would like to thank them for their kindness during my visits to the company.

Thanks to my colleagues and friends in the Engineering and Innovation department, especially, Yadu, thank you for all our coffee breaks and endless talks. Avishek, Anas, George, Rahul and Paheli thank you for always being here for me when I needed your help. I would like also to thank, Khadija, Saad, and Pam, who helped me settle into the office when I started this journey. Many thanks to my friends in the OU, Rahul, Vasso, Ketty, Loua, Sophie.

Publications of this thesis research

Eckert, Claudia; Earl, Christopher; **Lebjioui, Safaa** and Isaksson, Ola (2013).Components margins through the product lifecycle. In: Product Lifecycle Management for Society, 5-7 July, 2013, Nantes, France

Safaa. Lebjioui; Earl, Christopher; Eckert, Claudia and Isaksson, Ola (2014). *Design margins in the product development process*. Presentation in DART Design society conference, 10 September 2014, Coventry University UK.

Safaa. Lebjioui; Earl, Christopher; Eckert, Claudia and Isaksson, Ola (2015). *Designing using margins*. In: Tools and Methods of Competitive Engineering, 9-13 May, 2016, Aix-en – Provence, France

Safaa. Lebjioui; Earl, Christopher; Eckert, Claudia and Isaksson, Ola (2015). *Understanding the relationship between design margins and trade-offs*. In: International DESIGN Conference, 16-19 May, 2016, Dubrovnik, Croatia

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List of Acronyms

CAC	Charge Air Cooling
CAF	Cooling Air Flow
CAM	Cambridge Advanced Modeller
CF	Coolant Flow
CFD	Computational Fluid Dynamics
CPM	Change Propagation Method
ChAF	Charge Air Flow
DESM	Design Engineering Structure Matrix
DPF	Diesel Particulate Filter
DSM	Design Structure Matrix
ExF	Exhaust Flow
FMEA	Failure Mode and Effect Analysis
FUP	Front Underrun Protection
GCW	Gross Combination Weight
GRAI	Graph with Results and Actions Inter-related
GTA	Global Truck Application
GTT	Global Truck Technology
IDEF	Integrated DEFinition Methods
OF	Oil Flow
PDP	Product Development Process
QFD	Quality Function Deployment
SCR	Selective Catalytic Reduction
WCS	Worst Case Scenario

1 Foundations for product development and design margins

This chapter introduces the research presented in this thesis. The chapter begins with the motivation and background after highlighting the importance of design margins in product development. An overview of Volvo Trucks and an introduction to the case study follows. The chapter ends with a discussion of the key objectives and research questions.

> *The future is uncertain ... and in an uncertain environment, having the flexibility to decide what to do after some of that uncertainty is resolved definitely has value."* – R. Merton (1997 Nobel laureate).

1.1   Problem definition

The requirements of product design present a major challenge for many companies. Products in the automotive sector, particularly in truck design, the case study of this research, have complex interrelations between a large number of different components. The dynamic of this complexity is increased by the variation in transport missions, which determines the type of vehicle, load capacity, weight and body. Typically, companies provide a wide variety of versions for different use profiles and customer preferences. Customers demand products that suit their specific, yet constantly changing, needs. One approach to meet this demand is mass customisation; offering many variants of a product at a very low cost. Another potential solution to this increased demand for high variation is flexible systems. This leads to a critical challenge in product development. A flexible product means that the product has considerable margins so that it can accommodate changes to meet a new set of requirements, while a cost effective one is one that is optimised to a set of requirements, i.e. one that is not overdesign. At the heart of this challenge is the question; what are margins on components and systems? This is the first research question, (RQ1).

This thesis reports on an empirical study in Volvo which analyses how different groups in the organisation add and remove margins throughout the Product Development Process (PDP). As these margins are referred to by different names, such as room for manoeuvre, safety margins

or design margins, they can be complicated to manage. Moreover, margins on a component or on a system are not universal, but relative to the specific product and its intended use. In a product like a truck with a range of options and variability in use, the margins can be difficult to determine. However, an awareness of the state of margins throughout the product development process can help the designers to accommodate changes and make decisions about their design solutions.

On the other hand, there is a strong financial incentive for Volvo to reuse components from existing products to save development costs and minimise the lead time. Using common components and systems means that some components have large design margins with regards to the properties of particular brands. In some case the properties are highlighted in the marketing of one brand, but not of another. For example, the Volvo brand is promoted as an eco-friendly brand and has components developed specifically to assure a low level of carbon emission. Some of these components are used in other brands, or only introduced in the next generation of products when the general expectations on carbon emission will have increased. Volvo has a strong brand identity of trying to meet customer requirements, which leads to a great option proliferation, which the company wants to control.

One of the interviewee interviewed while carrying out this research said: "*Volvo philosophy is the other way round and it creates a lot of complexity and sometimes too much so we have maybe to go look into how to limit, how to make product planning reducing the offer when they add, when they want to add new things, how to get rid of old stuff and the variants that are not sold in the high number*" (SS)

Designers need to make trade-offs between many design parameters, which can be difficult to model and capture in complex engineering systems. Margins on different elements like requirements, geometry and material properties allow them to make these trade-offs. However

there is a range of key parameters that determine the performance of the overall product, such as emissions and noise. Accordingly, it would be enormously beneficial for companies to know the design margins on key components, and understand how these margins evolve over time, in order to improve the development process of complex products.

1.2   The challenge

In incremental products, planning is about the changes that are required to meet new design requirements. Product planning is often very closely linked with the design of a product platform and the flexibility that is designed directly into the platform. Flexibility has also been addressed from the view point of individual designs to make sure that a new product will be flexible. This research focuses on margins and addresses how they changes can be carried out knowing the state of margins.

Most companies cannot plan their products in isolation, but have to consider implications across an entire product platform. As Otto and Simpson, (2014) argues; optimising a platform is the key to profit and viability of an entire product offering. Understanding margins lies at the core of product planning.

Volvo GTT (Group Truck Technology) is a global company which develops trucks, construction equipment and engines that are used in different markets with different characteristics regarding operating environments, legislations and transport missions. A number of different transport missions is illustrated in Figure 1-1.
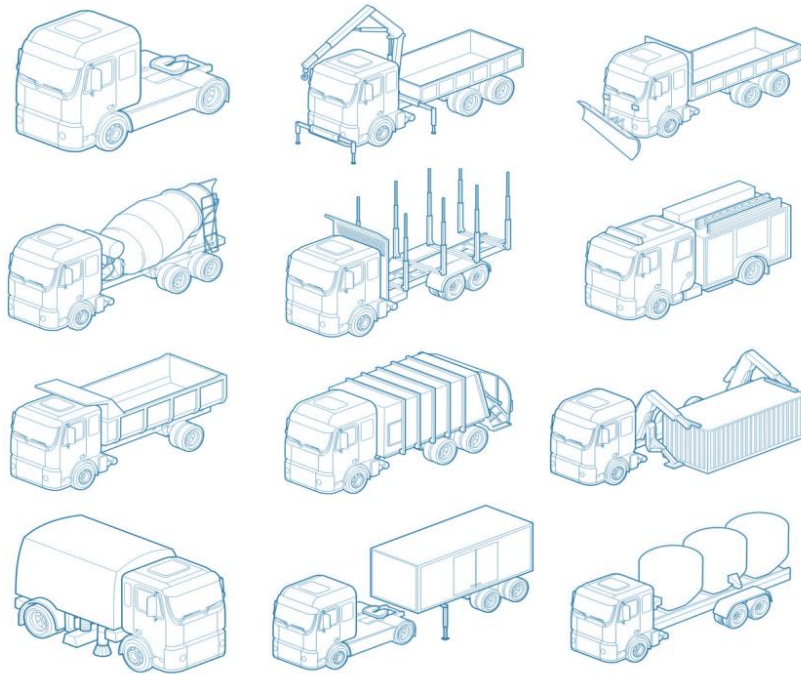
Figure 1-1 A number of different transport missions

This requires the company to deal with a large degree of variance and a huge number of configurations. For example, European trucks with overall length restrictions have the driver's cabin above the engine whereas US trucks with restrictions only on the lengths of the trailer have the cabin is behind the engine.

Volvo Group is one of the largest truck brands in the world, which develops vehicles that are sold and serviced in more than 140 countries. Over the last 20 years Volvo trucks have acquired several other brands to reach new markets. Mack trucks offer highly specialist trucks for the US market many for off-highway applications, while Renault Trucks designs and produces trucks for the European market. They have also acquired a Chinese and an Indian brand, which are not yet integrated in the product platform. The trucks of the three main brands are aimed at different market segments.

European trucks have overall length restrictions whereas US trucks have only restrictions on the lengths of the trailer which has led to very long cabs with a different configuration. In the

European trucks the driver cabin is above the engine and the cooling system, whereas in the US trucks, the cabin is behind the engine which give a generous accommodation for the driver.

In response to the high level of customisation, Volvo GTT has developed a platform called Global Transport Application (GTA) to have a common design language across different business units within the Group. GTA defines a number of parameters that support the selection of 'the right vehicle for the mission' according to the market segment, operating environment and legislations.

In this subsection, a description of Volvo products structure and the primary parameters defined in the GTA is given. In order to get the optimum vehicle specification, the GTA classifies the design parameters as follows:

Transport mission: the customer transport mission is the starting point that determines the vehicle type, size, capacity, gross vehicle / combination weight (GCW) and the body the product should have. Without exception, the customer wants to have an optimal load capacity, whether with regards to the maximum load for the platform length, or maximum load volume for maximum load weight in tonnes. Accordingly, Volvo truck design is predominantly about maximising the payload capacity and thus the income generated by the vehicle. However, in practice, for most transport operations, the authorities determine the maximum gross vehicle or combination weight permitted on the public roads. Therefore, the company has to specify these two parameters for which the vehicle is technically approved.

Vehicle utilisation: the vehicle's use is largely related to the driver, i.e. the conditions for being able to work efficiently. The vehicle utilisation is determined by speed changes, manoeuvring and the yearly usage. For each of these parameters GTA classifies a number of levels and ranges. Also, the operating cycle reflects how often the vehicle stops to load or unload goods or passengers.

Operating environment: determined by the type of road which has a major impact on all vehicle systems and affects the truck's operating reliability. The quality and condition of the road also affects the fuel economy since a poor road surface causes greater rolling resistance. GTA specifies four levels of road conditions: smooth, rough, very rough, and cross country. The landscape topography and the gross combination weight GCW are the two main factors determining the powertrain's specification. GTA classifies four levels for topography; flat, predominantly flat, hilly and very hilly. Then it classifies by climate and altitude. At very high altitude for example, the engine is subject to a higher stress. In a very hot country, the cooling requirements are different. Therefore, for a given climate zone, key parameters need to be considered so that the truck can still achieves a optimum performance.

The product offering in the company can be summarised as shown in Figure 1-2. Vehicle design based on GTA parameters means that the choice of materials, dimensioning, and performance needs to be tailored to each transport operation's driving and load conditions. However, the company wants to optimise the use of components and systems, therefore they increase the commonality of their platforms. For example, consider a component in a truck developed for rough road conditions and a load of 44 tons GCW (Gross Combination Weight). However, this component may also be used in trucks with a GCW of up to 60 tons if the road is classified as smooth.

Customer/Vehicle Parameters
Customer Interface

Customer Interface

Product offer

Models proposed by the sales system that fulfill the defined parameter configuration

Area
- Operation
- Registration
- Legislation

Transport mission
- Vehicle type
- Type of body
- Type of load handling equipment
- GVW/ GCW

Vehicle utilisation
- Operating cycle
- Speed changes
- Manoeuvring
- Yearly usage
- Quality of diesel fuel

Operating environment
- Road condition
- Road type
- Topography
- Altitude
- Ambient temperature
- Curve density
- Dirt concentration
- Dust concentration
- Bug concentration
- Rolling resistance
- Coefficient of traction
- Load bearing capacity of the ground

Vehicle type specific features
- No. of drivers
- Driver environment
- Chassis equipment
- Info systems
- Exterior trim
- Number of doors
- Number of seats
- Bucket size
- Tires
- Load receiver for wheel loader
- Density of material

Additional options, such as financing, service contracts, leasing, operating training (Eco Operator).

Figure 1-2 The product offer in the company (company document)

From the above cited parameters, it appears that every operational segment and type of cargo imposes its own set of requirements regarding the truck's specification. The goal for the company is naturally to satisfy each customer's needs. On the other hand, they also want to optimise their products and increase the profitability. Therefore, the company has developed a large specification database (variants) characterised by a broad scope for offering different cab sizes, chassis heights, wheel bases, powertrains and so on.

1.3   Overview and motivation

This thesis reports on research carried out at The Open University in collaboration with Volvo GTT and GKN aerospace in Sweden. The research investigates the concept of design margins and proposes a method which explores a way of managing design margins throughout the product development process.

The original motivation for the project came from engineering change and the need to predict the impact of changes on different components. A change to a component, can have a repercussion on other components. Whether a change propagates depends on whether the components can absorb the change or not. If they can absorb the change, they have had a certain margin in them, where the original component exceeded its initial requirements, and allowed them to accommodate an increase in the requirements. An understanding of the state of the components, their parameters and margins would allow engineers to predict the risk of a potential change more precisely and enable product planners to understand when components need to be changed or upgraded. **Margins have a significant impact on how easy or difficult it is to incorporate changes in existing products and systems** or **future generations.**

Exploratory research revealed the industrial receptiveness to evaluate new approaches and methods to tackle these challenges, since it would provide additional decision making support. Thus, this research reports the need that Volvo engineers expressed in estimating the effects of

change in key projects and for support in product planning particularly at the early stages of the product development process. Therefore, it was decided together with the project steering committee, to study first how margins are handled in the organisation with the aim of identifying the company terminology, as well as identifying margins that would not typically be conceptualised as such. The starting point for the study was chassis development as many of the margin issues around chassis are geometrical and therefore fairly intuitive. Once this was done, the second phase of the research looked at how changes into a specific system are carried out. The cooling system is selected as a case study for our research because the company needs support with its development and because it is one of the systems that are subject to various constraints from different features and therefore a number of trade-offs were present. The cooling system (Figure 4-5 in Chapter 4) has tight geometrical constraints. It has the cab flooring on the top, on the sides the chassis frame, the grille in the front, at the bottom the Front Underrun Protection (FUP) and the engine in the back. Therefore, the objective is to establish how margins play a role in carrying out changes and how they shape the design process.

This thesis argues that understanding margins on key parameters, components and systems would give engineers valuable insights in predicting and managing uncertainty and support in planning for change during complex product development.

1.4 Research Questions

This research aims to understand margins and the way they can be managed throughout the product development process. The work in this thesis is based upon two main hypotheses:

> *Knowing and managing design margins will help companies to assess uncertainty and handle engineering change more efficiently.*

This hypothesis was initiated by the published design literature, some of which is highlighted in Chapter 2.

The second hypothesis arose from discussions with academics, designers, engineers and managers in the company:

> *There is a lack of support approaches or methods to assist engineers to communicate design margins explicitly throughout the product development process.*

Research questions that arise from these hypotheses and which will be addressed in this thesis are:

RQ 1: How can design margins be defined ?

Obtaining such understanding first requires identifying:

What is the different terminology used to describe design margins?

What terminology is used at different stages of the Product Development Process (PDP) ?

Answering these questions is achieved by carrying out the following activities. First, the literature review (Chapter 2) was followed by a first case study, conducted in Volvo GTT Sweden to understand who is adding margins, at which point in the process and how they refer to them (Chapter 5).

RQ 2: How are design margins handled in the PDP ?

The initial issue to be addressed in answering this question was:

How are design margins managed in current practice?

How do design margins evolve over the PDP ?

Workshops and visits to the company were organised to discuss the findings and different modelling approaches (Chapter 5).

RQ 3: How can design margins be modelled to manage engineering change?

To answer this question, it is necessary to understand:

What is the relationship between the different types of margins ?

What approach will be most beneficial from the company's perspective?

A Design Structure Matrix (DSM) method is used to capture the relationships among components and dependencies between components. Further, the Change Prediction Method (CPM) is used to analyse the change propagation among components (Chapter 6). The understanding of these relations provides useful insights for a better way to model margins.

The relationship between the research questions and the various sections of the thesis is summarised in Table 1-1.

Research Questions	Sections Discussed	Sections Answered
Margins definition	Chap 2 & 5	§2.7, §5.3-5.4, §8.1
Margins handling in the PDP	Chap 2, 4 & 5	§4.1.3, §5.1- 5.2 – 5.6- 5.7,
Margins modelling and management	Chap 5 & 6	§5.7.2, §5.8, §6.5- 6.6, §7.2-7.3, §8.1

Table 1-1 Relationship between Research Questions and Thesis sections

The work described in this thesis aimed at improving the understanding of design margins and proposes a method to investigate the concept. The aim of this research was to bring new knowledge to the area of engineering design that would be of benefit to industry and academia. The initial research questions (RQ1, RQ2, RQ3) were the starting point for the investigations in this research and informed the analysis of data from a case study undertaken in Volvo GTT as

part of the research. Hence, a measure for success for this research was that any method or model developed must be of benefit to the company.

1.5 Thesis structure

The thesis argues that a key point in building new designs lies in understanding the margins that components have with regards to different set of requirements. It describes an example of a truck cooling system including (e.g. pump, heat exchanger, and fan) to demonstrate the importance of modelling the connection and the dependency between components (Chapter 4). It also looks at the cooling system throughout its life cycle, in order to determine how margins at different stages of the process affect the changes that could be made (Chapter 5). This leads to a discussion of the concept of components' and systems' margins and how companies can benefit from understanding and capturing the components' margins in designing new systems (Chapter 7). An overview of the chapters in the thesis is shown in Figure 1-3.
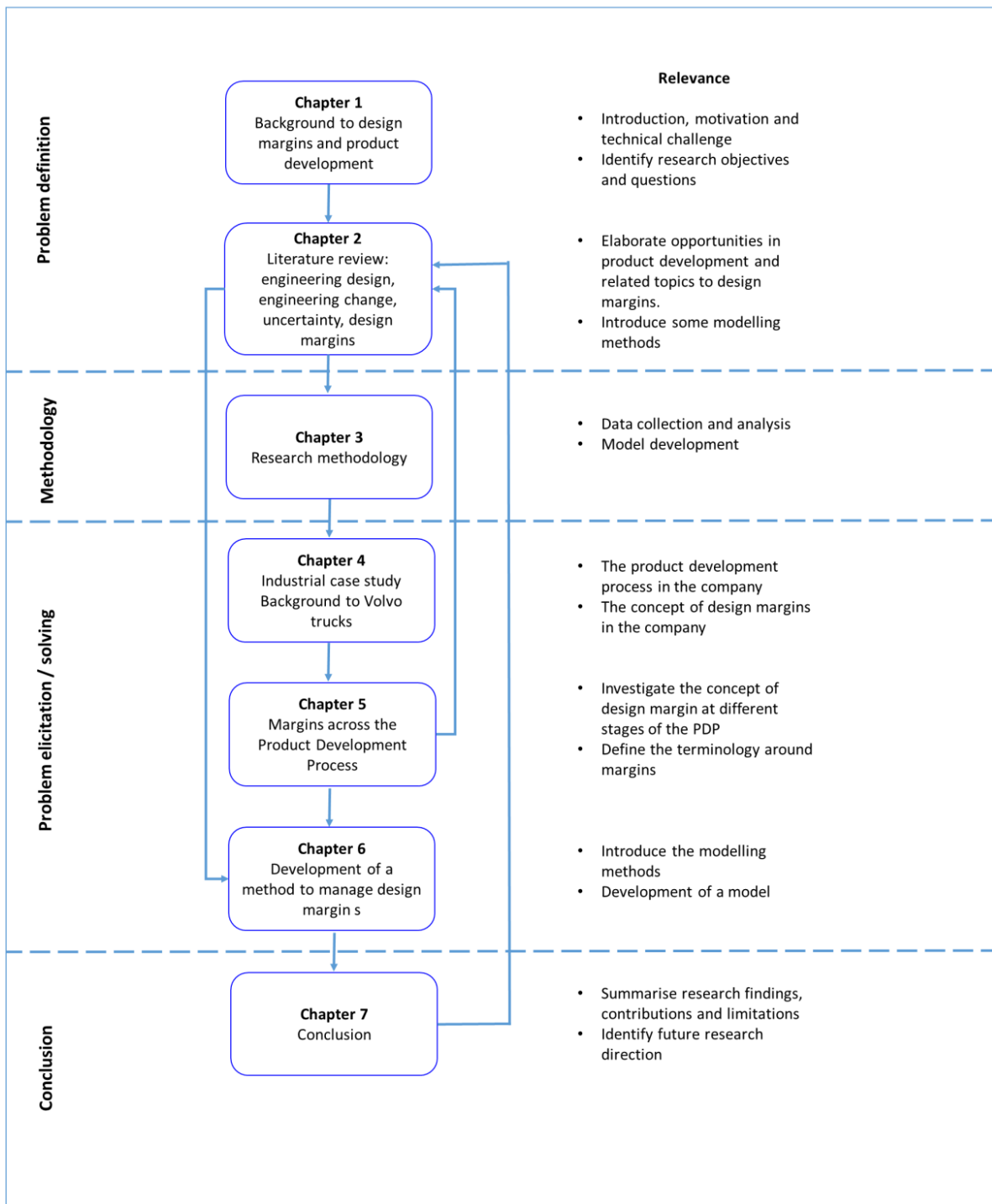
Figure 1-3 Overview of the thesis chapters

Having introduced the motivation of the work and the research questions in this chapter, the next chapter provides a literature review that was undertaken to examine the concept of design

margins in the product development process and related topics. The research methodology applied is described in Chapter 3. In Chapter 4, a background to the industrial case study is presented. In Chapter 5, a detailed description of the findings from the empirical study carried out at Volvo GTT Sweden is provided. A process method for modelling margins is proposed in Chapter 6. Finally, Chapter 7 summarises the research contributions, discusses strengths and limitations of the proposed method, and provides recommendations for future research direction.

1.6 Summary

This thesis argues through a literature review (chapter 2) and empirical study that:

- Academically, the concept of design margins is an under-researched design area. There is a need to carefully ground the topic and bring together different related topics from different research areas.

- There is an industrial need for support in the way that margins are managed.

- Margins are present during most phases of the product development process and have a significant impact on the working of many engineers, however they are surprisingly unaware of margins and do little to communicate them explicitly. Thus, there is a knowledge gap among engineers and designers. Moreover, the increase in complexity, subsystems, and organizations involved in developing a product increases this knowledge gap. Hence, there is a need to reduce this gap, by applying improved analysis methods; detailed documentation; and accurate information exchange.

A method to investigate and manage design margins is proposed. It is developed and discussed through an industrial case study.

2 Literature Review

The work presented in this thesis is concerned in modelling margins and managing design processes through margins. Therefore, this chapter starts with setting the context of product development which is subject to many sources of uncertainty that need to be resolved through the interrelation of different kind of design activities. One of the sources of uncertainty reviewed in this chapter is engineering change. Next, key concepts related to margins are discussed since margins play an important role in how engineering change affects a product and thereby the process of developing the product. The chapter ends with a discussion of tools and methods that can be used to support the design process .

The design process can be viewed as a system of "interrelated activities" (Wynn *et al.* 2011) which are performed with the purpose of reducing the uncertainties surrounding the design solution or, in other words, as a system of design activities organised with the goal of gaining knowledge and confidence that the solution will function and perform according to the specified requirement.

Wynn *et al.* (2007) describes that design is different from repeatable processes which can be defined *a priori*, since uncertainty and complexity forces engineers to explore opportunities, master continuous changes, perform complicated trade-offs and solve design problems which always exhibit (to some extent) a degree of novelty.

Another challenging aspect of carrying out design activity is how to accommodate evolving requirements. One can see requirements as *uncertain* information which evolves during the design and development process together with the environment in which they operate. Fernandes *et al.* (2013) argues that the classical paradigm of designing for "fixed" requirements has been abandoned in industrial practice. Changes in high-level requirements, changes arising during sub-system integration and late requirements change, were considered to be the most "damaging" by the companies.

One concept that can help in addressing these challenges is the concept of margins. In the available literature margins have been named differently depending on each sector but it was seen as a general concept that designers could use to account for imprecision and uncertainty, thus allowing design to absorb some changes without the need for major changes or redesign.

However, in most design research, margins have been considered primarily as means to cope with uncertainty, not as inputs that define opportunities.

The following review starts with approaches related to product development, and gives an overview of the published literature in engineering design which forms the background and

context for examining margins and their role. The second part of the review highlights the concepts related to design margins and gives a definition (section 2.7).

2.1 Engineering Design and Product Development

Product development is challenging for companies developing complex products, such as aircrafts, cars, trucks and big civil infrastructures. These types of products are composed of many multidisciplinary systems. Such systems are constructs of interrelated parts forming a complex whole (Blanchard and Fabrycky 2006), functioning together to achieve goals which cannot be attained by the elements alone (Clayton and Backhouse 2012).

The development process in systems engineering is commonly viewed in the literature as a decomposition process followed by an integration process (Pugh (1990), Krishnan and Ulrich (2001), Pahl and Beitz (2013)). During the decomposition process, the customers' requirements are analysed and defined in engineering terms and then partitioned into a set of specifications for several systems or components. The design process defines what the system have to do, how well the system must do it, and how the system should be tested to verify the and validate the system's performance.

The engineering design process illustrated in Figure 2-1, consists of a number of steps to find an optimal solution to a specific problem. Throughout this process there is considerable feedback and several iterations. First there is a definition of the need and the specification of the requirements for the system. This is followed by an investigation of possible solutions to the stated problem, leading to a conceptual design. The conceptual design is then analysed and refined, until it becomes a detailed design including the adopted solution and the system characteristics. The detailed design is then implemented through the process of developing, testing and product launch.
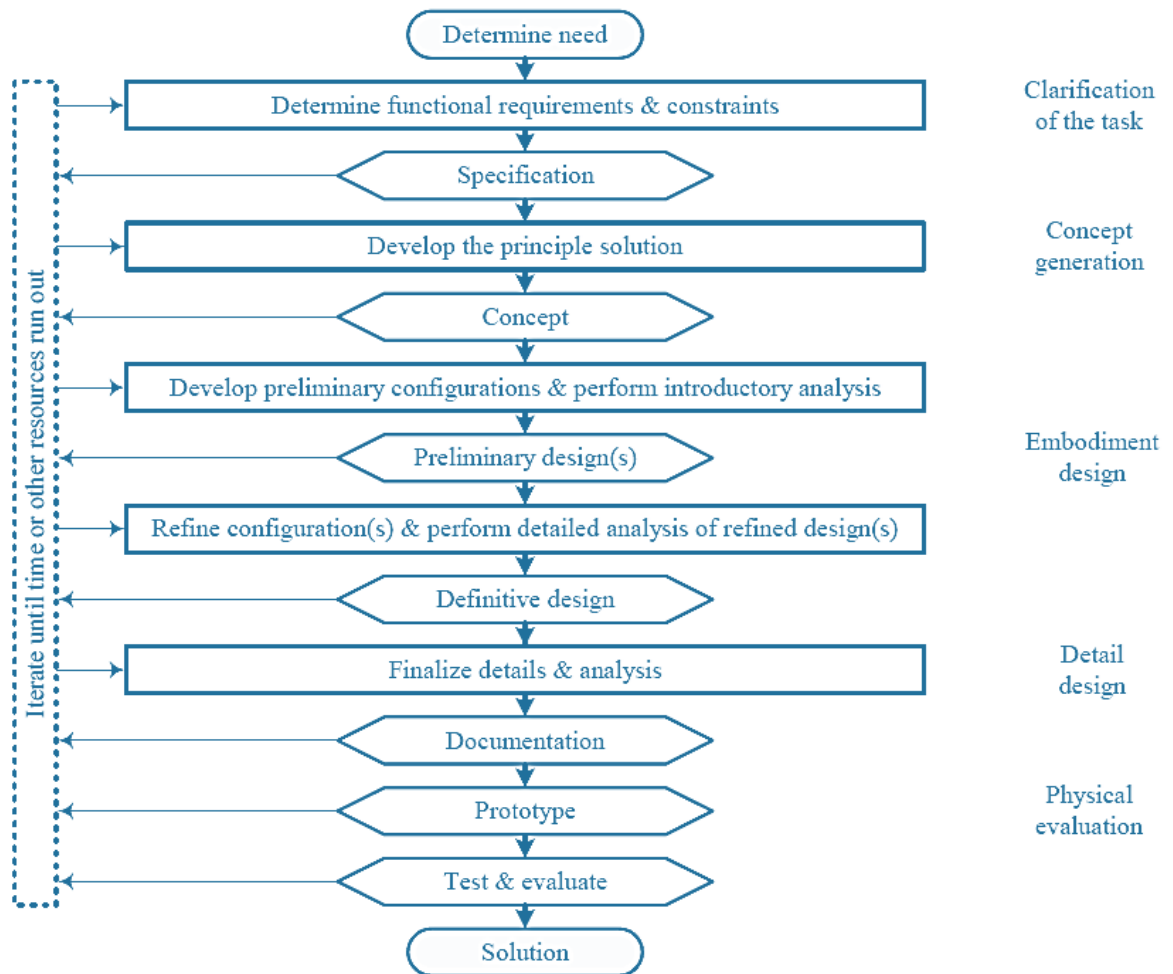
Figure 2-1 The design process adapted from Pahl and Beitz (2013)

The classical model of product development follows a sequential staging of design and development tasks. However, designing a product can be used in its narrow sense to refer to the design phase. As shown in Figure 2-2, the design activity starts by developing the product concept based on existing technical knowledge and the customer needs. As the process unfolds, the company develops new knowledge about how components correlate and interact in the product before getting to the detailed design. This knowledge gained throughout each stage enables design decisions which allow the next stage of development tasks to proceed.

Figure 2-2 Product development process adapted from Ulrich and Eppinger (2000)

However, some other research makes evident the likelihood of losses and delays in information flow, when product development processes are organised in a sequential way. Thus, another possible representation of the product development process described in the literature is shown in Figure 2-3 (adapted from Buede and Miller, 2016) beginning with the identification of need for the system and progressing through the retirement of the system. Some of the phases of the process are accomplished in parallel, as shown in the diagram; which phases occur in parallel depends upon the type of system, the organisation, and the context.

The product development phases associated with the engineering design are shaded in Figure 2.3. Design includes the preliminary system design as well as parts of the identification of need and concept definition.
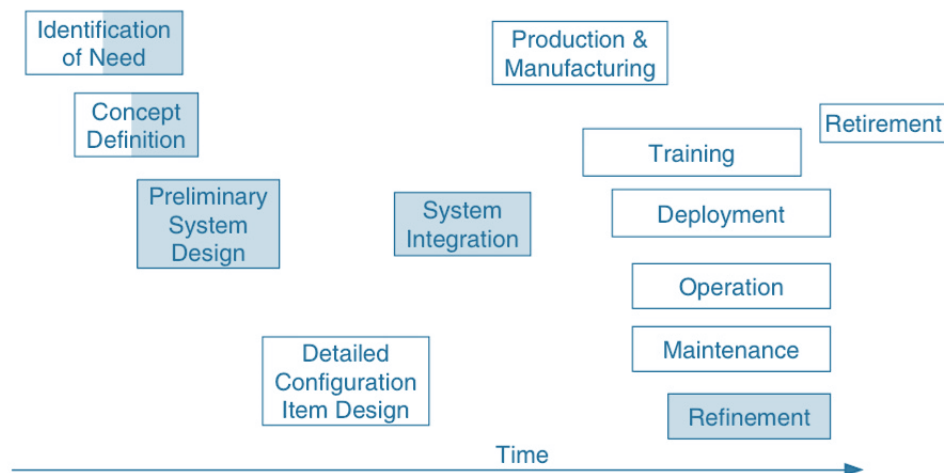
Figure 2-3 Product development process adapted from Buede and Miller (2016)

On the other hand, traditional approaches in product design and manufacture consider only limited information on the manufacturing issues. The concept of concurrent engineering (CE) is then introduced and many researchers such as Yassine and Wissmann (2007), Eastman (2012), Hartley (2017) argue that CE is a way to reduce the lead time between the start of a design and the manufacture of a product by ensuring that manufacturing issues are considered from the beginning of product design. However, this type of approach might not be applicable for all the engineering systems due to the complexity and the uncertainty associated with the product development.

Another approach to the classical development model is the gate review process which has been adopted by most companies in the automotive sector. This development process controls and coordinates design efforts and provides baselines guiding the development, production and operation of the system. The system's life-cycle is normally split into several stages, as shown in Figure 2-4.

Figure 2-4 Product development process and decision gate at each stage. Adapted from Blanchard and Fabrycky (2006) and Volvo GDP.

The conceptual design stage is the first phase in complex system development and follows the approval of a new development initiative inside the organisation. It typically includes the identification of stakeholder needs, requirements capture, concept exploration and design and the overall programme planning. The preliminary design stage occurs subsequently, to refine the system's conceptual solution and typically includes the preliminary definition of the key sub-systems and components. Detailed design and development follow with the full definition of sub-systems and components together with all the prototype development and testing activities and verification of internal and supplier manufacturing capabilities. Subsequent production approval triggers the start of large-scale manufacturing and the beginning of continuous system deliveries to the customer. The system is then put into operation and the last stage includes maintenance and logistic support to the customer, the release of product improvements and collection and analysis of operational data (Blanchard and Fabrycky (2006)).

These and other typical activities are performed during the stages of the system's life-cycle and are described in Figure 2-4, together with the typical decision gates in each stage. Major technical and business reviews (e.g. Concept Review, Preliminary Design Review, and Production Release Review) take place at each decision gate. Decision options at each gate, determine whether the team should move to the next stage or an iteration should be made in the current stage before moving to the next one.

While most published research on product development is focused on designing new systems or products, this is rarely the case in the automotive industry where products are often reusing systems or components from the previous generation or using shared systems or components across different products.

2.2   Product platform approaches

As discussed in Chapter 1, products in the automotive industry are platform based. Most manufacturers carry over a significant number of components between product generations and between different brands (models), in order to reduce the design effort and the risk associated with the product development.

In the literature, product platforms are described slightly differently depending on the product application. Meyer (1997) defines the product platform as a set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched. Muffatto and Roveda (2002) adds another variant to Meyer's definition and assumes that a product platform is "a set of subsystems and interfaces *intentionally planned and developed* to form a common structure from which a stream of derivative products can be efficiently developed and produced". This definition can be extended according to Hohnen *et al.* (2013) who defines a modular product platform as machines, sub- assemblies and components that can be combined as modules to fulfil different overall functions.

The several platform definitions show that there is significant variation in the level of concretisation, ranging from sharing specific components to common approaches to more general subsystems from which products can be developed. An example from automotive platforms where different products (brands) share the same module is shown in Figure 2-5. This is an example of a specific suspension module which can be used for different products with only few component additions.
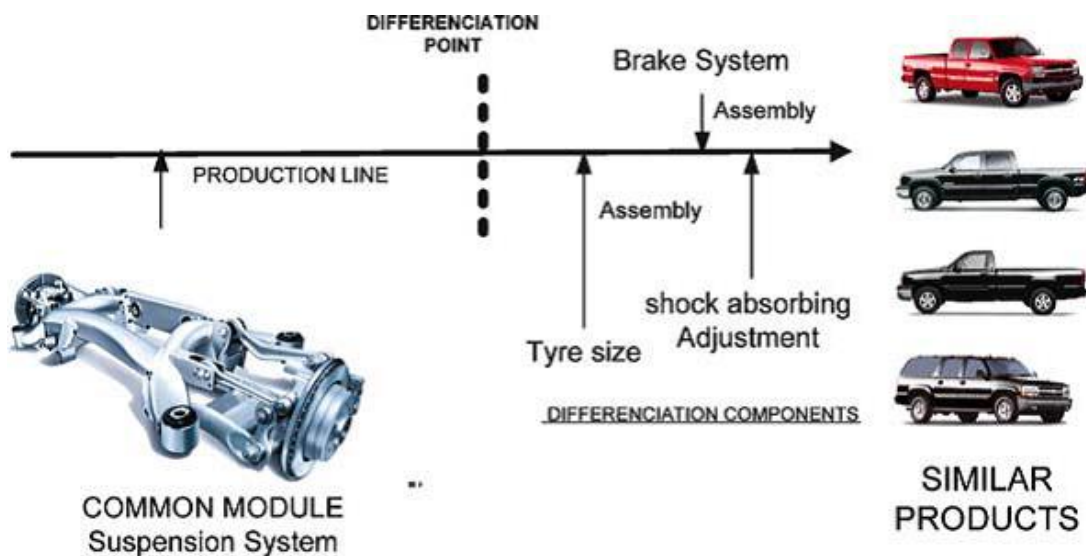
Figure 2-5 Example of a common module shared by different products

Product platforms are generally considered through component/part commonality, but some definitions do also include other aspects such as technology, people and relationships. Production aspects such as technology, process, operations and resources may also set the foundation for identifying and designing platforms. This type of platform is referred to as a production platform (Asbjørn and Ditlev 2011)

Platforms are generally described to be of one of either two kinds: (1) Module-based platforms are characterised by sets of components being clustered into interchangeable modules that

together form the product. The module-based platform can either be integral, where functions are shared by several modules, or modular, where each function is delivered by a separate module. (2) The second platform approach is the scalable platform. This platform supports adaptation by the stretching or shrinking of the product instances following variations in design variables (Jiao *et al.* (2007)). A platform approach is shown to be an enabler for efficient customisation, reuse and production standardisation.

A platform has implications like the use of common manufacturing processes, as well as technology and knowledge shared by multiple products in a family. Therefore, components in a product platform need to be designed in such a way that they can contribute to satisfying the requirements placed on all the products which are designed to be based on the platform.

Several works in the literature consider the product platform as the baseline for product family development. Product families are a way to increase the product variety while contraining the product development and manufacturing effort. Simpson *et al.* (2001) defines a product family as a group of related products that share common features, components and subsystems; and satisfy a variety of market niches. A product family comprises a set of variables, features or components that remain constant in product platform and others that vary from product to product. Krishnan and Ulrich (2001) defines product variety as the diversity of products that a production system provides to the marketplace. Product families are based on the idea of reuse. Therefore, if the customer needs are anticipated well in advance, modules and variants can be reused.

Martin and Ishii (2002) distinguishes between two types of variety when developing the architecture of a product range: variety within the current product line being designed and variety across future generations of the product. It refers to variety in the current product being designed as "spatial" variety, and the variety across generations as "generational variety". Du *et al.* (2001) adds to this distinction two other dimensions: "functional variety" and "technical

variety". Whilst functional variety mostly relates to customer satisfaction, technical variety is relevant to manufacturability and costs.

The crucial step in platform design is modularisation. Otto and Simpson (2014) gives an extensive overview of modularisation methods. Product platform design can be separated from the initial phase of platform planning and the subsequent phase of platform implementation. Schuh *et al*. (2011) provides a holistic approach for the creation of modular product platforms integrating the planning, design and implementation in one process model. The aspect of changeability in the lifecycle perspective of a product platform is still a deficiency in current approaches. Suh *et al.* (2008) addresses this issue with his work on flexible product platforms. This approach however lacks the focus on functions and ranges of function requirements that usually have to be fulfilled by a modular product platform. It is necessary to consider functions and ranges of function especially when designing modular product platforms, for mechatronic systems for example.

In the automotive industry, products are generally designed incrementally. New products are created by changing certain design parameters of the product. Typically, these changes enable an increase in performance or an adaptation to market-specific requirements.

2.3   Engineering Change

Engineering systems are constantly faced with changes and unpredictability in their environments. Engineering change has been tackled and understood from a number of different perspectives which are reflected in the literature.

Wright (1997) restricts engineering change to "a modification to the component of a product that normally takes place after the product enters the production phase". This definition takes

into account only the production stage, without considering the number of iterations that occur during the design and development of a product. This has been the common approach in much of industry which considers engineering change as a manufacturing issue to be addressed in order to ensure product quality and to meet delivery deadlines (Wright *et al*. 2000). Change before manufacture is regarded as a natural iteration of the design process.

Huang and Mak (1999) extend the above definition to "the changes and modifications in forms, fits, materials, dimensions, functions, etc of a product or a component". This definition is, in many ways, too general as it makes no mention or reference to the process or management of design. Hamraz *et al*. (2013) defines engineering change as "changes and/or modifications to released structure (fits, forms and dimensions, surfaces, materials etc.), behaviour (stability, strength, corrosion etc.), function (speed, performance, efficiency, etc.), or the relations between functions and behaviour (design principles), or behaviour and structure (physical laws) of a technical artefact". Drawing on the broad definition of engineering change by Hamraz *et al*. (2013), the component design change in the case studied in this thesis certainly lends itself to engineering change management processes. Also, subsequent change to the manufacturing systems can be described as an implicit change as opposed to an explicit one and may be included in the definition.

Although different terminology can be used, the basic engineering change process is the same whenever it is triggered in the design process. However, differences may become apparent in the detail of each stage of the engineering change process depending upon when in the product life cycle, the change process is triggered.

On the other hand, change can be considered to propagate through the design process, as well as through the design itself. According to this view, change to a task's input requires the task to be revisited, potentially causing a knock-on change to the task's output and hence to downstream tasks. The research conducted by Jarratt *et al*. (2011) considers the nature of the engineering

change process, which combines the procedural handling of design errors with the subtler and more substantial resolution of issues arising from uncertainties in designer, customer and market requirements and how engineering change is connected to the makeup of the product in terms of architecture, complexity and degree of innovation. Eckert *et al.* (2004) analyses the formal and informal processes that are used to handle changes and specifically looks at the potential causes and effects of changes. Ross *et al.* (2008) explains that the change can be characterised by three elements: (1) the agent of change, (2) the mechanism of change and (3) the effects of change.

Change is not only critical, but also difficult to manage. Change occurs across the entire product development process starting with the modification of existing products. Whether a change will propagate from a component or a system to another one depends on the ability of a component or a system to absorb the change. In fact, the capacity to absorb change means that a component or system has some design margins.

2.3.1 Product classification

According to Jarratt *et al.* (2011) the change impact on a product is influenced by three elements: (1) product architecture (2) product complexity (3) degree of innovation within the product. Products are categorised into two main classes based on their architecture.

Complex Products: For a system, many functional requirements must be satisfied at the same time. In this case, the complexity is determined by ability of engineering design to satisfy all the functional requirements within the specified design range. It can be difficult to establish a definition of complexity because product complexity is conceptualised in many ways. Pahl and Beitz, (2013) defines complexity as "the relative lack of transparency of the relationships

between inputs and outputs, the relative intricacy of the necessary physical processes and the relatively large number of assemblies and components involved". On the other hand, there are numerous opinions regarding complexity from the perspective of engineering change, which are brought together in Keller *et al*. (2005). The main type of complexity from a viewpoint of engineering change is connectivity. This measure of complexity describes the connections between components and their interaction inside a system. This complexity is mirrored in an integrated product architecture, consisting of a complex mapping from functional elements to physical components and/or coupled interfaces between the components. The complexity of technical systems relies on the diversity and number of distinct elements and their connectivity (Keller *et al*. 2005).

Modular products: Modules can be defined as a physical structure which has a one-to-one relation with the functional structure. More and more products are constructed based on modular product platforms, but modules and subassemblies are often developed for individual products and not for the entire platform. In function-oriented modularisation, modules are designed to independently fulfil partial product functions. These functions can mostly be realised by the application of various different technologies. An example is the air conditioning technology for a car, which can either be implemented with water or air cooling. Using only one of these technological alternatives for the entire product range requires applicability to all planned platform products but leads to reduced efforts in testing and design as well as a reduction of variance by the realisation of commonalities.

The modularity that is linked to the application of modular product platforms allows independent development of each module. Therefore, each module becomes an independent unit of selection (Morkos *et al*. 2012) . A module is a product block whose structural components are strongly linked among themselves and comparatively weakly linked to the other unit components. Thus, a change in a module's component has a high probability of causing changes

in components within the same module. A change in a module can propagate to the other modules because interfaces and linking parameters exist between them. A change to one module can be made without changing the other modules if the interfaces remain unchanged.

2.3.2   Components / sub-systems classification

The components or sub-systems of the product are interlinked. Clarkson *et al.*. (2004) identifies four types of change propagation behaviours named as multiplier, absorber, carrier and constant. These four types of change propagation represent four different situations. When the change is initiated by one component and it propagates to other components through linkages, so different components behaves in different ways. These classifications are illustrated in Figure 2-6.
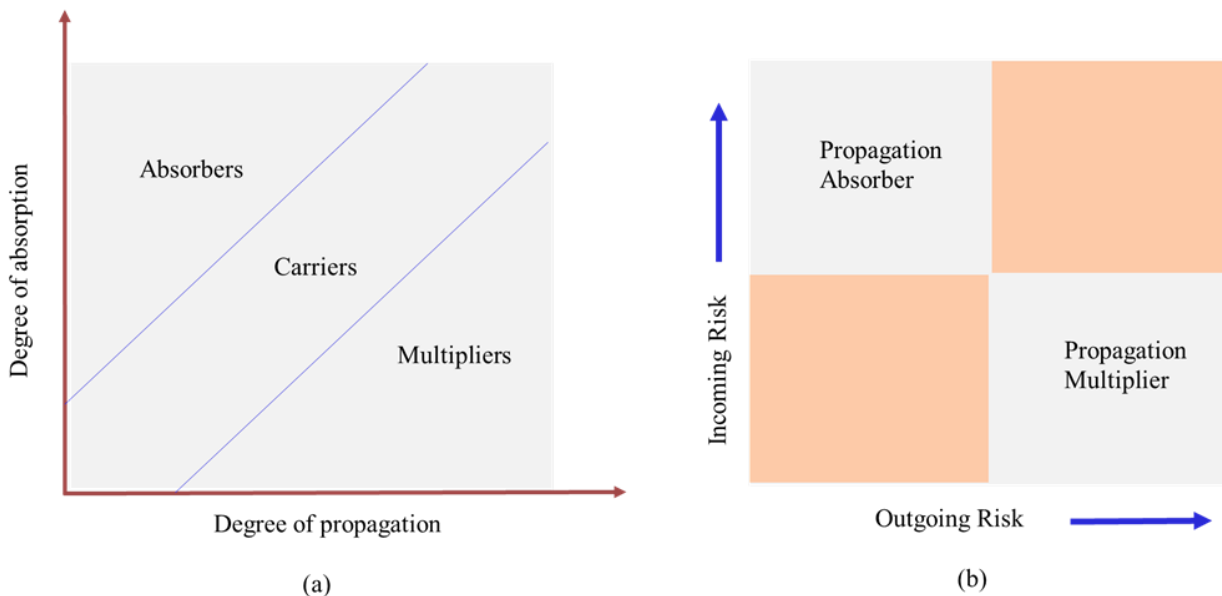
Figure 2-6 (a) Component change propagation characteristics (Eckert *et al*. 2004) ;
(b) Component classification based on change risk (Keller *et al*. 2005)

Absorber: An absorber absorbs all the changes without passing them on. Absorbers reduce the complexity of the change propagation.

Carrier: A carrier can be defined as a component that neither adds nor reduces the number of changes. It means that these components pass on the same degree of change as they have received. They do not increase the complexity of the overall problem (Eckert *et al.* 2001).

Multiplier: Multiplier is a component that causes more changes than it receives. These components can provoke an "avalanche" of changes (Mokhtar *et al.* (2000), Eckert *et al.* (2004)) and is also referred to as the snowball effect (Terwiesch and Loch (1999)). Such changes have, potentially, a major effect on the budget, product lead time and the organisation as a whole.

Constant: This component remains unchanged and the change is being passed without any effect (Eckert *et al.* (2004), Fei G *et al.*(2011)). It just transfers the change from one component to the other components to which it is interlinked.

The difference between a change carrier and a constant component is that a change carrier absorbs and propagates the change to the other components to which it is connected while a constant component remains unchanged and passes the change to the other components.

Change propagation behaviour is not a static property of the part or system, it depends of the state of the design (Eckert *et al.* 2001). A change absorber can easily become a multiplier if the particular change is too big to absorb. For example, an engine might be able to support a certain increase in weight. However, if the weight-increase is too large the engine must be modified or a new engine selected.

2.4 Requirements Change in Complex Product Development

The importance to engineering of managing requirements more effectively during development projects has captured the attention of various research and industrial communities during the recent decades. In fact, requirements management appears as an important topic in various bodies of knowledge. It arises in the engineering design literature which is concerned with the

design and realisation of physical systems (often comprising some kind of mechanical system) and has been traditionally focused in consumer products and capital goods (Pahl and Beitz 1988). Managing requirements is a central topic in software engineering, known to be primarily focused on the design, realisation, operation and maintenance of software products such as information systems and embedded systems (Sommerville *et al*. 2012). It is also a key issue in the systems engineering literature which is concerned with the design, realisation, management, operation and disposal of large technical systems (Blanchard & Fabrycky 2006).

Academic research, Pikosz & Malmqvist (1998), Fricke & Schulz (2005) and Jarratt et al. (2002), for instance, point out that requirements change is one of the main sources of engineering change. An industrial survey conducted by the Aberdeen Group (Brown 2009) on 65 design and manufacturing companies to understand their product development practices shows that 40% of the companies experience engineering changes on a weekly basis, and that changes causes additional rework and costs to 57% of the companies on a monthly or quarterly basis. Delays resulting from engineering change are experienced by 23% on a weekly basis, 26% on a monthly basis and by 24% of the companies on a quarterly basis.

Fernandes *et al* . (2013) suggests that requirements change triggers changes to design solutions previously completed for the system, sub-system and components of complex products such as gas turbines. These changes precipitate new design iterations and the rework of many design activities and can propagate across sub-systems and components (Clarkson *et al* .2004) due to design dependencies arising from decomposition, leading to higher development costs and time-to-market. However, Unger and Eppinger (2011) argues that design iterations can be employed to address various risks. The specific risks addressed depend upon what activities are involved in the iterations and upon the timing of the iterations. For example, market risks can be managed by iterations that allow market feedback during the design process. Also, Wynn and Eckert (2017) advocates that iteration has positive effects, such as enabling progressive generation of

knowledge, enabling concurrency, and integrating necessary changes. Nonetheless, iteration also increases duration and cost of a project. The industrial survey done by Brown (2009) shows that most companies normally go through 4 to 5 major design iterations before the product is released (Figure 2-7) and Souder *et al.* (1998) estimates the number of rework cycles within the aerospace industry to vary between 4 and 9.
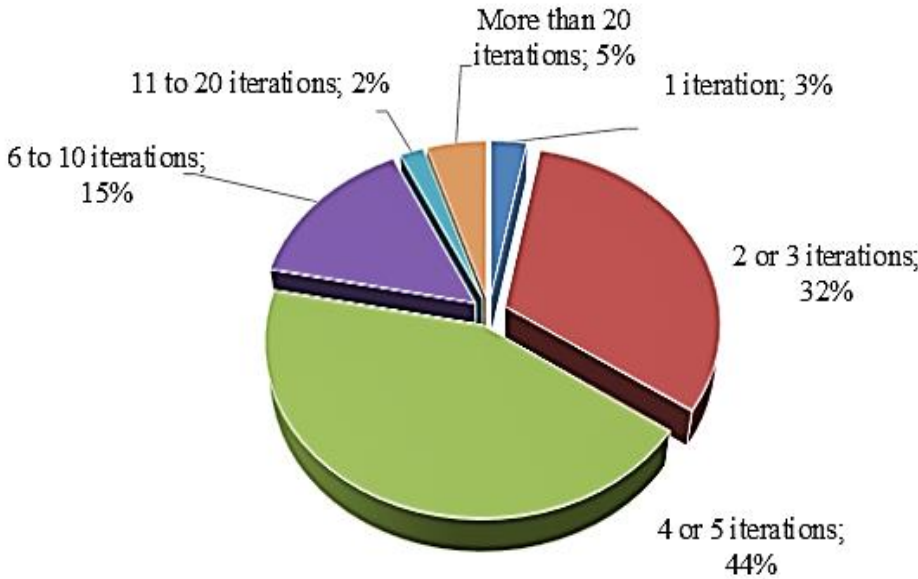
Figure 2-7 "Typical number of design iterations before product release in design and manufacturing companies". Source: Brown, (2009)

Understanding and managing the uncertainty associated with requirements and the ability for products, systems and components to accommodate changes in requirements are both critical factors for companies in developing complex projects over a long period of time. Requirements change leads to unplanned design iterations during projects. This means that redesign can have a large impact in organisations such as Volvo, not only due to the financial resources needed to

revisit design activities but also from the large financial penalties that may be demanded from customers due to delays in the product's release.

In addition, the difficulty of understanding when and how much change should be expected is a challenging issue for the industry. Designers need to understand the complex system being analysed to determine which parameters are most important in satisfying the requirements being placed on components or systems. Therefore, one of the main research motivations for the research is the importance and difficulty of managing uncertainty and change during the product development process.

2.5 Uncertainty

A distinguishing characteristic of complex design processes is the presence of many sources of uncertainty that need to be resolved through the interrelation of different kinds of design activities.

An in-depth survey across the social sciences, physical sciences, engineering and management sciences by Thunnisen (2004) shows that definitions and taxonomies vary considerably across these fields. For instance, Thunnissen (2003) reports that research in economics acknowledges the existence of fundamental uncertainty (situations where insufficient information conducts to unreliable probabilities) and ambiguity (uncertainties about probabilities that could be known). Management science defines aleatory uncertainty (arising from randomness in a system), epistemic uncertainty (originating from lack of knowledge of a system), parameter uncertainty (surrounding the true values in mathematical models), model uncertainty (coming from approximations in a model) and volitional uncertainty (arising from decision making) (Oberkampfa *et al.* 2004). In addition, the work of Thunnisen (2004) demonstrates that various definitions of uncertainty co-exist in engineering itself. Thunnissen (2003) argues that some disciplines, such as control systems, view uncertainty essentially as errors between

models and reality while others, such as the computational analysis and simulation community, view uncertainty simultaneously as variability, lack of knowledge and incomplete information in addition to errors. The topic is therefore far from unified across different sciences and applications.

Various authors have also defined and classified uncertainty within engineering design. For example, Earl *et al.* (2001) and de Weck *et al.* (2007) classifies uncertainty in design into four categories: *known uncertainties, unknown uncertainties, uncertainties in the data* and *uncertainties in the description*. Known uncertainties are those that can be described and managed well based on past experience. Unknown uncertainties are those where the specific event or type of event could not have been predicted, for example the occurrence of Brexit and its impact on research. Uncertainty of data includes factors such as precision, consistency and quality of the measurements themselves. This is different from uncertainty in the description of a system, which focuses on the vagueness of descriptions, the selection of elements and the lack of clarity in their scope.

Another definition of uncertainty, not too different than the one discussed by (Earl *et al.* 2005) is the one proposed by McManus *et al.* (2004). This latter paper establishes a framework for understanding uncertainty that also includes mitigation/exploitation strategies and distinguishes between: lack of knowledge, lack of definition, statistically characterised variables, known unknowns and unknown unknowns. Both lack of knowledge and lack of definition are similar to Earl *et al.* (2005) uncertainties "in the description". The subsequent work by de Weck *et al.* (2007) classifies uncertainty relevant to system design according to its source into *Endogenous* and *Exogenous* uncertainty. According to this taxonomy, endogenous uncertainty relates to factors within the domain of the system itself, such as uncertainties concerning product technologies and reliability or the company's strategy and its business relationships. On the

other hand, exogenous uncertainty relates to those which are outside the company's control (de Weck *et al* . 2007).

Performing uncertainty analyses generally involves obtaining the variations in the response (design metric) given variations in the input variables. Various approaches are typically used to obtain this output variation. Among others, these methods include differential analysis (Cacuci and Ionescu-Bujor, 2004), Monte Carlo analysis ((Lévárdy *et al.*, 2006), and Pareto frontier analysis (Lewis and Mattson 2012). Pareto frontier-based concept selection, seeks optimal decision-making early in the design process where the uncertainty is still significantly high. Overviews of these approaches are available in several reviews including; van Griensven *et al.* (2006), Saltelli *et al.* (2006).

A second engineering systems challenge is in their cyber-physical nature (Farid, (2016); De Weck and Roos, (2011)). Engineering systems, as expected, are largely physical in order to realise their important primary function. In the meantime, by virtue of their size and complexity, they require many decision-making components. Farid, (2016) argues that designing, planning, and controlling such large-scale cyber-physical systems go well beyond traditional control theory research. It now includes more fundamental questions that balance centralisation versus distribution, automation versus human decisions, and authority versus cooperative negotiation bounded within a context of human stakeholders and actors.

Many decisions during the product development process, especially at the design stage, are made under considerable uncertainty. The uncertainty may come from a lack of information regarding the final performance of the product, inaccuracy in simulations, or imprecision in requirements definition. Consequently, designers attempt to anticipate these uncertainties with a design margin. Uncertainty can be identified as a primary driver of the need for design margins.

2.6 Conceptual approaches to system protection against uncertainty

As discussed in the previous section, dealing with uncertainty and its effects has attracted a great deal of attention in the product development literature. Many of these studies have focused on ensuring that products, systems and processes are capable of functioning as intended in the presence of uncertainties. The underlying assumption is that all systems have properties that can collectively be called "ilities" (Chalupnik *et al*. 2013). Ilities are systemic properties that arise not only from the parts of a system, but also from their interactions. De Weck *et al*. (2012) advises that some ilities are much more prominent than others and discuss them from a "means-ends" perspective as shown in Table 2.1. A "means-ends" hierarchy is one that represents the relationships between ilities in terms of using one ility as a "means" for accomplishing another ility ("ends"). For example, modularity can be a means to achieving flexibility and evolvability by reducing the switching cost and providing options for swapping system components.

In this section, some of these ilities are discussed that are related to the concept of design margins and the product development. The literature review on ilities is not claimed to be rigorously complete. The relationship between the concepts discussed in this section are summarised in Table 2-1. Note: S=System, E=Environment, R=Requirements.

Concept	Variables			Source of uncertainty
	R	S	E	
Reliability		√		S
Robustness		√	√	S+E
Adaptability		√	√	S+E
Flexibility	√	√	√	S+E+R

Table 2-1 A classification of conceptual approaches to system protection against uncertainty (adapted from Chalupnik et al . 2013)

2.6.1 Flexibility

Flexibility is a "popular" concept used as an attribute for a design, a process, or an organisation. In the engineering design literature, despite its popularity, it is a word rich with ambiguity. Saleh *et al* . (2009) defines flexibility as "the property of a system that allows it to respond to changes in its initial objectives and requirements both in terms of capabilities and attributes occurring after the system has been fielded". Flexibility is a characteristic which is widely perceived as the most effective way to deal with uncertainty in engineering systems (McManus *et al* . (2004), Nilchiani and Hastings (2007), Shah *et al*. (2008), Saleh *et al*. (2009), Ryan *et al.* (2013)). However, in many cases the words flexibility and adaptability are used almost interchangeably. A definition for product adaptability is given by Gu *et al*. (2009) "product adaptability is the capability of a physical product to be adaptable to satisfy changed requirements". Among all the "ilities", the term "flexibility" seems to be the most carelessly employed.

In a study by Saleh *et al* .(2009), the authors present evidence showing that the term "flexibility" (and its variants) is used in a colloquial sense far more often than other design terms, concluding

that the concept of flexibility lacks "scholarly maturity". However, these authors also support the notion that the "concept of flexibility is today where the concept of *quality* was some 20 years ago," (p. 309) suggesting that its definition is destined to mature.

It is also important to note that there is a fundamental distinction between process flexibility and design flexibility. Saleh with his co-authors is one of the few authors to distinguish between the two types: "*The literature on flexibility in engineering design addresses two distinct problems: the first one focuses on the flexibility of the design process, and the second one on the flexibility of the design itself (not the process through which a product or a system is designed). This distinction between the flexibility of the process and flexibility of the design is not often made in the literature, and it sometimes adds to the confusion*" (Saleh *et al*. 2009).

The process flexibility provides a set of tools for allowing a product development programme to better respond to uncertainty, including management reserve, incremental deliveries, iterative development, and delayed differentiation (Mikkonen and Pruuden (2001), Krishnan and Bhattacharya (2002)) . On the other hand design flexibility has been mainly defined from the point of view of the ability to respond to requirements changes, which "can be known or unknown upfront".

2.6.2 Adaptability

Adaptability has also been defined in a number of ways. For example, it has been associated with a system's ability to accommodate predictable changes in operating environment (Olewnik and Lewis, 2006); to exhibit self-organising and emergent behaviour (McCarthy *et al*. 2006); to be amenable to change in order to fit altered circumstances (Engel and Browning, 2008); to be easily changed to satisfy different requirements (Li *et al*. 2008) and to change within a given state (Bordoloi *et al*. 2009). However, definitions do not agree on or do not pinpoint whether system change is instigated in response to changing requirements and/or changes in the environment.

Fricke and Schulz (2005) defines adaptability as the ability of a system to be modified in order to do its basic job in uncertain or changing environments. Omitting response to requirements changes means that the definition covers only a subset of the discussions in the literature, but aligns with some definitions and allows the concept of adaptability to be distinguished from that of flexibility.

In this research, it is argued that flexibility refers to designing products that are able to work under a wide range of conditions (hot and cold water for e.g.), whereas adaptability means designing products that are able to run under a specific set of requirements (hot or cold weather). This differs from robustness, where a *fixed behaviour* is specified for an uncertain range of external influences on the system (Banerjee and de Weck, 2004).

2.6.3   Robustness

Following the seminal work of Taguchi and Clausing (1990) the concept of robustness has attracted attention in the product development literature. A variety of system types have been considered, including product, process, project and organisation.

Many sources of uncertainty have also been accounted for in the robustness literature, including noise, variation in design control variables, uncertain task duration and product development project budget instabilities. Consequently, the concept of product development robustness has many different interpretations. For example, it has been interpreted as a measure of variation in performance (Taguchi and Clausing, 1990); insensitivity to anticipated risks (Floricel and Miller, 2001); insensitivity to "*unforeseeable changes*" in the operating environment (Olewnik and Lewis, 2006); insensitivity to both expected and unexpected variations; the ability of a system to continue to operate correctly across a wide range of operational conditions (Gribble 2001) and the ability of a system to absorb change (Yassine and Wissmann 2007).

The understanding of robustness put forward in this thesis builds upon McManus and Hastings (2005) definition of robustness: "the ability of a system, as built, designed, to do its basic job in uncertain or changing environments".

2.7   Design Margins

Design margins help the component and system designers understand the key performance parameters, their requirements and thresholds, how robust they are to the required inputs and constraints, and how they interact with other components in a system or a product. However, a key challenge is that the word "margin" has different meanings to different people; moreover, there are several types of "margin" that should explicitly be evaluated during the design process. Design margins are either discussed from the perspective of engineering change and product flexibility or from the view point of negotiation; however individual researchers use different terms to express the concept of margin. Although design margins are critical to both functional performance and manufacturing cost, they are not well defined either by engineers or researchers. From an engineering perspective, a margin refers to a design margin over the theoretical design capacity that allows for uncertainty in the design process. There are also safety margins introduced to provide the needed "safe flexibility" in operating conditions as defined by Gimenez *et al*. (2002). A safety margin can be seen as an incremental margin introduced to account for the estimated total effects of unknown and underappreciated risks (Benjamin *et al*. 2016). The main objective of adding this type of margin is to account for the difference between unknown risks and actual risks in attempting to validate compliance with probabilistic safety goals.

Designing margins into products gives them flexibility later in the design to meet different requirements in particularly those arriving from new options that are added at a later point in the design process. Zhao and Tseng (2003) discusses the value of flexibility in multi-level

parking garages. In this study, stochastic dynamic programming models the demand and the optimal infrastructure expansion process. Then, a model with flexibility was compared with a model without flexibility. Zhao and Tseng (2003) argues that the difference in value between the two models is the value of flexibility. De Neufville *et al.* (2006) uses the same example with the real options analysis to introduce design (real) options as a form of deliberate planning for potential future changes. For an engineering system, there are a great number of design variables, and each design variable can lead to a design option. However, it is difficult to determine where the flexibility can be and where options can be designed into a project without major cost. Ross *et al* .(2008) develops a method for comparison of the possible options in order to understand which designs are more changeable than others. The method assesses the changeability of a system by mapping out the trade space, i.e. the range of possible parameter values that provides potential solutions. The design margins of a product could be defined by the trade space where the design should be.

The actual parameter values for a component in a design may exceed the predefined values under which a component has to deliver the expected function regarding the whole product design. Most components are designed with a margin at the beginning to cover the variability in manufacturing and assembly, as explained in robust design literature (Zhu and Ting 2001). A good specification of dimensional tolerances has always been recognised by the industry as a key element to increase the efficiency of their manufacturing process and it is important to include manufacturing considerations in the early design phases. Tolerance accumulation in assemblies controls the interfaces in a design; however, designers often assign tolerances following only limited analysis of the product or base their decisions on insufficient data. On the other hand, engineers involved in the production and assembly process know that tight (or loose) tolerances increase the cost of production. Design margin thinking is a way that can solve the issues of the competing requirements regarding the tolerance specifications in early and late

design phases. It is then an important link between engineering and manufacturing. Design margins allow more flexibility while tolerances constrained to stay within certain boundaries.

Thunnisen (2004) proposes a formal method to propagate and mitigate uncertainty in the design of complex multidisciplinary systems. This method uses a probability approach to identify design margins on *tradable parameters*. The technical work is based on distribution based assessment of margins for tradeable parameters which are high level including performance, cost and schedule. The margins in the research work presented by Thunnisen (2004) requires calculations through the physical models for the system components. However, the same approach cannot be applied to the Volvo cooling system presented in this work. The company uses fixed point estimations with worst case scenarios and 'known' performance rather than a probability distribution for assessing the performance of the components.

Margins also contribute to the adaptability of an existing product to particular requirements. Such adaptability is designed into an individual product at the beginning to allow for changes in the course of the product life cycle or during the design of the follow-on product (Ross *et al.* 2008). Both Ross and Hastings (2005) and Qureshi *et al*. (2006) advocate assessing the flexibility of a product by systematically anticipating and rating the potential future changes to the design. In Ross and Hastings (2005) this assessment is achieved through mapping out the trade space, i.e. the range of possible parameter values that provide potential solutions. Where the design sits within this trade space indicates margins on the product. Guidelines and principles for design of products for future evolution have been brought together by Tilstra *et al.* (2008) and extended by recent work of Tan *et al*. (2016) which aims to assess the impact of margins on systems performance and develop a composite margin index.

Tackett *et al*. (2014) addresses margins from the perspective of how a given design can be upgraded by identifying margins in terms of excess, as the "the quantity of surplus in a system once the necessities of the system are met" and capacity as "the ability of a system to meet future

performance objectives using existing system excess". It concentrates on system level properties as excess factors such as volume and show how these values can be calculated. This is based on a functional basis approach given by Hirtz *et al.* (2002) which offers a set of general functions through which systems can be described and differentiated between excess in these functions, i.e. flows and excess in the emergent physical properties of the system, like volume, with which the functions are realised. The concept of excess developed by Tackett et al. (2014) just looks at an existing design at the beginning of a design process to see where changes have to be made. White *et al.* (2015) builds on this idea and argue that excess is deliberately included in a system for reasons characterised by four categories. The first three categories: deterministic, epistemic, and aleatory are differentiated by their associated uncertainties. The fourth category, consequent, originates as a by-product of other design decisions. On the other hand, Cansler *et al.* (2015) explains that the excess that is originally designed into the system may not be constant over time, since designers are do not know the future. Rather, the excess present in a system may vary due to system evolutions or changes in system specifications while in service. When lower than anticipated service requirements are realised, excesses are created in the components that are consequently underutilised.

Although design decisions made during the early development stages have a much larger impact on the final design quality and cost, there is a shortcoming in considering how close the key components are to their limit (i.e. their margins), at the early stages of the design process. Which trade-offs are important at which stage of the design are not well defined and depend on the results of other trade-off analyses.

A company, however, has to consider margins across the design process and also across multiple products. As components and systems are deployed in different applications, there might be huge margins with regards to one application in order to be optimal for another, so that the cost of creating an optimal product has to be traded against the cost of creating a bigger platform and

less commonality across applications (Lebjioui *et al*. 2016). This makes it practically difficult to suggest optimal margins for a product if platform commonality needs to be considered. However, margins sit at the heart of a trade-off between product cost through optimising components and increasingly commonality and process cost through either avoiding rework through changes but also the cost incurred through creating optimal platforms.

In this research, a design margin is defined as *"the value a parameter has above and beyond what it needs to meet its functional requirements regardless of the motivation for which it was included"*(Eckert *et al.* 2013).

2.7.1 Mapping of the related concepts in the literature

The main issue in dealing with margins is the existence of a wide range of taxonomies across fields and within engineering design. This issue was also observed while carrying out the case study for this research work as discussed in chapter 4 and 5. This suggests that the meaning of margin is wide-ranging and consequently it is interpreted differently according to the particular context under consideration. Table 2-2 Mapping of the concepts related to margins

 provides a mapping of the available concepts (in the literature) that are related to margins. The outcomes of the related concepts have also been discussed above from the point of view of design ilities.

Reference	Domain	Case study	Related concept/ Exploitation	Related ility
(Hockberger, 1982)	Conceptual design	Ship design	Assurance margin	Adaptability
(Sobek, Ward and Liker, 1999)	Product development process	Example of Toyota	Set based design	Flexibility
(McManus, Hastings and Warmkessel, 2004)	Conceptual design	Space systems	Uncertainty mitigation	Robustness
(Ross and Hastings 2005)	Conceptual design	Space systems	Trade space	Adaptability
((Snape *et al*. 2005)	Meta models	-------	Margins of performance	Robustness
(de Neufville, Scholtes and Wang, 2006)	Project study	Garage	Options	Flexibility
(Qureshi *et al*. 2006)	Patent database	Modular products	Future evolution	Evolvability
(Lewis and Mattson, 2012)	Conceptual design	Aircraft	Pareto frontier optimisation	Robustness
(Tackett, Mattson and Ferguson, 2014)	System in service	Aircraft carrier	Excess	Evolvability
(Tilstra *et al*. 2015)	Product study	Camera	Flexibility for future evolution	Evolvability
(Austin-Breneman, Yu and Yang, 2015)	Conceptual design	Aerospace	Biased information	Interoperability
(Benjamin, Dezfuli and Everett, 2016)	Failure analysis	Space systems	Safety margins	Robustness

Table 2-2 Mapping of the concepts related to margins

Domain : The work presented in the literature regarding margins focuses on customised engineered systems such as ship design and aerospace systems. This type of product is *one-o-a-kind*, typically designed and built from scratch. In this domain of applicability, margins were discussed from the point of view of flexibility and evolution of the product while in service. Several probabilistic approaches were developed to mitigate this type of margins. However, trucks, the case study of this work, are mass-customised products. This manufacturing approach produces products based on individual customer requirements while maintaining the quality and efficiency of mass production. Therefore, the approach to margins in this domain is slightly different. It focuses on increasing the adaptability of systems and components to satisfy new requirements. The approaches that were developed to handle these types of margin tend to be more deterministic such as trade-space exploration and real options analysis.

Exploitation refers to the technical approach which represents an opportunity arising from understanding margins.

Outcomes are attributes of the system that a user may find valuable, specifically those which quantify or at least characterise its interaction with margins.

These attributes (ilities) will be considered/ defined in this thesis as follows:

Flexibility: *Ability of the system to be modified to do jobs not originally included in the requirements definition*. The modification may be in the design, production, or operation of the system; each has a unique flavour as defined by McManus and Hastings (2005) .

Robustness: *Ability of the system to do its basic job in unexpectedly adverse environments.* This is well understood for non-aerospace products; aerospace products tend to be designed for expected adverse environments already, leading to minor ambiguities. There is a tendency to use 'robustness' for any of the attributes on this list, which can cause confusion.

Evolvability: *Ability of the system to serve as the basis of new systems (or at least generations of the current system) to meet new needs and/or attain new capability levels.* This is an area of recent research interest (Tackett *et al*. 2014)

Interoperability: Ability of the system to "play well with others" both with the systems it was originally designed to work with, and with future systems. It also enhances flexibility and evolvability of systems.

After reviewing the literature, it became clear that there is a link between uncertainty and the need to accommodate possible changes into products, systems and components. Uncertainty can be identified as a primary driver of the need for design margins. Meanwhile, design margins have a significant impact on how easy or difficult it is to incorporate changes in existing products and systems (or future generations). Therefore, it seems that the available literature focuses more on the two aspects: (1) how to anticipate changes (managing uncertainty) and (2) how to incorporate changes into the next generation of products. However, there is a gap in the literature on how to respond to change using margins (Figure 2-8).
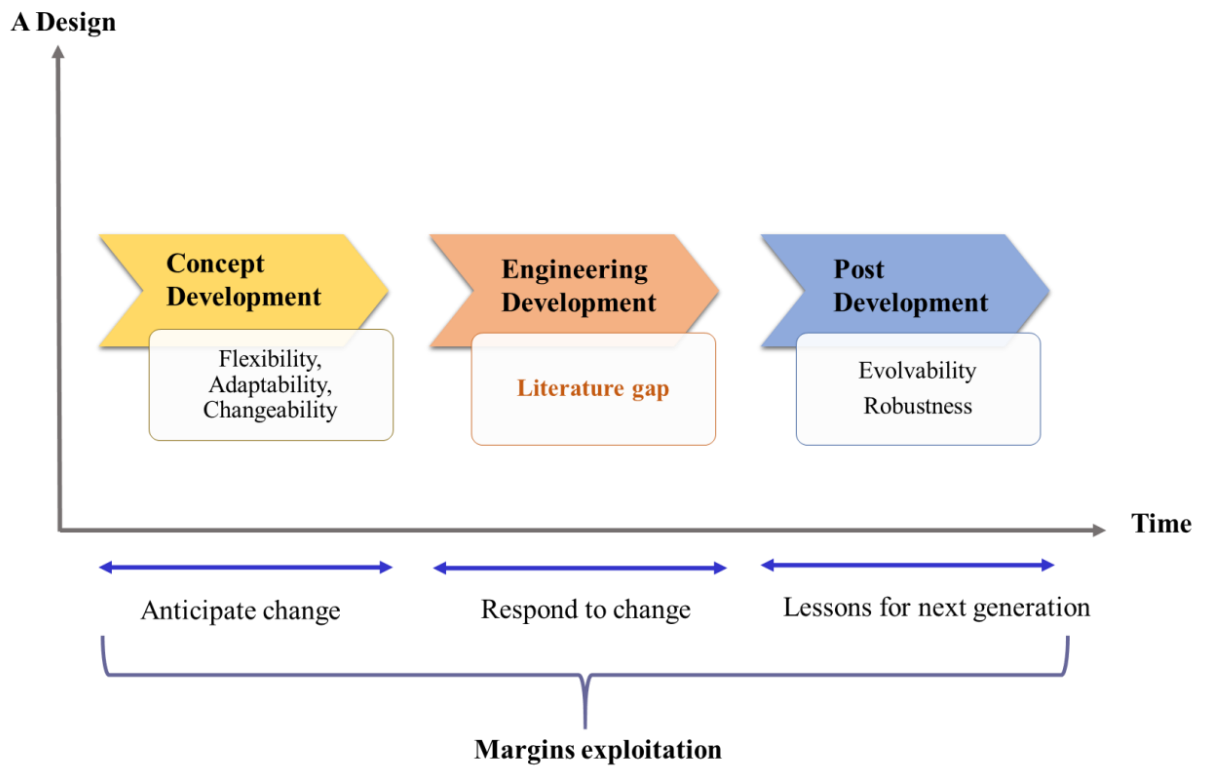
Figure 2-8 Margins exploitation in the literature review

The kind of change which arises can be less complex when existing interfaces between the single parts of the architecture remain the same. This can mean not having to change all parts completely. To gain an overview of the dependencies between single components, it is crucial to not only reveal the directly visible connections between them, but also the indirect ones, where their linkage is achieved by the interplay of one or several other components. Several methods for this visualisation are available, e.g. the Design Structure Matrix (DSM) and the Change Propagation Matrix which are both discussed in more detail in Chapter 5.

2.8 Summary of key points and research gaps

Margins are of a great importance in the product development process, especially at the early stages. However, most of the work related to design margins, has been limited to the margins on the parameters, components and systems. Relatively little work has been published on the role that margins play in the development process itself. This thesis attempts to provide the academic research community and industry with a description of (i) how margins are handled in current practice, (ii) the evolution of margins throughout the product development process and (iii) how they can be managed. Knowing where the margins are in a product, can inform engineers about the actions to take and changes to make during the development process.

The literature review shows a lack of models and methods allowing organisations to understand and quantify the evolvement of margins in key performance variables so that project planning activities can take them into account. This thesis argues that this is a major opportunity for research, and proposes a method to investigate design margins in complex system development. Exploratory findings revealed that companies need to understand how to respond to a change, predicting and managing uncertainty and their need for support in planning for change during complex product development. A good understanding of margins and how they evolve over the development process can greatly enhance the efficiency of product development. Discussions with academics and specialists revealed also the industrial receptiveness to evaluate novel approaches and methods to respond to these challenges, since it would provide additional decision-making support and that was considered to be highly valuable.

3 Research Methodology

The study of design margins and product development processes was initially undertaken as a descriptive study. The analysis of the design process and the evolution of margins over time became the focus later on. Throughout the course of the investigation, multiple sources of information have been used, from document analysis, to semi-structured interviews and expert knowledge elicitation. This chapter discusses the research methodology that has been followed in this thesis.

Engineering design is a complex and multi-layered study. The methodological challenge of design research lies in understanding the multi-disciplinary and multidimensional aspects of a design problem. In this research project we adopted the methodological framework introduced by Eckert, Stacey *et al.* (2003), which is described in the first section of this chapter, followed by the application of the framework.

3.1   Overall research methodology

The research has been set up as an explorative study because there was limited literature directly on the topics at the outset of the research. Some of the relevant literature reviewed in chapter 2 has been published since the research has started and without the analysis carried out for the thesis it would have been difficult to recognise it as related work, since the terminology is different. In addition, the study of margins across the product development processes at different levels is complex since there are different levels of granularity and dependencies between those levels. Hence is it necessary to explore which concepts and kinds of support are useful for meeting the goal of this project.

Within the research area of engineering design, Blessing and Chakrabarti (2009) proposes a framework for conducting research called Design Research Methodology (DRM). DRM is based on descriptive studies to understand the problem in hand and prescriptive studies to develop suitable methods and tools and iterations to evaluate the developed methods. The DRM has become a standard research methodology in the field, however, there are a number of drawbacks to DRM, which have mainly emerged from how people interpret and apply the method. This led Eckert *et al.* (2003) to propose a spiral model of design research which is shown in Figure 3-1
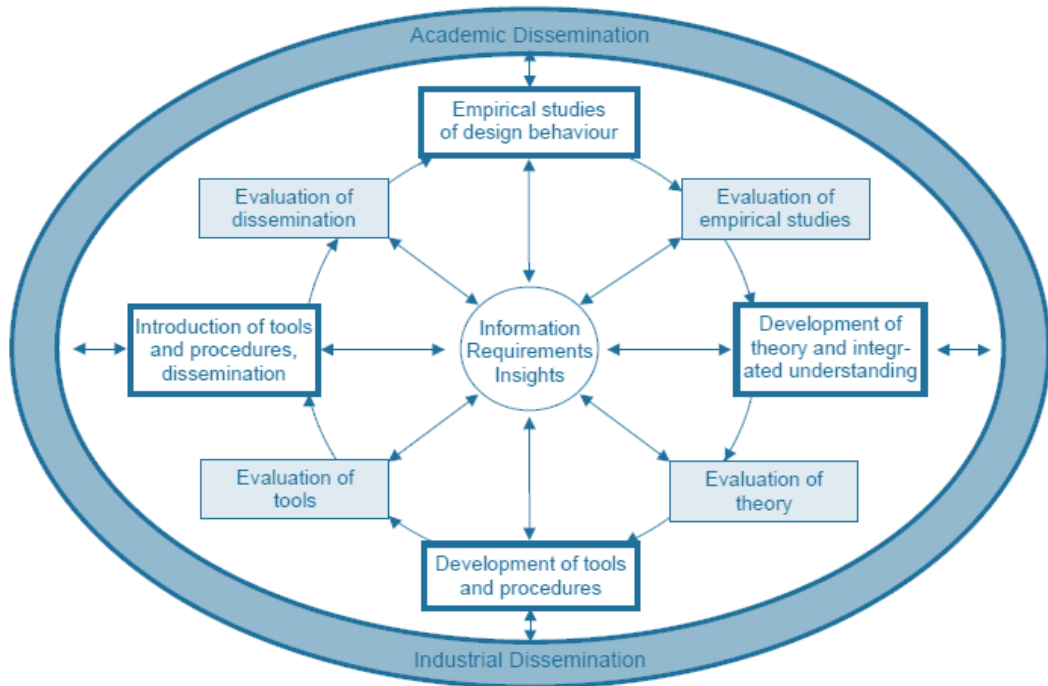
Figure 3-1 The Spiral Design Research Model (Adopted from Eckert *et al*. 2003)

The model consists of eight steps with different research objectives.

1. Empirical studies of design behaviour;

2. Evaluation of empirical studies;

3. Development of theoretical understanding;

4. Evaluation of theory;

5. Development of tools and procedures;

6. Evaluation of tools and procedures;

7. Introduction of tools and procedures into industrial use; and

8. Evaluation of the dissemination of tools and procedures.

The steps which were undertaken in the course of this PhD and how they were applied will be described in the following section.

All of these activities generate information and insights that can be used to formulate the requirements and hypotheses that guide the research within other steps. A research program can enter into this cycle at any of the four steps (bold squares). However, in the course of a PhD, an individual researcher cannot usually complete all the steps. According to Eckert *et al*. (2003), PhD projects should present at least the first four steps while long- term projects performed within a research group normally tackle all or several stages with such in-depth studies.

Although other approaches to Design Research is proposed by Checkland (1981), Blessing and Chakrabarti (2009) the author selected the approach of Eckert *et al*. (2003) due to its higher generality and also because the framework in this approach takes into consideration the insights from the industrial practice and industrial needs.

3.2   Application of the spiral model to this research project

Eckert *et al*. (2003) suggests that the research that delivers tools or procedures into industrial use should address these following four questions:

- How does design happen in concrete situations we can study, in particular within process we would like to improve?

- How can we understand the cognitive, social and cultural mechanisms that underlie the phenomena we observe, by building theories?

- What computer tools, pencil-and-paper techniques or design methods might be useful, and how can we develop them?

- How can we introduce these tools or methods into industrial use, and what happens when we do*?(Eckert *et al*. 2003)

The work described in this thesis aims to answer question 1, 2 and part of question 3 from the above list. These questions can be answered by following the set of research phases presented in the spiral model (Figure 3.1)

3.2.1 Mapping between Research Questions and Research Phases

The work described in this thesis enters the spiral model at "Empirical studies of design behaviour" and carries on until "Evaluation of theory", in order to answer the research questions discussed in Chapter 1 (Figure 3-2).
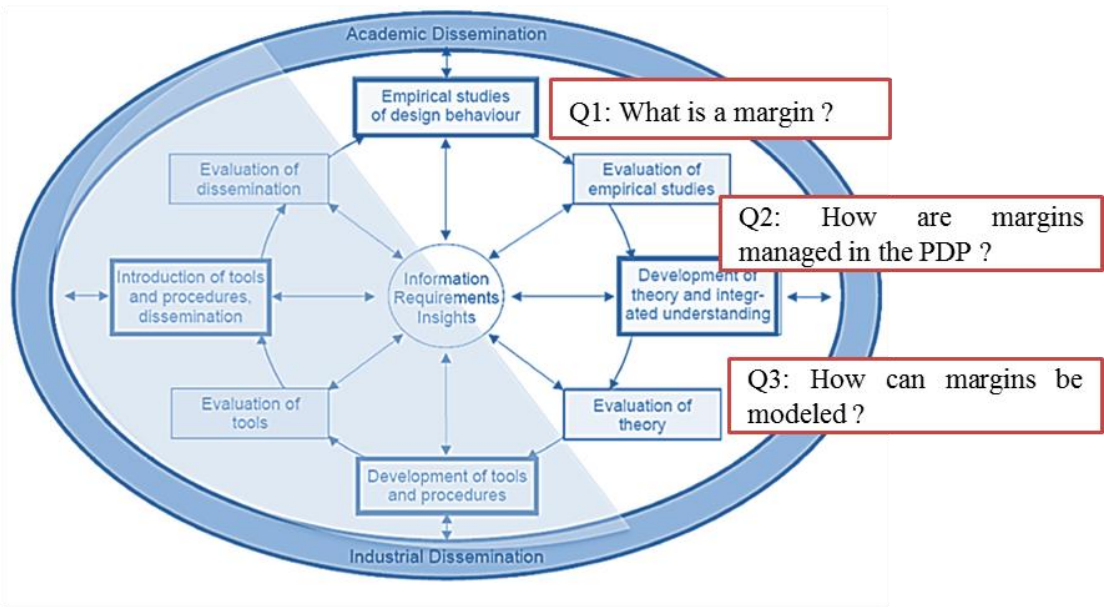
Figure 3-2 Mapping between Research Questions and Research Phases

Empirical studies of design behaviour:

In this research, the objective was to understand the relevant subjects related to design margins and product development processes. In order to elaborate the initial understanding and to determine the factors that influence design practice, several interviews were carried out. Also, observations and document analysis were used to understand current practice.

Evaluation of empirical studies:

At this stage the main purpose is to validate the information and data in the empirical study. The qualitative analysis of empirical data provided a better understanding of design practice carried out in Volvo. The evaluation focuses on what has been learnt and how this learning can be generalised.

Development of theoretical understanding:

The understanding from the empirical study helped to model the cooling system which is the case study of this research. A Design Structure Matrix was developed to visualise the connections and relationships among the different parts of the truck cooling system. The data from the DSM was then used to identify essential relationships and to see how changes in critical components may affect key design margins and the overall design process. This information was applied to propose a framework which could help the company to get a better understanding of design margins and to manage them in an effective way.

Evaluation of theory:

The theories are evaluated in terms of their methodological approaches and assumptions that have been made during the first stage. The proposed framework is first validated by checking whether the problem definition has been supported. Second, it was later presented to the steering committee group on the project to get their feedback and measure the effectiveness of the suggested framework.

In this research, these steps are iterative and often overlapped. Overall, the research starts by understanding how margins are currently handled in the company and how much engineers at different phases of the design process are aware of them. It then formulates the problem in managing margins and proposed a model to describe them effectively.

3.3 Research scope and methods

The work described in the thesis was informed by grounded theory as a research method for developing theory that is "grounded in data" systematically gathered and analysed (Urquhart *et al.* 2010) with the use of spiral model as an overarching framework for the study.

The following section gives an overview of the research shown in Figure 3-3 and describes the phases of the study.

After an exploratory research stage leading to the clarification of the research motivation and objectives, the author spent over ten weeks at Renault Lyon in France (a company acquired by Volvo Group) to learn about the organisation and to understand the existing practices at Volvo Group. This first phase of the study helped addressing the first research question (RQ1). Then a second phase was initiated to capture how engineers and designers deal with margins during complex development projects. This was performed by empirical collection of data from different sources in the company and by conducting a first set of interviews (3.3.1 for more details). At the end of this phase, research question 2 (RQ2) was answered. Later, in phase 3, a case study was conducted to identify how margins can be modelled (RQ3).
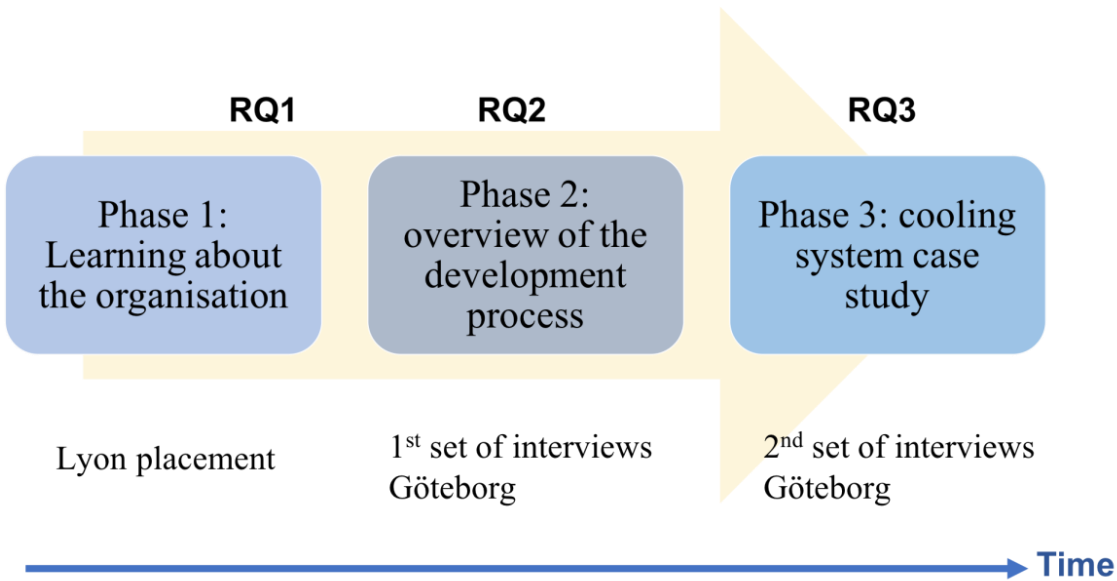
Figure 3-3 Overview of the research

3.3.1 Interviews

Twenty semi-structured interviews from between 45 minutes and two hours were carried out with employees from Volvo GTT which has been designing and building trucks for nearly 100 years. The interviews were conducted in Gothenburg site by the author and the supervision team; Professor Claudia Eckert and Professor Chris Earl between October 2013 and December 2014. Three or four interviews were held on a single day every two to three months. Each session was recorded on audio tapes and selected conversations were later transcribed for analysis. The interviews were carried out in English and were semi-structured in that there was a list of topics that the interviewers wished to cover, but the interviewees were allowed to move the discussion onto related issues if they felt that it was necessary.

The first series of interviews took place in October 2013, which focussed on chassis engineering across the product life cycle. The second set of interviews was conducted while carrying out the case study of this research and took place in December 2014. The interviewees were designers,

engineers and managers who work in different departments, with at least five years of experience within the company and industry.

At the beginning of each interview a brief introduction was made to give an overview on the project status and introduce the objectives of the session. The questioning was relatively general with each person initially asked to describe their role. As the interview progressed the questioning focused more on design process and in particular on design margins, and whether they have room for maneuver to take up new requirements. An example of the questions asked can be found in Appendix A. Practically, the questions can be grouped as follows:

– Questions on the role of the interviewee.

– Questions on the main constraints

– Questions on the company structure and the structure of their products

– Questions on the new product design process

– Questions on the design change

– Questions on the design of the cooling system.

– Questions on the key parameters of the cooling system.

During the discussion of design changes, the interviewees were asked if they are aware of the design margins they may have on specific parameters and if so how they deal with them.

In this research two main series of interviews were carried out. The first set of interviews was conducted to figure out some of the vocabulary used around margins with the aim of getting a definition for margins which is compatible with the language used in the company. For this, ten interviews were conducted with ten employees from the Chassis department. The interviewees were selected to cover different phases of the design process and different level of detail. These interviews helped to establish an understanding of the current practice in the company.

At this stage of the study, specific research problems started to emerge. Combined with a literature review about the concepts related to design margins and the previous empirical

research at Volvo GTT, this led to investigation of a new method aiming to support designers and engineers, understanding, managing and communicating design margins across the product development process. This method and its potential application was investigated through a case study. A second set of interviews was planned for this purpose.

A set of follow-up interviews focused on understanding how design changes affected the margins on components during the design process. It was decided to focus on one system to get a better understanding of the concept. The cooling system team was interviewed as many of the margin issues around the cooling combine geometrical issues which are fairly intuitive with thermodynamics and fluid flow issues which are more technically complex. This study gave an understanding about the core parameters for the cooling system that the designers and engineers need to consider in the first place. It enabled an examination of how margins on key parameters are handled and helped establish how margins play a role in carrying out changes. This allowed patterns in the mapping between changes and margins to be identified.

Fourteen engineers and designers from the cooling system team were interviewed for 60 / 90 minutes. The interviewees have different positions and functions within the cooling team.

At a high level, the interviewees could be split into two categories: engineers (14 interviews) and managers (6 interviews). This is illustrated in Table 3-1 by a reference code: "Eng" for engineer and "Mng" for manager. It should be noted that the managers all had extensive engineering experience either with Volvo or with other companies. Each session was recorded and the conversations were transcribed for analysis. At the beginning of each interview a brief introduction was made to give an overview on the project status and introduce the objectives of the session.

Interview	Role	Classification
1	Specialist in Geometry, high level view of computer tool in the organisation	Eng 1
2	Design engineer	Eng 2
3	Specialist in virtual testing	Eng 3
4	Specialist in virtual testing	Eng 4
5	Product planning	Mng 1
6	Specialist in mathematical optimisation	Mng 2
7	Design Engineer, head of fuel system	Eng 5
8	Design Engineer, focusing on urea tank	Eng 6
9	Manager for the global platform strategy	Mng 3
10	Expert in product options	Mng 4
11	Cooling module team manager	Mng 5
12	Fan installation engineer	Eng 7
13	Cooling module engineer	Eng 8
14	Cooling module designer	Eng 9
15	Pipes and hoses designer	Eng 10
16	Cooling performance simulations, 3D, CFD	Eng 11
17	Durability feature engineer	Eng 12
18	GTA specialist	Mng 6
19	Coolant pump engineer	Eng 13
20	Cooling performance testing	Eng 14

Table 3-1 list of interviews and interviewees role in the company

3.3.2 Summary of the interviews

The first 10 interviews were discussions about a range of topics in product development, product planning and company process. These helped to establish an understanding of the current practice in the industry.

The next set of interviews focused on understanding the company's design process and their understanding of design margins concepts. At this stage of the study, specific research gaps started to emerge and explicit questions were formulated according to these problems.

After these two main sets of interviews, a visit to the company in June 2015 mainly focused on analysis and evaluation of the proposed solutions.

3.3.3 Case study

A case study approach has been recognised as a key method that facilitates a deeper investigation of a real-life phenomenon in its natural context ((Yin 2009), (Woodside 2010). It is suitable for investigations intending to provide "cause-effect" relationship and for explanatory types of research, dealing with "how" and "why" research questions (Lindvall, 1997)

In this empirical study, it was not possible to separate the phenomenon of interest; the concept of design margins; from its industrial and technical context. The nature of preliminary answers to the research questions RQ1:How can margins be defined ? and RQ2: How are margins handled in the product development process? were also mostly explanatory. The work presented in this thesis was concerned in understanding how design margins are handled at present and how they can be better managed, as well as how and why design margins vary during the product development process. Explaining the causes behind adding or removing margins is about understanding a cause-effect type of relationship. All of the above supports the choice of a case-study approach. Figure 3-4 captures the research approach and methods used throughout the case study.
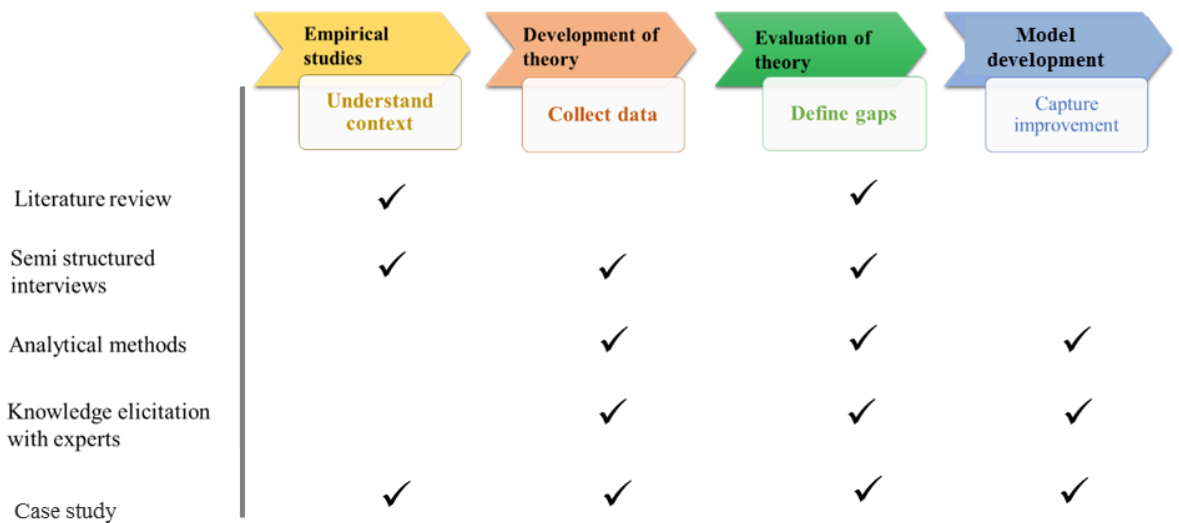
Figure 3-4 Research and methods applied in the thesis case study

3.3.4 Document analysis

During the interviews and the placement in the company, documents, diagrams and software tools were analysed and all provided useful information on how the company design their products. Some of the content of these documents were discussed during the interviews to get a better understanding.

3.3.5 Data analysis

Data analysis involves drawing of inferences from raw data. An important phase of this research, was to get the relevant data and to analyse the interviews. This analysis started with a transcription of the recorded interviews. Although the transcription exercise is time consuming it is an important one to get familiar with the context and the content of the interviews. The process of translating the raw data to findings requires interpretation of empirical data. The first stage of qualitative data analysis in grounded theory is to use a *coding* paradigm to ensure conceptual development (Strauss and Corbin, 1994). According to Boeije (2009) and Woodside

(2010), the coding is usually undertaken at three levels: *open coding*, *axial coding* and *selective coding*. Open coding is conducted by distinguishing different themes and concepts found in the data. This involved analysing the interview transcription (e.g. a sentence or a paragraph) and summarising the quotes by the use of a categories like: platform planning, product development, and component design. Once these pieces of data are regrouped based on their relevant content categories, the second stage is the interpretation of categories. This interpretation step is axial coding. Finally, selective coding is conducted by making logical links between the core categories and design margins. The coding exercise helped in understanding the concepts related to design margins and the reason behind using different terminology (overdesign, room for growth, safety margins) at different stages in the process and during different kinds of activity (the categories). Professor Eckert helped in the analysis of the first set of interviews and further details are given in chapter 4.

The findings were presented to a group of Volvo engineers including the steering committee members to which all interviewees were invited. The participants were invited to comment on the presentation and add issues that were missed in the presentation. These comments were captured and incorporated into the presentation and checked again with members of the steering committee.

Regarding the ethical concerns about anonymity and confidentiality, it was necessary that all the information was approved by the company (i.e. before publication).

3.4 Model development

Evaluating the understanding of the empirical work was undertaken by modelling in two different ways: conceptual modelling and mathematical modelling. The motivation for this choice is due to one of (at least) three reasons which relate to features of the models : "*models that describe* the behaviour or results observed; *models that explain why* that behaviour and

results occurred as they did, or *models that allow us to predict* future behaviours or results that are as yet unseen or unmeasured" (Dym 2004) .

The conceptual model helped to get a better understanding of the different types of margins and how they are related to the product development phases. The mathematical model in the other hand helped to highlight the relationship between the margins and their behaviour.

3.4.1 Conceptual modelling

The final part of the research aimed at supporting organisations planning complex product development processes during the early design stages and across the product development process. The literature review conducted an evaluation of existing product development modelling approaches and allowed an assessment of the main strengths and limitations of the different methodologies and tools.

To trace the development of margins throughout the design process it is important to understand the dependencies between components and systems. A Design Structure Matrix (DSM) was used to identify the connection between the components in the cooling system. A DSM is a square matrix that displays the interaction between sub-systems and the relationship between components. In order to identify the key connections and a reasonable level of granularity for the model, we worked with the cooling system team manager and another engineer from the team. To understand the potential change behaviour of the components, we used the DSM to build a change propagation matrix based on the change prediction method (CPM). This method evaluates the risk of changes spreading through a product; risk is the product of the likelihood of change propagation and the impact of change (Clarkson *et al.* 2004). The Cambridge Advance Modeller (CAM) was used as a tool for modelling the DSMs and CPMs models developed in this research. The CAM tool was used for visualising and identifying the key components and their relationships. This helped to identify patterns in the mapping between changes and margins.

3.4.2 Mathematical modelling

The company offers a wide range of truck variations and configurations. The product development process is aimed at creating platform based products, using common components and systems. This means that some components have large margins in performance with regards to the requirements of particular installations.

The fan is one of these critical components that are shared among different variants of a specific engine. The fan performance and parameters were studied to understand how margins on multiple parameters that need to be traded-off against each other. A MATLAB code was generated to simulate and illustrate the margins on fan's parameters. Further details can be found in Chapter 6 of this thesis.

3.5 Summary

This research aims at investigating the concept of design margins and better understanding the role of margins in the product development process. Through analysis of the current practice in handling margins in the company. The research aims at revealing issues and scope for improvement. The outcome of this research contributes to academic knowledge about the way design margins are handled in the product development process. Further, the research proposes methods to investigate design margins and a model to manage those margins in industry.

4 An industry example to understand Design Margins in the PDP

This chapter describes an empirical study into design margins carried out at Volvo GTT Sweden. The case study was carried out as a part of an industrial project between the Open University and Volvo Trucks Technology. The main purpose of the study was to draw attention to the concept of design margins. In the first stages, the objective was to review the product development process of Volvo Trucks and the wide range of products they are offering. Later the focus was on studying the concept of design margins and how these margins are added and / or used by designers during the product development process.

4.1 Background to Volvo trucks

Volvo was registered as a trademark back in 1915 and made their first truck in 1928, since then the group produces around 200.000 trucks each year. Yet, the average number of identical trucks is very small as the automotive industry is increasingly characterised by specialisation and customisation. Volvo Group is one of the world's leading manufacturers of trucks, buses and construction equipment. The Group employs about 100,000 people, has production facilities in 19 countries and sells products in more than 180 markets. The company has acquired several other brands including Renault trucks, Mack trucks and UD trucks in order to reach different markets. Figure 4-1 illustrates a range of Volvo trucks.

Figure 4-1 Range of Volvo trucks

The products developed by Volvo Group are used in different markets with different characteristics relative to operating environments, legislations, and transport missions. This fact, together with a tough competition, has led to a high degree of specialisation and truck customisation for individual customers.

The research work presented in this thesis has been carried out within the product development of Volvo 3P. Volvo 3P is a business unit within the Volvo Group in charge for product planning,

product development and the purchasing for the brands; Volvo trucks, Renault trucks, Mack trucks and UD trucks. Their interest in this project was to study the concept of design margins and explore the possibilities of using a framework to manage these margins in order to support the development process of their products.

4.2 The product development process at Volvo

The global development process in the company, illustrated in Figure 4-2, is divided into six phases. Each phase has different objectives that need to be met before proceeding to the next one. These phases are:

Pre-study phase: define the scope of the project, goals, directives, target description and requirements development, known in the company as prerequisites.

Concept study phase: analyse alternative concepts and select one for development. The concept is chosen through a process of market research, environmental impact assessment, and the business case.

Detailed development phase: define and approve the solutions to be implemented. This phase includes the technical feasibility study and freezing of the requirements.

Final development phase: the development phase includes developing, verifying, and validating the product solution. Market, aftermarket, manufacturing and assembly solutions are refined at this stage.

Industrialisation and commercialisation phase: is where the industrial system has to be installed, prepared and verified to enable production. At this stage the product and the aftermarket products are launched.

Follow-up phase: follow up the project target fulfilment, summarise the experience and close the project.
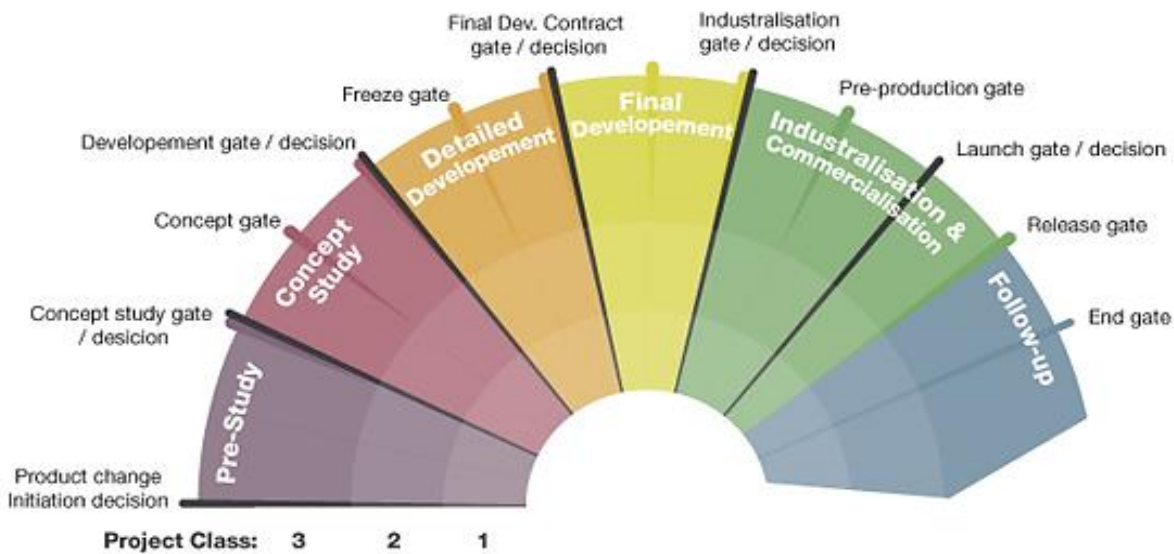
Figure 4-2 Volvo Product Development Process

This development process controls and coordinates design efforts and provides baselines guiding the development, production and operation of the system. Major technical and business reviews take place at each stage gate (e.g. Concept gate, Freeze gate, Industrialisation gate, Production gate and Release gate). Decision options at each gate normally encompass proceeding to the next stage, continuing or revisiting development activities of the current or preceding stages, putting project activities on hold or terminating the project as described in section 2.1 of chapter 2.

The goal for the company is naturally to satisfy each customer needs. On the other hand they also want to optimise their products and increase the profitability. Therefore, the company has developed a large specification database (variants) characterised by a broad scope for offering different cab sizes, chassis heights, wheel bases, powertrains and so on.

4.2.1 Product variants

In the automotive industry, the customer has to select his desired product design within a predefined solution space, but over and above that a large part of the product needs to be

developed according to the customer requirements. Similar-based product configuration represents a broad range of potential commonality (form and function) but could have a number of parts which are different. Since customers are different and have different needs, companies are required to design product variants in order to offer a wide range of product to satisfy customers requirements and to target different niches.

At Volvo, a truck is defined by what they call a *vehicle specification*. The vehicle specifications describes a vast variety of entities named *variants*, some of them represent physical alternatives such as the engine type, while others describe the functional ones, for example the type of road the truck will be driven on. Generally, a truck is completely specified by being based on a list of variants, in almost all cases, one variant from each variant family is chosen, based on the type of the truck. The truck specification, i.e. the list of all variants, can be viewed as the DNA profile of the truck.

Figure 4-3 gives an example of a truck specification each line is a code for a variant from a variant family. Some entries are highlighted to give examples of actual variants and variant families; these are explained in   Table 4-1

```
O4-TLV      FM 62R B  MAT-GREY  UXFUEL    ULADDER   SPOTP-R   UDECALTP
TMPF166     URUPP     UACMR     U1ACM     U2ACM     FFL1295   USPWCAD
UBULBKIT    ULAMPIN   UGAUGETP  UCHAINS   VERSION2  EMBL-TRP  WSTUD-S
UCROSSRE    RFE-T     UEGR      TYPE-FM   TP-DICON  ULOADIND  6*2
DASH-BLU    CABPT-R1  RIGID     RC-ROUGH  GCW60.0   CONC-BAS  UALARMB
ENG-VE13    VH4.4     WARNVEST  UBUNKBOX  UAIRBAG   EXHP-SAC  SUNV-SMO
APF-ENH     USIGNSWC  UCOMEQ    SUPH-TEX  SEATBRIA  AUXSW-6   WRITEPAD
USIGNS      TELECARD  UFUFIWH   STWPOS-L  RAA21T    DIMPLATE  UPAXLE
VW2600      MATT-PRE  FA-HIGH   FRAX-UNI  FAL9.0    FATYPE90  FAP3040
FAA10       TA-FIXED  RAL21     RADT-AR   RAP7340   LUGOP-BS  INST-MED
AUD-MED2    UADR      VERS-BAS  CHH-STD   BSR1365   URSTS     UCBRKTOW
UCBRKT      D13A440   VOLENG    ETOR2250  CHOSE-RU  EBR-VEB   BUGNET
RADI-NAR    VAL-BAS3  WTD-DUAL  UMRUP     UWCAP     CLUT-BAS  COOLC40
USPEEDDU    SPEED90   CRUISEC   FAN-VISE  UFUELFP   AIRIN-HI  FUELSEC2
FUELTFIL    UAUXFUEL  ULFUEL    RFUEL490  FUELTS71  TNK-SING  FTANK-AL
FCAP-L      MUF-HOR   EXD-VERR  EXSH-ST   EXSTH40   EAS-SCR   EM-ECO6B
NR-80EC     ACL1ST    URPLCR    ENGPROT   UPSCOOL   24V       TRANSF-H
UTRACON     UTABS     UACC      PHONE     LOWB-DAY  UFLASHL   HL-ASYMR
DETECT-S    HORN-ELS  SWS-RP    HORN-JER  HBAT-CF   ELCE-CK   BBOX-L
BBOXC-BA    2BATT225  UHOOKSC   UFMS      UADTL     RAG-ADBL  TWEETER
URTOLL      EST-AID   TL-BAS    MAINSW-M  FOGL-WC   DRIVL2    FUP-X1
UHLADJ      HL-CLEAN  UIMMOBIL  UIDLAMP   MARKL-SR  UALTTR    DOL24S12
RLIGHT-W    UWPREBOC  UWLAMP    BEACONA2  SPG-KM    ESUNV2P   ASCOP85
UPSCAT      SBD-BLAC  SBP-BLAC  EPTT650   CIRCP-F   TEMP-AMB  TEMP-TRA
```

Figure 4-3 An example of a truck specification

Variant	Variant family	Description of the variant
RC-ROUGH	Road condition	Badly maintained road
6*2	Axle arrangement	6 wheels of 2 driving
RFUEL490	Fuel tank at the RHS	490L right side fuel tank

Table 4-1 Examples of variants shown in Figure 4-3

A truck may have about 500 variants family, each containing at least two variants. Therefore, the number of possible configurations is very large; about 2^{500}. However, in practice, not all variants can be used, due to geometrical, functional and legislative constraints.

Design and development based on variants implies that the components need to be used optimally for a variety of transport missions. For example, a component may be developed for rough road conditions and 44 tonnes GCW (gross combination weight). However, this component may also be able to be used for up to 60 tonnes GCW if the road is classified as smooth. It might also be used for trucks with smaller loads, even if it would be over specified for these applications. Considering that, engineers will decide to support the standardisation of the components among different configurations in order to increase the payload and decrease the product cost. In this case there will be a margin in the GCW for a specific installation. Therefore, the company needs to understand the real cost of having such margins, but also the benefits, so they can make better decisions.

4.2.2 Product Features

Volvo manages product performance and product properties by what they call "Features", which covers everything from fuel consumptions and drivability to load capacity and vehicle safety. Volvo has 32 distinct features that they manage separately. The overall product offering is described in terms of features and variants. Features represent the customers' needs and variants describe the product offering from a technical point of view. The product offering comprises all allowed truck configurations, i.e. each single possible truck configuration that can be sold. Basically, the Variant Structure consists of building blocks, called Variants, and rules for how these building blocks can be combined.

The Volvo product offering is very flexible; each truck model comes in many different configurations. A configuration is as a combination of features. The most obvious features are those offered to a customer. When a customer orders a truck, a series of choices based on the

customer's needs is made for each available feature (Figure 4-4). The sum of the customer's choices becomes a specific truck configuration (order).
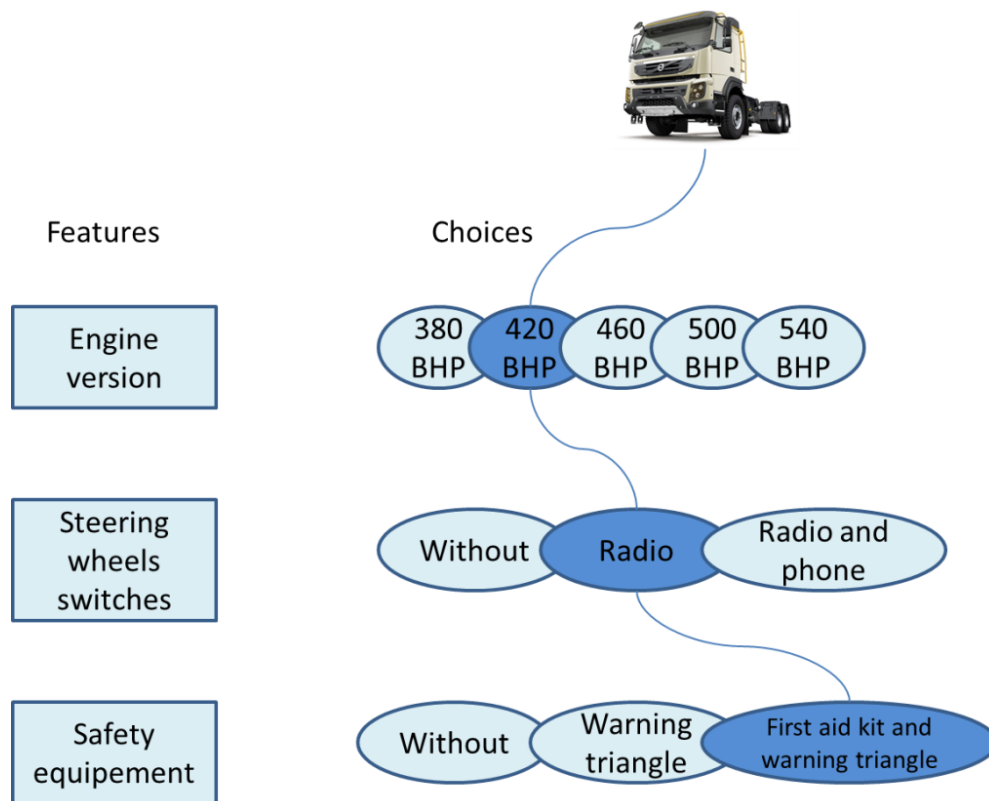
Figure 4-4 The customer's choices

Features are focused on customers and are set up to represent customer voice or needs rather than presenting technical specifications. Volvo decomposes features into 32 customer features, such as: durability, exterior noise, ride comfort, fuel consumption and so on.

For example the fuel consumption feature expresses the customer's wish to reduce the fuel consumption and has the role to assure that fuel consumption is minimised by translating this into technical features which should be quantitatively measurable. However, the measurable quantities are dependent on each other which implies that the feature requirements given by a design are not obvious from the design itself. Therefore, the margins that are potentially

associated with the features requirements can't be divided into independent measures, which can be individually controlled.

4.2.3 Product Platform

As discussed in the literature review, product platforms are developed in order to reduce the amount of redesign effort for future generations of products. Volvo uses the term platform for two different but interrelated concepts: commonality across the entire product offering and the option package offered for a particular model of truck. In both concepts the underlying idea of producing the greatest range of product from the smallest range of components is the same.

The powertrain technology is used across all the Volvo truck brands as well as construction equipment sold by Volvo. There is a range of engines with different properties for each truck tailored to different emission legislations and use profiles. At the same time the company aims to standardise parts across all of its trucks. This means, components that are used in multiple products must be designed to the criteria of the most demanding product or as they call it in the company designed for the worst case scenario, which may result in a component that far exceeds the requirements of the other models in which it is used.

The platform for a specific truck is the set of all components required to produce all the versions on the market. The product options are usually offered as option packages for particular types of trucks, such as truck with integrated trailers, trucks with separate trailers, logger trucks etc... Volvo also produces specific component to meet particular customer requirements but is trying to keep this to a minimum. The company also wants to reduce the number of these platform components to maximise production volumes. Producing an option package requires significant design effort because the company needs to assure that the options are compatible or at least be aware which options are incompatible. This is a matter of managing demands on space and understanding interferences between different product options. Eckert *et al*. (2014) argue that there is an inherent contradiction between an optimal platform, which offers the maximum range

of product options and an optimal product in terms of weight or other product specific characteristics.

The design of the product platform is largely driven by the production cost to be offer a product that can compete on the market rather than the design effort involved in generating them, which is often covered by other budgets.

4.3 Industry example

4.3.1 Introduction to the cooling system

The engineering example presented in this section is a complex product subsystem from the automotive industry; namely the cooling system of a truck. This system is subject to different competing requirements. The coolant system's main functionality is to cool the engine so that it does not overheat. However, the coolant system can also be used for heating; the heat transferred from the engine to the coolant is for example used in the cab heat exchanger in order to give the driver a comfortable temperature inside the cab.
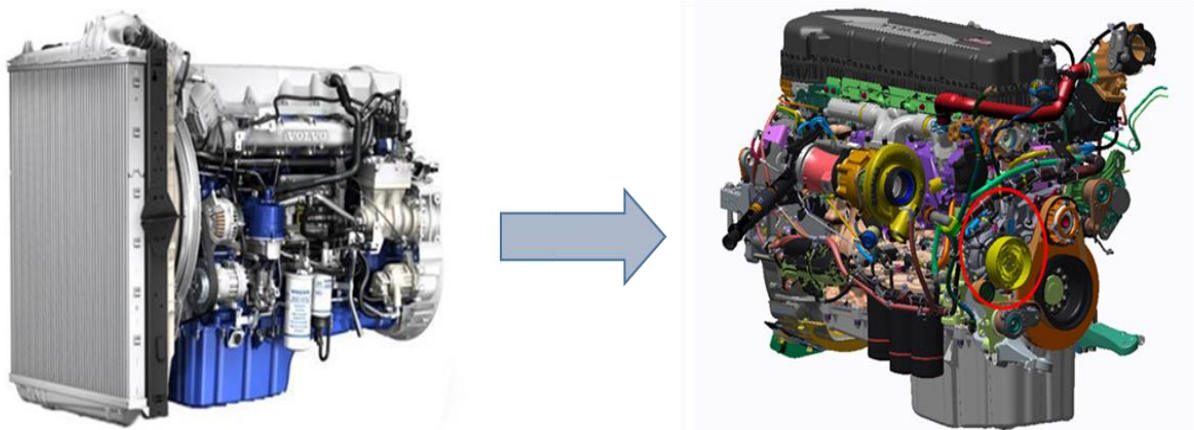
Figure 4-5 A truck cooling system

The cooling system (Figure 4-5) has tight geometrical constraints. It has the cab flooring on the top, on the sides are the chassis frame, the grille is in the front, at the bottom is the Front Underrun Protection (FUP) and the engine is at the back. This system was selected as a case study for the research because the company had a need for support with its development and because it is one of the systems that are subject to various constraints from different features and therefore a number of trade-offs were present.

Different engine specifications have different cooling needs. Generally, the heat that is produced in the engine needs to be cooled. This is performed by the cooling package which is the radiator and the fan. Fan performance is critical for an efficient cooling system.

Radiator

The vehicle's radiator is a big heat exchanger located in the front of the vehicle. It utilises the air meeting the vehicle when it is moving forward. The purpose of the radiator is to reduce the temperature of the coolant leaving the engine by about 5-10 degrees C depending on the driving conditions. The radiator consists of two tanks connected together by tubes. The coolant first enters the upper tank where it is distributed in the small narrow tubes. Across this tubular system, the air passes and cools the coolant. The coolant is then collected in the lower tank of the radiator from where it is sucked back to the engine by the coolant pump.

Fan

In many driving conditions, the air flow crossing the radiator is not enough to cool the coolant. This happens for example in hot climates, or when the engine is running for a long time without moving the vehicle. When this is the case, the fan, located behind the radiator, is engaged and pulls more air across the radiator.

Coolant pump

The coolant pump is the "heart" of the engine cooling circuit. The pump creates a pressure so that the coolant fluid is circulating through the circuit. The pump is usually 1 meter underneath the tank.

The coolant pump, as show in Figure 4-6, has different interfaces with other components. The coolant pump has a tight space constraint, but also a long lead time
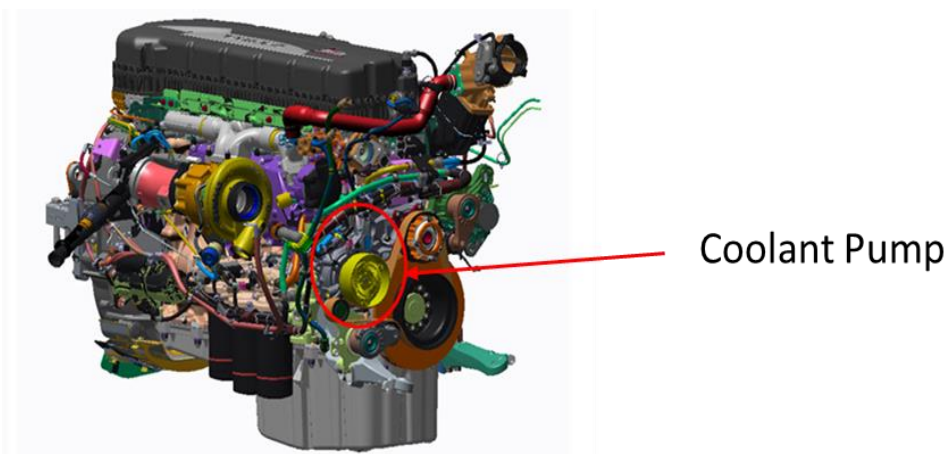
Figure 4-6 Coolant pump position in the cooling system

The coolant pump has many interfaces which are listed below:

Engine block

Belt drive with pulley

Coolant inlet manifold

Fan attachment for some variants

Block heater for some variants

Connection between the pump and the fan:

The fan is driven by the same belt as the coolant pump, however, there is no performance connection between the fan and the coolant pump. "*There is no performance connection*

between the fan and the coolant pump, there is only a mechanical connection that we want to get rid of…because we have to handle over dimension of the coolant pump bearing" K.J

The main requirements for the coolant pump are: the pressure drop in the system and the coolant flow that this needed. There is a ratio between the speed of the engine and the speed of the coolant pump.

Different components need to get the air flow, the key parameters for the coolant pump are:

Flow

Pressure drop

Absorbed power

Transmitted torque for different engine speeds

Coolant temperature

The pump suppliers are different from one product development project to another. However, all suppliers should have the specifications of the coolant used in the engine to verify the compatibility.

Designing the cooling system

At the beginning of a new project, a project prerequisite (this is a term used specifically within Volvo) is sent from the product planning team to the cooling system team which analyses the cooling performance needed for the complete system. The cooling need is analysed and broken down into requirements for each component.

When a new requirement is sent to the cooling module team (mainly from the engine developers in powertrain) they first consider two things: the size and the amount of the heat they need to cool away. At the beginning of the project they send a test matrix with all the tests that should be passed, to their suppliers.

The most difficult requirement for the cooling module team is the endurance (the capacity to resist extreme conditions i.e. worst-case scenario), which is identified by testing the truck.

Because engineers do not know at the beginning the final load on the truck and they do not know the amount of the air flow needed for the cooling until they have tested all components. "*The most difficult requirement for us is endurance... it is set by test truck so we don't know from the beginning the final load they will have on the cooling until they have tested cooled components*". J.B

"*…in the beginning of our project we use the old knowledge, we use loads from previous projects*". K.J

However, they can still make a judgement regarding the load, by simulation "*…You can always guess max load, so they can make a judgement of brackets. But it's tricky to make a good simulation of the connection between tubes and header plate and joint… joint is very tricky this is the point where it's usually fails, you really need to do the test and guess this is maybe better than that*". M.S. However, some other parameters might be difficult to simulate such as the temperature.

Some components are outsourced. Thus, suppliers play an important role in the design of the cooling system. The company has different suppliers for different projects and different markets. The component requirements, derived through analysis of the cooling needs, will be sent in the form of specifications to potential suppliers. A Request For Quotation (RFQ) is then generated and the suppliers make offers. The best offer is selected in terms of cost, quality and the requirements target. The components are designed by the supplier, pre-assembled for the module then assembled at a Volvo site. Hence, the suppliers can challenge the design. They might have a better knowledge about the component's capability than the company itself.

The cooling system is subject to many geometrical constraints which include: the size of the cooling module cannot be increased because on the top is the cab floor, on the sides is the chassis frame, in the front is the grille, at the bottom is the front underrun protection (FUP) and at the

back is the engine. "*…None of these are changed unless we do a major change to the chassis, cab or engine, which we do once every 20 years or so"* K.J

This inability to change is also due to the fact that some components and systems are used in several products over a long period of time. They may be used in several platforms and among different brands (models).

4.3.2 Margins in the cooling system

When it comes to design margins, the concept emerged in discussions of engineering change and the process of making the change. For example if powertrain send a change request regarding the engine temperature, the engineers start to think about alternative solutions, *inter alia*, margins that could absorb this change *"...Let's say powertrain says we allow 3more degrees maybe the expansion tank volume is not good enough maybe we need to increase that, then we will start asking the supplier what do you think can we cover 3degrees, if they say yes immediately then we do nothing , then if they say am not sure ... okay…what kind of test do we need to do or simulation then if its critical we must figure out what kind of change do we need to do to meet the new requirement, we will have to take it up with the concern of the supplier because we have signed all targets that are related to durability or endurance so if it is the case we would increase the temperature ..."* M.J

Design margins are also discussed as a form of overdesign. At the beginning overdesign is seem as a mean of controlling future development cost and risk, which arises from too much innovation in each product generation and as a means to make sure that the product will work reliably even if it is not used in the originally intended way. Chapter 5 discusses the types of margins in the company in more details.

4.4 Summary

At the early phases of the product development, there is a focus on long-term development by making sure that the company is designing systems and components that can be reused. However, when a project is launched, the focus becomes more on designing cost efficient products and the objective becomes to optimise individual components by taking out design margins.

The aim of this study is to understand how design margins shape the design process. Because when there is a margin either you don't make a change or you might change some parameters where some margins remain.

A key aspect in understanding margins is to know what a component can do now and what it can do for the next generation of products. However, the dependencies of features across the system and the product complexity make it hard to capture margins which are specific to different levels (product, platform, system and component).

In a company that adopts a product platform strategy, where a high variation and a high number of configurations are the main characteristics, there will be attention to components and their design. It becomes necessary to consider the margins on components.

5   Margins across the Product Development Process

The study conducted in the company aimed, in the first phase, to study the concept of margins and how margins are added and used by designers. The next phase of the research demonstrates that margins on components profoundly affect how a design process is carried out. We argue that designers look for components or subsystems with margins, which are not frozen, to accommodate changes and analyse design alternatives. This chapter describes that process.

5.1 Design margins and the design process

The design process has been the focus of research for many years. There are a number of design models and methodologies available in the literature (Chapter 2). Almost any product, such as a washing machine, a mobile phone or a car, requires input from stakeholders of many disciplines, including product planners, engineers, designers and this requires considerable co-ordination.

On the other hand, finding a satisfactory solution to a design problem is an iterative process (Wynn *et al.* 2017). As the solution to a design problem evolves, engineers continually refine the design by adding or removing design margins. While implementing the solution to a design problem, they may find out that the solution they have developed is not feasible, too difficult to implement or too expensive. They then go a step back and modify the solution until it meets the requirements. However, the study carried out at the company showed that there is no explicit documentation of the co-evolution of both requirements and design solutions at different levels of the product's hierarchy throughout the product development process. Moreover, the way engineers and designers use margins is not recorded explicitly. In this research, we are proposing a method to capture this tacit knowledge and to investigate design margins.

5.2 Concepts of margins in the company

Volvo wants to optimise their products in order to reduce their cost and their lead times by increasing the commonality among different installations and several brands. Thus, systems and components can accumulate significant margins when they are used in different product variations. For example, the company uses a limited number of sizes of cooling fan (concentrating on two main sizes) across many engine variants. This means that some trucks

which are operating in cold environments for example will rarely need the capacity of a bigger fan.

From the case study conducted at Volvo and after analysing the obtained data, we noticed that for most engineers and designers, margins are implied rather than an explicitly stated concept, for example the fan module manager said *"…And that is one of the dilemmas in engineering is very much … you need … a significant part of the workforce managing information throughout the business,…, and we're very poor at that.."*

Margins are considered by different groups in the organisation, who use different terminology. Different groups are not necessarily aware of the margins other groups have added. Margins are added both to the requirements that are given to the designers and to the design itself by the designers.

5.2.1 Changing terminology across the product development process

The main objective at the beginning of this study was to determine some of the vocabulary used around margins with the aim of developing a definition for margins which is compatible with the language used in the company. For this, eight interviews were conducted with ten engineers from the Chassis department. The interviewees were selected to cover different phases of the design process (Chapter 3 gives more details).

Each session was recorded and the conversations were transcribed for analysis. The questioning was relatively general with each person initially asked to describe their role. As the interview progressed, the questioning focused more on design process and in particular on design margins. The analysis started with a transcription of the recorded interviews (see Appendix A, for a transcript example). Although the transcription exercise is a time consuming it enables the investigation to get familiar with the context and the content of the interviews. The process of translating the raw data to findings requires interpretation of empirical data. The interpretation

of the data was made through a coding method (Chapter 3), conducted by distinguishing different themes and concepts found in the data. This involved analysing the interview transcription (e.g. a sentence or a paragraph) and summarising the quotes by the use of categories such as platform planning, product development and production. Once these pieces of data are regrouped based on their relevant content categories, the second stage is the interpretation of categories. The process is described at the end of Section 3.3. and Figure 5.1 summarises these findings.

The interviewees discussed margins and concepts related to margins. They used different terminology and that was an underlying issue. The following terminology was used in discussion of the concept of margins:

Room for manoeuvre or future growth: Engineers and product planners talk about margins in terms of a room for manoeuvre or a room for growth mainly when it comes into planning for the next generation of products. They focus on major systems or sub-systems, such as powertrain, which are common across the different brands. To manage the design effort, as well as the cost and risk associated with new designs, engineers plan a small number of "fine-tunes" to systems in each generation. Each new design requires modifications or changes to the existing systems and variants to accommodate them. For example, when a new technology is available, such as new types of fuel or hybrid systems the company explores when and whether they can be introduced into their trucks. They estimate the demand on other systems arising from these technologies and schedule the changes to these systems accordingly. Therefore, they look for systems that can directly support the new technology or the ones that need to be modified in a way that will only require small changes in a future generation. It also enables them to plan margins into systems that are designed to avoid unexpected major redesign on systems.

Room for growth is a term mainly used by product planners who are involved at the early stages of the product development process. They mainly think of margins when they need to predict which systems or components need to be changed to meet new sets of requirements.

Overdesign: Designers tend to overdesign some components or systems when they are uncertain about the final technical solution or cannot accurately predict the final performance of the product. Consequently, they add some margins to cater for uncertainty especially at the early stages of the development process, in order to avoid having a major redesign later. *"Yes, we overdesign but after the project start, we try to optimise the tubes for example ...we can see that we have the possibility to down the size of the tubes to save cost"* (J.B).

Overdesigning components or systems against some sets of requirements is also seen as a measure of assuring maximal product commonality across the product platform and therefore a way of reducing production cost; especially when the company are merging brands. However, as the development process unfolds, the overdesign is seen progressively as a source of cost. The manufacturing engineers therefore look for components or systems that they consider overdesigned, and target them to cut down the production cost of the current generation of products. Hence, the way overdesign is considered is different at each phase of the development process. At the beginning, the engineers think that overdesigning some components or systems can help them cope with the uncertainty and/or risk associated with the product development, whereas towards the end of the process, overdesign is seen as a source of cost that it is necessary to minimise.

Safety margins: To design a truck a large number of objectives are considered. The company tries to meet the customer requirements by developing the right vehicle for the specific mission. However, they can neither monitor nor control how the trucks are actually used or potentially misused. For example, if a truck is delivered to an European market where the weather is cold

with a good road condition, but the company cannot stop a customer using the same truck somewhere in the desert where the weather is very hot and the road condition is poor. Therefore, the company plans in safety margins, both in terms of safety against failure and misuse by customers but also to cater for future changes. "*In one way, it means that since you don't know exactly how the truck will be used you need to consider a certain safety margin. They call it safety margin at school but we don't use that word, but what we mean is that in certain systems you need to be very sure that they don't fail*". (P.J)

Not all safety margins are added explicitly as an addition to explicit requirements. Some properties of the product are difficult to quantify, in particular those associated with product features. The specialist feature engineers make generous estimation of the values to give high likelihoods that the products can achieve the desired overall performance.

In the interviews, engineers used "*safe*" in two ways. First, it meant the safety of the truck in use and second, that the design engineers themselves can be assured against changes to components or systems. Therefore, they tend to add a "safety margin" to cater for this uncertainty. This is an example of an ambiguous use of terminology in the company and raised the risk that margins are added many times as engineers and designers miscommunicate and misunderstand each other's intention. For the purpose of this thesis, the term safety margins will be used as margins on requirements.

The capability of components, systems and products is often not known, because the effort in testing is concentrate on at meeting the requirements. Only destructive testing would reveal the limits of capability of the product. However, this could be simulated. Virtual test data is also available earlier in the development process, so that it is possible to consider margins explicitly earlier in the design process. Even virtual testing is limited by the number of the scenarios that can be tested. It is only possible to test against known unknowns, therefore there is a residual

risk. Testing for the actual capability could reveal margins which would allow companies to optimise the product further.

Tolerances: which are added to components for manufacturing variability and robustness.

Clearances: A specific type of margin considered during the design phase of a product is clearances around components. These are considered by the design engineers either as margins of components or as components in their own right. Clearances refer to the physical and geometrical domain. They often exist at the interfaces between different systems or different components, and ensure that parts have space to bed assemble together in a mass-production context. For example, the radiator is allocated a defined space at the front and beneath the truck cab. The space that is not occupied by the actual radiator then becomes a clearance.

Clearances are important in managing engineering change, because having clearances means that a component's dimensions can be changed if necessary, using up the clearance without the change propagating to the other components. Therefore, they can fulfil this function of absorbing change while being at the same time allowing the design to be sensitive to the impact of interchangeability and manufacturability of parts.

Design margin: Designers add margins to their components to avoid making changes to the component later in response to emerging changes in requirements, in changes to their knowledge of capability through testing or in available technologies. Designing margins into the product gives design engineers flexibility later in the design process to meet different requirements, particularly those arriving from requirements for new product options that are added at the later point in the design process. "… *The margin that they want to have a bit more extra than what they need…. Because this is question in the future which is something we need to trade how much… sometimes you need to see to down size do they really need these huge engines*" (S.E). Design margin as a term is often used by designers interchangeably with safety margin.

However, the emphasis of a design margin is to allow flexibility in the process of design. A design margin allows for uncertainties in the design itself. For example, engineers may not know exactly how a product will perform until after tests have been completed and build in a design margin early in the process. Further, design engineers may envisage that it may be necessary to change the design in the future, perhaps to meet new requirements or incorporate new and emerging technologies. For these possibilities, they might introduce a design margin. As noted above the emphasis of the safety margin is on requirements and indeed the safety margin may be expressed directly in terms of allowances to cover uncertainties on these requirements.

Figure 5-1 illustrates the changing terminology at different stages of the product development process.
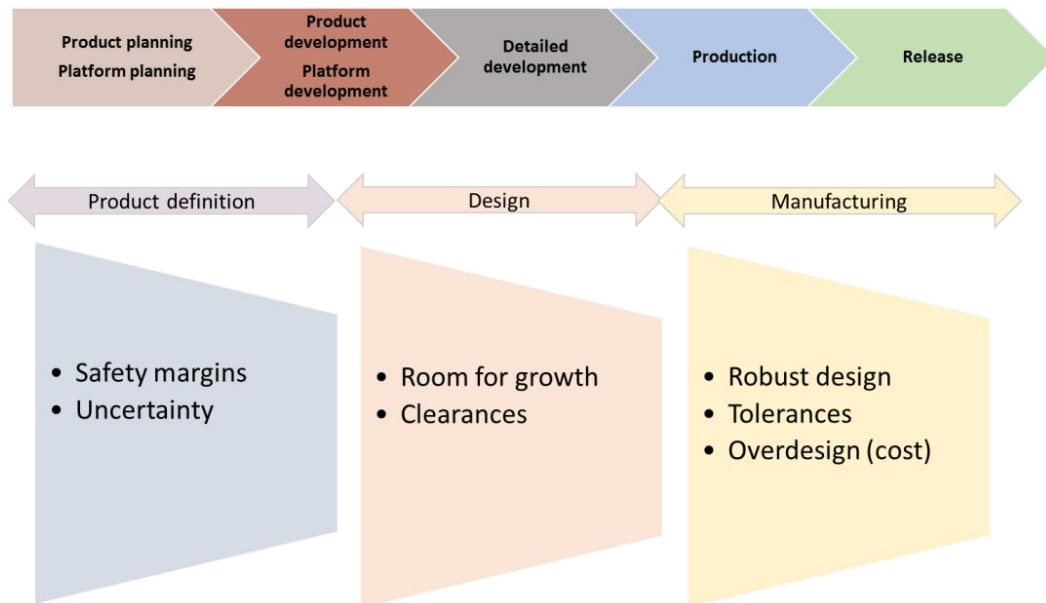
Figure 5-1 Margins related terminology throughout the product development process

This diversity of terms also contributes to margins being hidden from people in other teams. At the beginning of the product development process, the main concern is understanding existing margins of components and systems scheduled for reuse and specifying the need for future margins to avoid changes in future developments. In the organisation two interrelated but parallel activities occur: product planning and development and platform planning and development. The planning of the platform occurs both before and after the requirements are set. Steps in a platform development can be set as requirements or can be responses to the range

of requirements that the company is confronted with. Safety margins are added to the requirements once a fairly clear picture of the needs has emerged. Design margins are planned as soon as the requirements (including the safety margins) are known. During the design of a component or a system the discussion of margins is wrapped up in assessing engineering change and the risk of change propagation. Designers are also taking active steps to avoid changes by designing flexibility into the details of the systems. Margins are seen as a positive way of managing design effort. However, as soon as the product definition is finished and the product is tested, margins are seen as a source of cost and engineers look to remove the associated overdesign.

They also talk about tolerances in the context of robust design. Yet, margins are more than tolerances, when robustness is essentially associated with manufacturing tolerances delivering the required levels of performance. However, robustness can be interpreted more widely, especially in terms of the performance against a range of requirements. In this wider sense margins (i.e. safety margins) and robustness are similar.

There were also many discussions around the commonality of components in systems versus efficient platforms and in particular when the products have some components which are overdesigned for particular installations. This is a clear example of design margins. These product platforms could be developed for a determined life, or be evolutionary in design to incorporate changes over time. The main outcome of this first study was that margins are additive. Some engineers might add a safety margin to a system, other designers might add design margins as room for maneuver for future changes that they might foresee while other may add manufacturing tolerances. As they do this design engineers can accumulate several different margins as they proceed through the stages of product development.

Designer engineers may not be particularly aware of the margins that have been added to the requirements as opposed to the margins that have been added to the components above the requirements. Figure 5-2 gives a simple illustration of how margins can potentially be accumulated throughout the product development process.
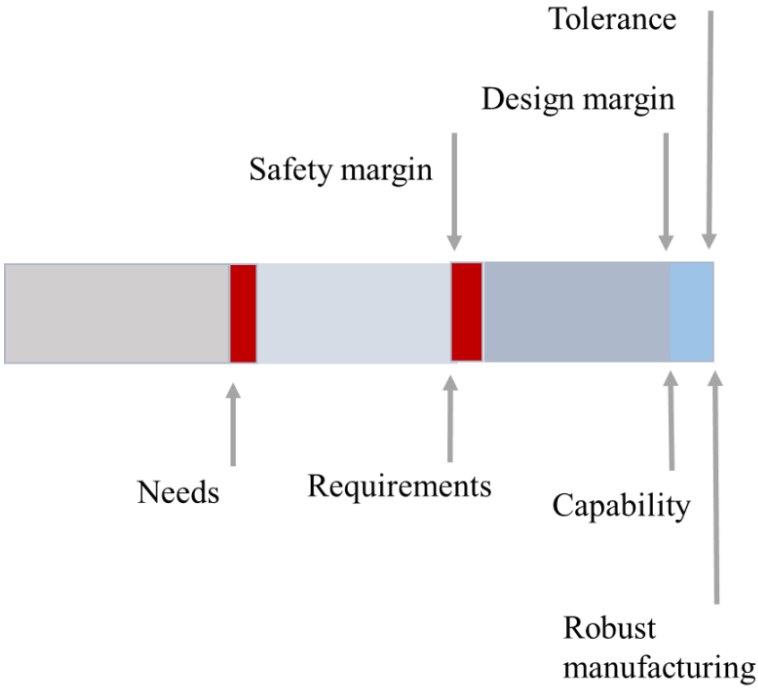
Figure 5-2 Cumulative margins

This accumulation, is a result of margins being added and /or used up across the product development process, without necessary, all teams that are involved in this activity being aware of what their colleagues have added or used. This can result in components or systems being largely overdesigned, which potentially adds extra cost to the product. As mentioned above, explicit overdesign occurs at two points (marked in red in Figure 5.2); as a room for growth for future generations during the product definition phase, and as buffer for changes arising from changes in the requirements at the beginning of detailed design. As the product reaches the test phase, the features that are identified as overdesigned to meet uncertain requirements in the

product definition phase do not necessarily reveal the extent of their overdesign. This is because such overdesign types of margin can rarely be quantified exactly since testing of components, systems and products is usually conducted for compliance with the requirements rather than tested to the limits of their capabilities to see by how much they exceed the requirements.

5.3 Formalisation of margins

Design problems are often vaguely defined by comparison with analysis problems where there is only one answer. When conducting the case study in the company one of the engineers stated "*We know how to do things but it is challenging to describe it in an abstract way*", also "*If I have a problem I know how to solve it or I don't have a clue, I know at least whom to ask to solve it*"(P.G). The research carried out at Volvo GTT, which is described in Chapter 4, indicates that the knowledge about the way design is carried out is tacit.

Different teams are typically working in parallel on different aspects of design, which are integrated through several loops of convergent iterations ((Eckert *et al*. 2001). During these design iterations, key requirements and key parameters can still change significantly requiring others teams to accommodate these changes. Anticipating potential changes during the design process is a key element of managing the risks associated with those changes. The work presented in this thesis addresses this problem in terms of design margins and argues that design margins are an active mechanism to improve the efficiency of the development process.

The design activity of a system or a component can be described with regards to four main concepts described as follows:

Constraints: the values parameters should not exceed. Constraints are the controlling elements which define an envelope for the total design activity.

Capability: the value a design parameter could reach regardless of a specific requirement or constraint (what the system/component *can* do).

Requirements: the values parameters must meet in order to get the desired solution. (what the system/component *should* do).

Technical solution: the final values parameters will have at the end of the design process. This represent the solution that will be implemented for a particular design problem. (what the system/component *will* do).

Margins in the design process can be defined in relation to these concepts. Margins can refer to a simple parameter p or vectors of parameters $P = <p_1, p_2 \ldots p_n>$. This gives the pattern of margins in a component or a system, which is described below. The following discussion will refer to a "must be exceeded" scenario, i.e. the capability of the system must exceed a certain value. For example, the truck must carry at least a load of X kg. In practice, many requirements are phrased as "must not exceed". For example, the engine temperature must not exceed Y Celsius. The two cases are analogues and only the must be exceeded case is dealt with here for simplicity. The first type of margin M(P) on the parameters P, represents the difference between capability of a design and the requirements it is intended to meet.

$M_1 (P) = Cap (P) - Req (P)$

The margin of a component or system is expressed as the difference between the values of the parameters representing the capability (Cap(P)) of the component and the values of the parameters Req (P) which would enable the component to meet the requirements. This is illustrated in Figure 5-3.
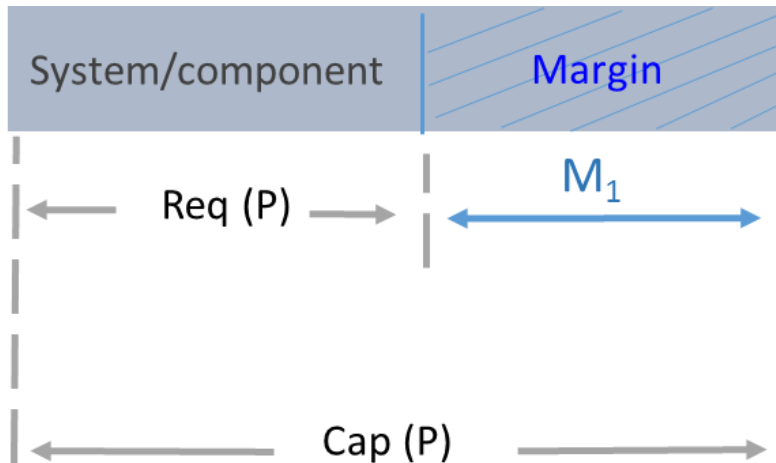
Figure 5-3 Margin M1 between requirement (Req) and capability (Cap)

The second type of margin recognises that parameters are subject to constraints. If the product parameters are constrained to exceed the values for the constraints $Const(P)$ and the product actually has capability represented by values $Cap(P)$ of the parameters, then this margin $M_2(P)$ represents how much the capability exceeds the constraints as shown in Figure 5-4

$$M_2(P) = Cap\ (P) - Const(P)$$
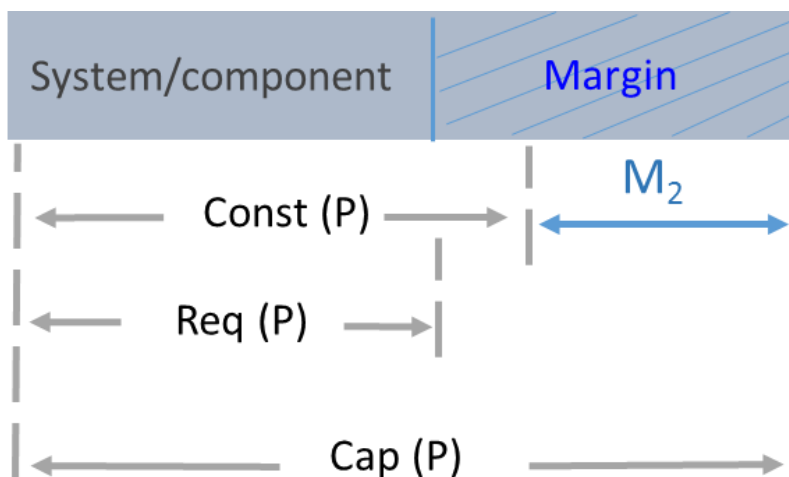
Figure 5-4 Margin M2 between capability (Cap) and constraints (Const)

The third type of margin considers the case when there are not-to-be-exceeded constraints. In this case, not all of the capability can be used and the margin is reduced to the difference between the values for the parameters Const(P) and the values corresponding to the requirements Req(P).

M_3 (P) = Const (P) – Req (P).

In situations where the component or the system is subject to both requirements and not exceed constraints on the performance, the usable margin of the system lies between the requirements and the constraints. This is illustrated in Figure 5-5.
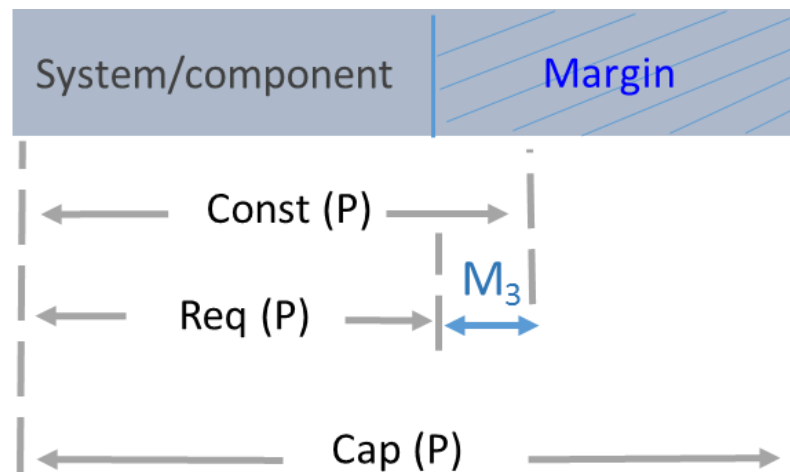
Figure 5-5 Margin M3 between constraint (Const) and requirement (Req)

If we consider a simplified example. In the design of a computer desk, suppose we assume that the desk can carry a load of 100kg and the customer requirement is for a desk that can carry 80kg. The margin in this case will be M_1 (P) = Cap (P) - R (P), M_1 (P) =100-80=20kg. The same design can be constrained by the choice of the material used to build the desk. If the customer prefers to have a light desk that he or she can move easily, the designer will have to choose a material which is light but strong at the same time so it can carry 80kg.

The way different parameters combine depends on the nature of their relationship, most of which will be governed by the underlying physics in the product. However, we can detect recurring patterns of margins

Min/max margins, where the overall relationship is governed by the smallest or largest member. This applies for example to clearances, where one would intuitively think of the clearance of a component or system as the smallest values.

Additive relationships, where all the parameters accumulate and only the total is more important. This applies to weight for example.

Key equations, where many parameters influence the final outcome, the overall value is basically the result of a small number of key parameters that can be expressed in relatively simple equations.

In any system the margins are interrelated, performance margins arise from the relationships between different parameters, which each have their own margins arising from either constraints or requirements. System margins results from components and sub-systems being put together, which in turn have their own margins. However, the margins do not decompose or aggregate in a linear way as implied by the nature of the different relationships among the parameters. In particular, as margins are hierarchically composed or decomposed, margins can be gained or lost through the ways they are combined.

5.4 Design margins and uncertainty

At any stage of product development, the evaluation of performance is to an extent uncertain, depending on the maturity of a design proposal as well as the resources and tools employed in evaluating the proposal. These uncertainties push designers to add margins, as allowances made in parameters, in order to provide high probabilities of meeting functional requirements.

However, an important point to note is that although design margins can exist above these limits, margins can also be created or increased by reducing uncertainties, for example by better models, more exhaustive simulations or physical testing of components and prototypes. Hence, uncertainty tends to decrease as the product development process progresses.

Margins can be considered as consisting of two elements: a buffer B, which allows for uncertainties, and an excess E, which can be used to meet possible new requirements. This type of excess margin is primarily concerned with operational capability and performance rather than predominately with design as is the case with future growth.

$M_i (P) = B(P) + E(P)$.

This view of margins relates into the concept of excess introduced by Tackett, Mattson *et al.* (2014), which addresses margins from the perspective of how a given design can be upgraded. They identified margins in terms of excess, as the "the quantity of surplus in a system once the necessities of the system are met", while acknowledging that product design is subject to uncertainties. By reducing the uncertainties on a component, for example by conducting tests and understanding the capabilities better or by understanding the use profiles better, designers can reduce the uncertainty a component is subject to and therefore increase the excess on the component for a given margin. The excess is the part of the margin that designers can make use of, for example to deal with changes or increasing requirements. For the margin M_1:

$Excess = E (P) = Cap (P) – B (P) – Req (P)$

Product parameters may have buffers, which are not immediately usable in design but offer the potential that they can be reduced and release tangible and usable margins. These offer options for meeting higher levels of functional requirement or optimising product parameters against existing functional requirements. On the other hand, changes in requirements are inevitable

during the design process and this is difficult to manage for companies developing large technical systems, such as cars, trucks or jet engines.

While many requirements are fixed at the beginning of the product development process, others change during the process due to the dependencies between components and systems in the product. An important finding from this research was that lack of knowledge about the level of uncertainty around requirements and other design variables, particularly those communicated by one project team as inputs to the tasks of another team (e.g. product planning to design team), creates communication and management issues for the company. For example, the designers of the cooling system start their activity with an assumed engine temperature as a key requirement. This temperature can however change during the design process due to the changes to details of the engine or the use profiles considered. However, at some point in the process the engine temperature is frozen and remains fixed for the rest of the process.

Moreover, regarding design margins, we found that there is a lack of quantitative knowledge characterising margins which in most cases raised many questions for engineers and designers. These design margins are empirically selected, that is, they are specified based on experience and/or standard practice and not through a theory or systematic methods.

5.5 Margins as a crisp value vs margins as a range

Designers need to deal with several uncertainties, before defining the physical characteristics of the truck design best capable of satisfying a certain set of customer requirements. To provide some protection against those uncertainties, designers tend to anticipate those uncertainties by adding a design margin. For example, the product may have the structural strength to carry more load or a system may have enough space to accommodate an extra component, thus increasing the product capability to meet new requirements or to compensate for uncertainty.

In the case study presented in Chapter 4, designers attempt to design for what they call the worst-case scenario. In this scenario, for example, the temperature for which a cooling system is being designed is a single value obtained from simulating the worst-case scenario. The truck is generally used in a drive cycle and the variation across the cycle of the heat that needs to be transferred by the cooling system is quite large. For example, consider the variation between a truck driven in a cold climate on a flat road where the heat that needs to be transferred by the cooling system is low compared to another driving condition where the weather is hot and the roads are rough. Therefore, designers use simulations and take into consideration one, worst-case, operating condition which is going uphill (hence at slow speed) and running the engine at 100% capacity. These extreme driving conditions give them the maximum amount of heat the cooling system needs to transfer. However, if for a specific Engine A, the required temperature (for the ambient air) that needs to be accommodated is 38°C but they take a design variant that can accommodate 46°C, which satisfies the requirement for the worst-case scenario (WCS), the Engine A would have a margin in a normal driving condition (Figure 5-6)
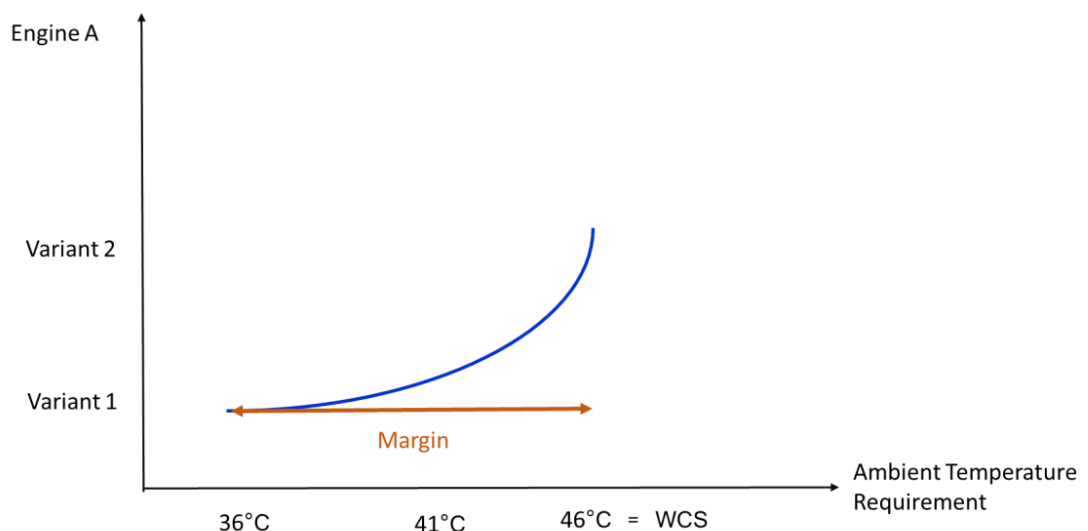
Figure 5-6 Margin arising from the consideration of the worst case scenario requirement

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Moreover, some design variables that are communicated by a design team and used as inputs to activities performed by other teams are imprecise. Design imprecision is a form of uncertainty formulated in the literature (Wood *et al.* (1990), Antonsson and Otto, (1995)) to express uncertainty in decision-making during the design of a new product, especially at the early stages of a design process where engineers and designers have not yet acquired sufficient knowledge to decide what is the final value that a design variable would have. Moreover, at this stage, requirements are not definite and are often subject to change. Therefore, engineers work with a range of alternative values for design variables and explore concurrently different concepts for systems, sub-systems and components.

For example, consider the case when the requirements for which a truck is being designed is not a single known value but rather a range of possible values forming a distribution having a mean µ and a standard deviation σ. The capability of the system to carry that probabilistic load is again not a single known value, but a range of possible values forming a second distribution. This can be seen in Figure 5-7 which illustrates the relationship between requirements, capability and margins. There are two capability distributions. The one on the left is the capability of an existing variant whilst the second represents a redesign of the variant with an enhanced capability.

Engine A
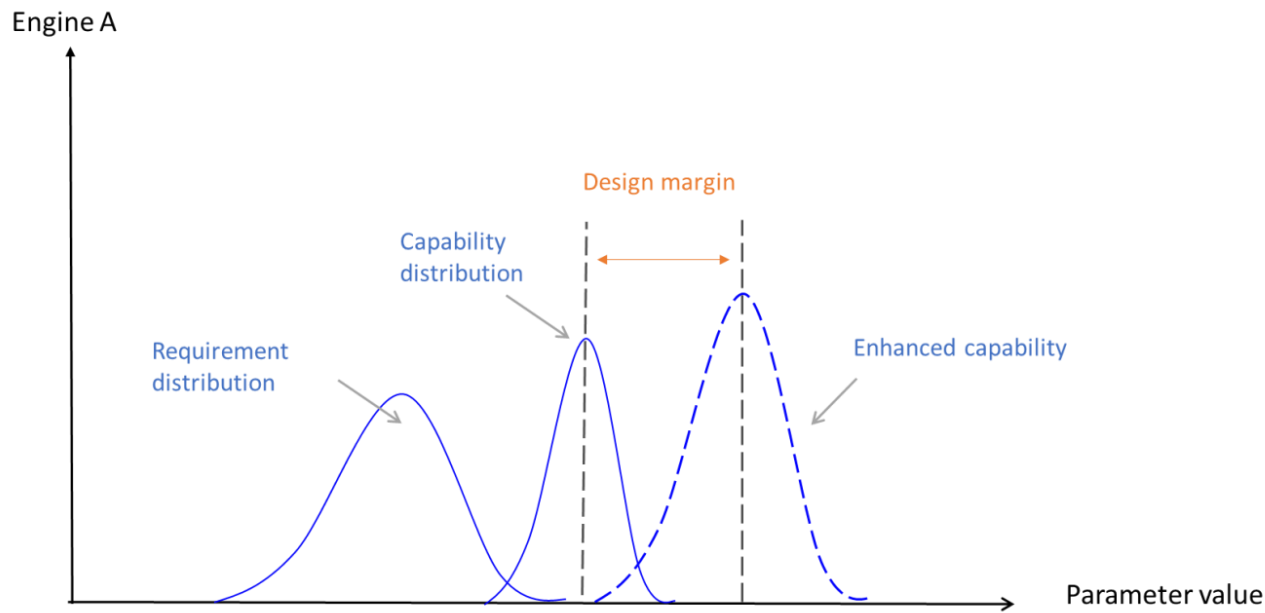
Figure 5-7 Relationship between requirements, capability and margins

Therefore, the probability that the system will meets its requirements can be increased by considering what the design can do to meet the customer requirements and moving the two distributions further as shown in Figure 5.7. The design margin as shown, is effectively added to enhance the probability of meeting the customer requirement.

However, in the company, the capability of a design is not defined in absolute terms, but rather as the capability of a system to work under specific conditions. This makes it difficult to capture the accurate relationship between requirements, capability and margins. In the case of the engine temperature for example, the capability is expressed in terms of requirements, i.e. the engine should not overheat after a certain use time.

On the other hand, trucks have different use profiles, they operate under very different operation conditions from smooth, rough to very rough roads and cross country. They also operate under different temperature ranges from less than − 40 to over +50 degrees C, so that many

components need to be heated or cooled even though they would not need this under most circumstances. Thus, to meet the customer requirements a combination of many parameters needs to be considered (Figure 5-8).

In practice designers consider the extreme situations under which a truck should perform. For example, using the air conditioning at a full blast, stop and go driving in a very hot day, can raise the engine temperature above normal. Still, the driver should be able to deliver his cargo, without sustaining long term damage to the truck. These extreme situations correlate with the Worst-Case Scenario (WCS) which are concrete and detailed scenarios that help the engineers to think through potential failure modes. For example, engineers and designers will think of driving a fully loaded truck up a mountain road, like the Sierra Nevada, with a constant slope, in hot summer days, with stop-start traffic. This is similar to what was introduced in the literature by Taguchi and Clausing, (1990) and defined by Clausing, (2004) as the Operating Window which they consider as the boundaries of a critical parameter at which certain failure modes are excited. Therefore, the road conditions mentioned in the example above can be considered as an operating window, since they consider the worst scenarios (high values) which lead to one failure mode and other scenarios (low values) lead to the other failure mode. Hence, designers choose a design to maximise the operating window, i.e. they respond to the worst case scenario.

To minimise variety in the product platform many components have traditionally been designed to take the highest demands coming from worst-case scenarios. For example, systems like the fan are generally overdesigned for some installations. Design engineers address this range of possible scenarios, and therefore a range of parameters by considering one point which is the worst-case scenario, which might generate margins for some applications later on in the development process. On the other hand, to be able to more accurately and optimally set the limit of the use of components and their reliability, all external parameters such as temperature,

are virtually tested by simulation and compared to running time/ running distance up until failure occurs. Even if the choice of material, dimensioning and performance is adapted to each transport operation's driving condition and load condition (Figure 5.8), some components are used in different products, therefore some these components will only have margins for some installations. For example, a component in a truck might be designed initially for a rough road condition and 44 ton GCW (Gross Combination Weight, which determine the total weight of the truck). However, the same component might be also used in trucks with a GCW up to 60 tons, if the road is classified as smooth.
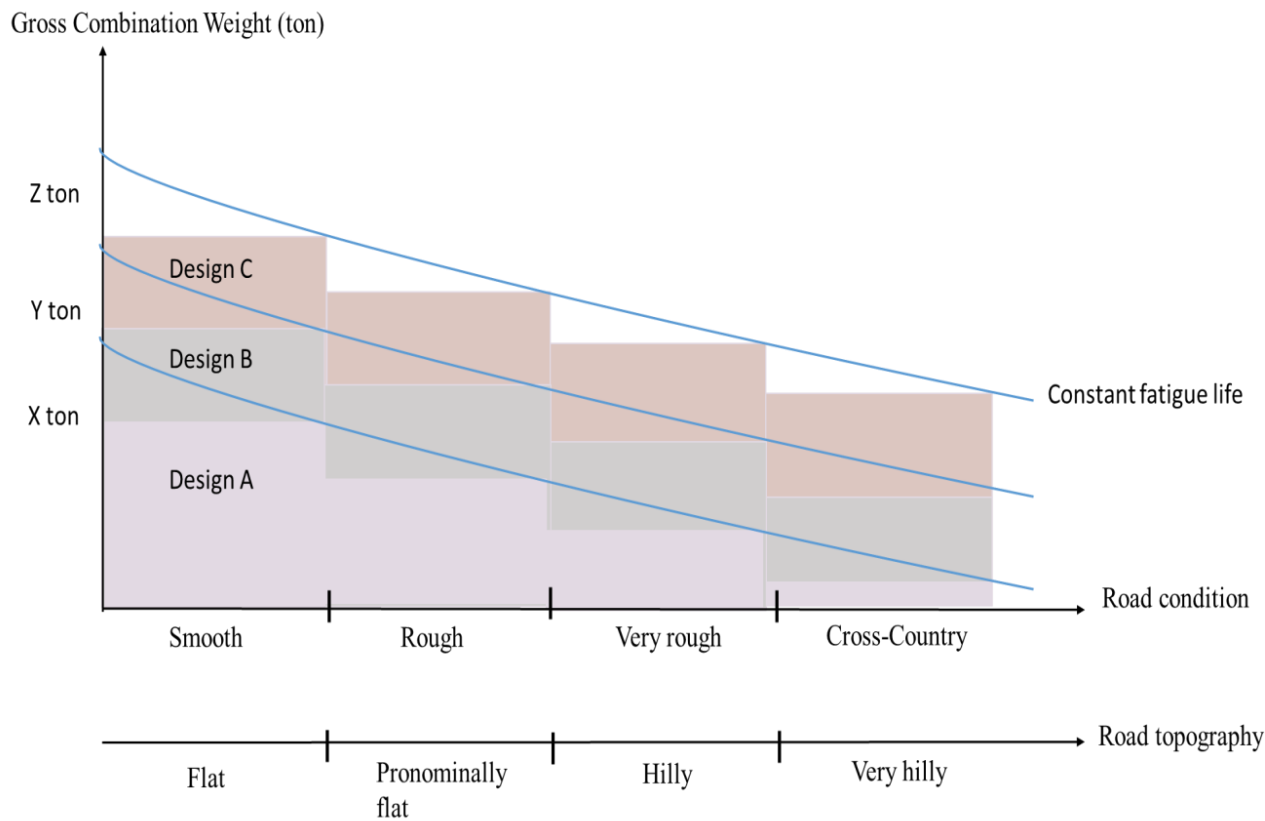
Figure 5-8 Combination of different requirement's distribution

To assess the values given to the worst-case scenario, and to make sure that the design will meet the customer requirement, engineers and designers rely mostly on virtual testing (Tahera *et al.* 2012). These virtual tests or simulations are a form of design analysis, which uses the virtual models of components or systems to test different scenarios. These tests can give an indication where margins might be hidden and have the potential to be an effective way to identify margins. However, since the majority of these tests are virtual, margins may be underestimated through this process. The company does not test a product until failure. This can be problematic for engineers as they might not be able to quantify some margins and can be surprised at later stages in product development. This is a particular issue for the outsourced components. Suppliers test their components and guarantee that the component meets the requirements, but they might not tell their customers by how much. In some cases, even if the suppliers are aware of the margins they have, they do not necessarily communicate them. In this way, they might still be able to sell the same or slightly different components for the next generation of products.

5.6   Design margins at different phases of the design stage

Margins arise at different stages of the product development process, especially at the design stage. At the concept design phase, when engineers are uncertain about some requirements or the final performance of the product, they tend to put margins on some parameters to provide high probabilities of meeting the functional requirements (Figure 5-9). This type of margin can be seen as a buffer, which is used to cater for uncertainties resulting from deficiencies of knowledge. As the design state evolves over time and becomes more detailed, designers are able to reduce uncertainty by conducting tests and therefore they get a better understanding of the components capabilities or by evaluating the conditions of use. Reducing the uncertainty that a component is subject to, allows an increase in the excess on the component. The excess in this

case is the part of a margin that the designers can make use of to deal with changes. At this stage, it becomes possible to respond to the worst-case scenario in a different way and thereby limit redundancy in the product.

CONCEPT DESIGN

- Most of the requirements are defined
- Some of them are not well known (use of the WC)

Buffer to cater for uncertainty

DETAILED DESIGN

- Designs are optimised against many factors
- The design is refined

Buffer might be removed or moved to excess

FINAL DESIGN

- The requirements are well defined
- Performance is known from test and simulation

Buffer shift to excess

Figure 5-9 Margins state at different phases of the design stage

As mentioned earlier, at the beginning of the product development there is a lack of information available about the product design or how well the product will perform in relation to the conditions of use. Therefore, there is a relationship between requirements / performance and unknown/ known dimensions as the uncertainty can be, to some extent, manageable over time by allocating buffers. Although these buffers are not immediately usable in design, they do offer the potential that they can be reduced and thus release excess which is immediately usable. This gives a relationship between buffer / excess and unknown / known.

5.6.1   Example from the cooling system

At the beginning of a new project the cooling system team analyse the pre-requisites which contain directives, goals and target descriptions. Accordingly, they define the requirements specification and analyse the existing cooling system concepts to select the one that will be implemented. However, before getting to the final design stage, designers and engineers need to deal with a considerable number of constraints and uncertainties. For example, when determining endurance, which is defined by testing the truck, engineers don't know from the beginning, what the final load on the cooling system will be until they have tested all components. However, they can still make a judgement regarding the load by simulation.

Consider this example from the perspective of design margins. The designers use a buffer at the beginning of the process in order to determine an endurance parameter because they were uncertain about the final load. Therefore, they created a buffer margin. As uncertainty is reduced through more exhaustive simulations, the buffer becomes usable excess.

In the example of truck engine cooling, designers include a design margin which increases the load that the system is able to cool by 10%, and a head loss margin which increases the pump power by 10%. The design process follow the pattern shown in Figure 5-10
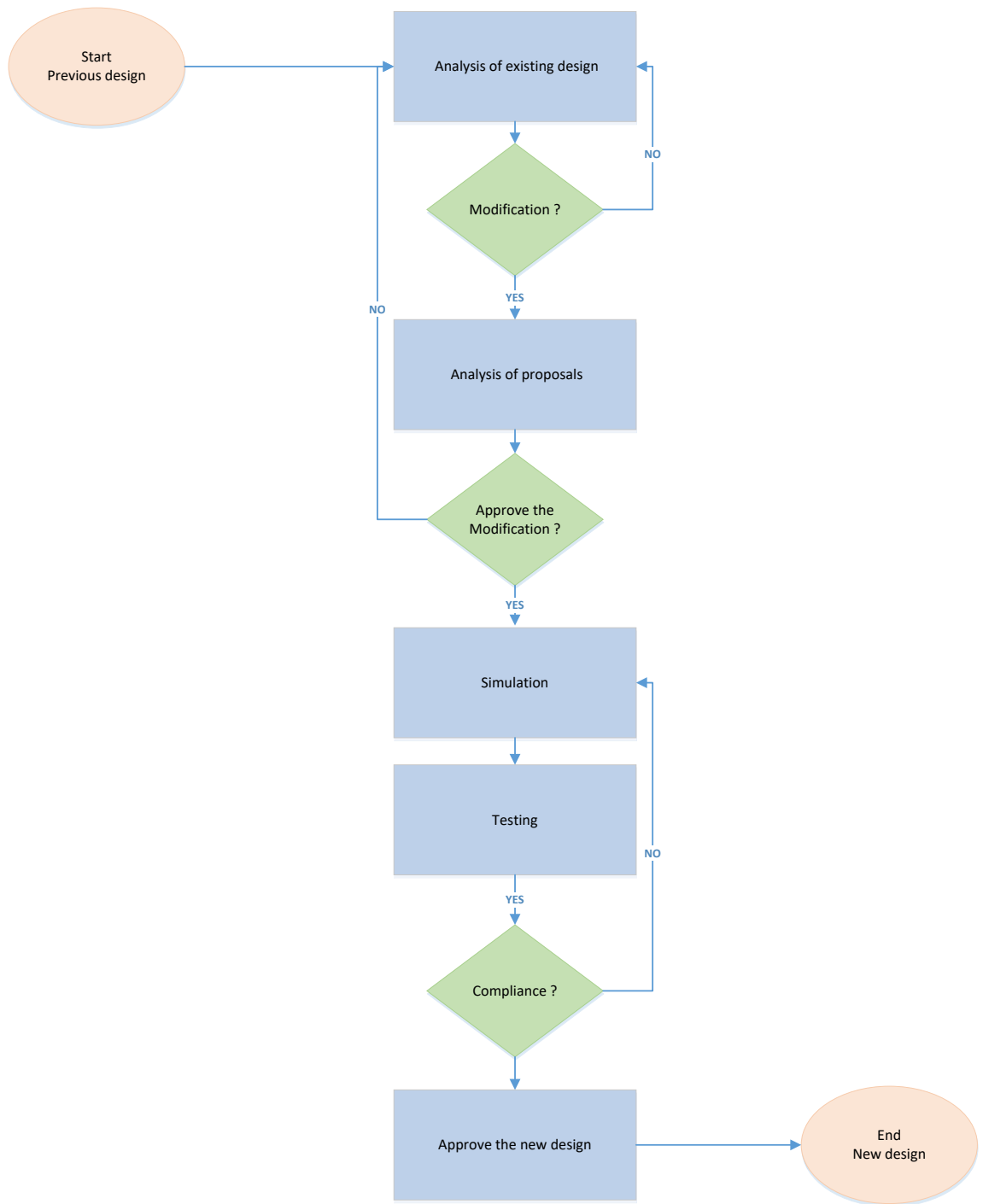
Figure 5-10 The design process model

In setting out the concept design to cover worst-case requirements there is the interesting observation that on the one hand the requirements seem to be known accurately and definitely

(the details of the worst case) whilst on the other hand the reason for using the worst case in the first place is that the actual requirements are not known well.

Later in the overall product development process there will be a refinement phase. Here designs are optimised against many factors, perhaps manufacturing costs for example, and the design is improved while still being set broadly against the worst-case scenario of requirements. At this stage buffers may be removed or moved across to excess which can be exploited at the next stage.

At a third stage the design team are tasked with designing a product for particular set(s) of requirements. Here more is known of requirements and they are considered together, in parallel. Because this is later in the overall product development, more is known about performance from test as well as use information from earlier versions. So, buffers tend to shift to excesses which then offer usable margins against the specific requirements. Consequently, the design team have options. Knowing the margins and how they have developed through the first two stages means that designers can now make rational and informed choices about their options. Taking away excess margins, might be achieved at considerable design costs, although ultimately product costs may be reduced. Note that usable margins are excesses. The bits of margin which are buffers are not usable as they are absorbing uncertainties in requirements and performance.

Margins can also be discussed from the view point of change and the process to make a change. For example, if the powertrain team send a change request regarding the engine temperature, the engineers start to think about alternative solutions, inter alia, margins that could absorb this change. In this case, the designers can make use of the excess which is the part of the margin that has been incorporated for dealing with increasing requirements and small changes.

Additionally, since the suppliers are highly involved in the product development process, the interaction between the company and its suppliers is more than the purchasing and supplying of

parts. It also concerns detailed knowledge about margins on these parts which is difficult to identify explicitly in the main company who do not have the necessary specialist knowledge.

5.6.2 Design margins across the product development process

Automotive products (the case study of this research) are complex multidisciplinary systems which require dozens of different specialists to design as well as significant resources to develop. These systems are usually designed by a team of engineers, with other teams each with responsibility for different subsystems. The design team aspect means that there is often a lack of communication and differing information among the team members. These products are often built by more than one organisation since a single organisation rarely has the expertise in all the subsystems required in the design. When multiple organisations are involved, the complexity and informational asymmetries often increase further as interaction among specialists is more difficult.

Complex multidisciplinary systems are also characterised by increased uncertainty in design. They often have hundreds of independent variables that uniquely define a design. A large number of interdependent components must all come together for the product to work. These systems are both difficult to model and to understand because no single person has the detailed knowledge in all discipline areas, all variables, and all components that are required to comprehend or predict the final performance of the system.

At the beginning of the product development process, there is no definitive set of requirements, the set will be refined as the design unfolds. Requirements generation consist of elicitation, analysis, specification and validation activities. Design margins are planned as soon as the requirements are known, mainly to reduce uncertainty in the design process. Margins are seen

as a positive way of managing design efforts, however, as soon as the product is proposed for production, margins are seen as a source of extra cost which engineers will try to remove.

Margins are mainly captured at the beginning of the development process, from the requirements. By doing calculations and tests design engineers can decide whether the current solution can meet new requirements or whether they need another design solution. At the beginning of any product development process there are many uncertainties associated with the design parameters and how they are described in the project scope. A number of key issues related to the evaluation of design margins are identified by the use of probabilistic design methods to rationally and analytically make design decisions in the presence of uncertainty.

According to the company where the case study was conducted, the project starts with the prerequisites which contain a description of goals, directives and targets expected by product planners for a generation of products. At this stage, the knowledge about the final value of a design parameter as well as the overall performance of a system is limited. As the product development process proceeds to more detailed design, the knowledge increases because designers at this stage are able to better understand the capabilities of their components, for example by running simulations. At a later stage, when the design parameters are defined and a solution is selected, the level of uncertainty is reduced further.

At the start of a project, engineers might have an initial requirement value for a parameter which may not be the value they will finally design against. For example, Figure 5.11 shows the relationship between the requirement (full line) and the capability (dashed line) of a fan. At the beginning of the product development process, there is a small margin (M_1 in Figure 5.11) between the prerequisite and the capability of Fan 1. Later in the process, when the requirements are fixed to a value higher than the capability, then the designers need to change to Fan 2, which has higher capability and can meet the new requirements. Consequently, this will generate a

large margin (M_2 in Figure 5-11) for other variants that do not need a bigger capacity for their fans. In the case of the binary choices between the two fan sizes, at the product definition stage, the company did not leave enough buffer above the prerequisite.
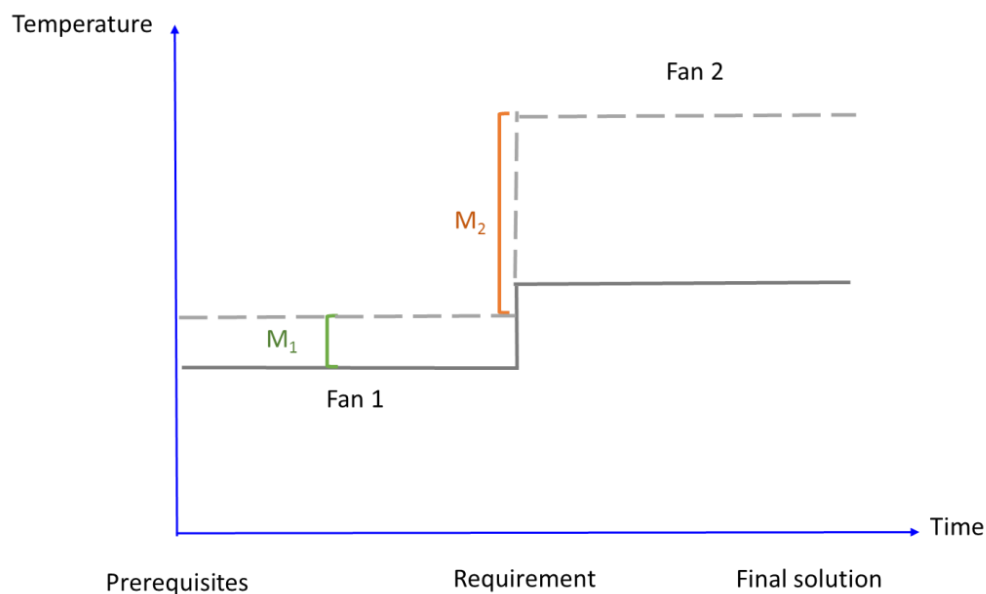
Figure 5-11 Margins evolving over time

During early design stages, the prerequisites can be subject to changes as many uncertainties have not been considered and the values might be affected by change propagation. The design proposed at this stage can exceed the prerequisite in two ways:

There is a buffer (B) to take account of uncertainties of many types in product performance and in the knowledge of the product characteristics which may not yet be defined.

There is an excess (E) which represents a known or guaranteed 'extra' in capability over and above what is specified in the prerequisite.

The process, within the case study company, of translating the prerequisites into requirements is an iterative process where designers and engineers make models and run simulations in order

to establish the set of requirement values. In the particular case illustrated, the buffer decreases and the excess increases to reflect reduced uncertainty and increased room for manoeuvre.

As the project unfolds, engineers need to select a technical solution which is the result of trade-offs made between different characteristics such as technical feasibility, expected service life, and cost.

The validation of the selected solution is achieved through further detailed analysis as well as an extensive physical test. The result is further reductions in buffer and possible increases in excess. However, excess is also eroded in two ways; the requirements can increase using up the excess and the design might be optimised by removing the excess deliberately for example to reduce the cost of the part.

In the case study, it was observed that when engineers receive the prerequisite from the product planners, they are uncertain about some requirements or the final performance of the product. Therefore, they create a buffer by adding margins on some parameters to provide high probabilities of meeting the functional requirements or requests for change. Later in the product development process, when the requirements are more detailed, and the technical solution is more refined, designers were able to reduce uncertainty by conducting tests or by evaluating the conditions of use. At this stage, designs are optimised against many factors, for example the manufacturing costs. A buffer has effectively been removed or reduced and moved across to the excess part of the margin which can then offer a scope for optimisation. At the final stage, the design team has a target to design a product for a particular set of requirements. As they know more about the requirements they also know more about the final performance from tests and simulations. Therefore, the excess can be reduced without compromising the performance or the reliability of the component against current requirements. On the other hand, it is observed

that as engineers reduce uncertainty on a component, parts of the buffer can be shifted into excess, and therefore released for future design changes.

Engineers and designers tend to freeze requirements at the early phases of product development. However, product requirements may themselves have buffers that are not immediately usable in a design but give the possibility to be reduced and therefore provide usable margins (i.e. excess). These margins provide options for meeting higher performance and allow the trade-off between different requirements.

So far, it has been demonstrated that knowing the status of design margins on parameters in terms of buffers and excesses gives a range of possible values that provides potential solutions. Therefore, design margins play an important role in framing the design process. The way different parameters are traded off against each other depends on the nature of their relationship. These relationships define how margins on different parameters can be considered together. Margins effectively act as a range of values that provide possible alternatives to meet requirements.

Nevertheless, margins may not be communicated explicitly across teams. At the early stages of the product development process, engineers are not often aware that buffers have been added to cope with possible or expected future changes to requirements. Furthermore, engineers in different parts of a team may have a little sense of how much excess was used up by another part of the project team. This is because margins may not have been explicitly documented.

5.7 Design margins and trade-offs

For a performance parameter ,the margin is the difference between the required and the actual performance. This can be illustrated with a simple example. A rectangle that has an area of 4 m^2 but only requires 1 m^2 has a margin of 3 m^2. If the requirement is increased, but is still < 4 m^2,

no change is required. However, if the requirement is greater than the area 4m^2 then the component size needs to be increased. As the area = length * width, either the length or the width or both can be changed. In practice one of the parameters might be a constraint, such as when the material is cut from a roll with a fixed width. In this case, the length would be increased. If both are variable there might be other constraints or requirements that govern the ratio of both and the designers might need to make a trade-off between the lengths and width to find the best solution for this square. In the case of continuous variables, it might be possible to find an optimum through carrying out a multi objective optimisation. This is a trade-off involving discrete variables which might employ weighted parameters. For example, when selecting a chair a choice might exist between a red chair with armrests and a green chair without. Your favourite colour is green, and you prefer armrests. The choice depends on what is weighted as more important.

The margins on an individual parameter provide a space in which to trade-off change. Some parameters might be harder to change than others. Figure 5-12 illustrates the different trade-offs between two parameters P_a and P_b that could be made. The designers might want to build a margin into the new solution. The values of each of the two parameters includes a margin. Thus $P_a min$ a minimum value for parameter P_a which is not an absolute minimum for that parameter but includes a margin to allow for upcoming uncertainties. $P_a max$ might give a maximum value for the parameter, for example size.
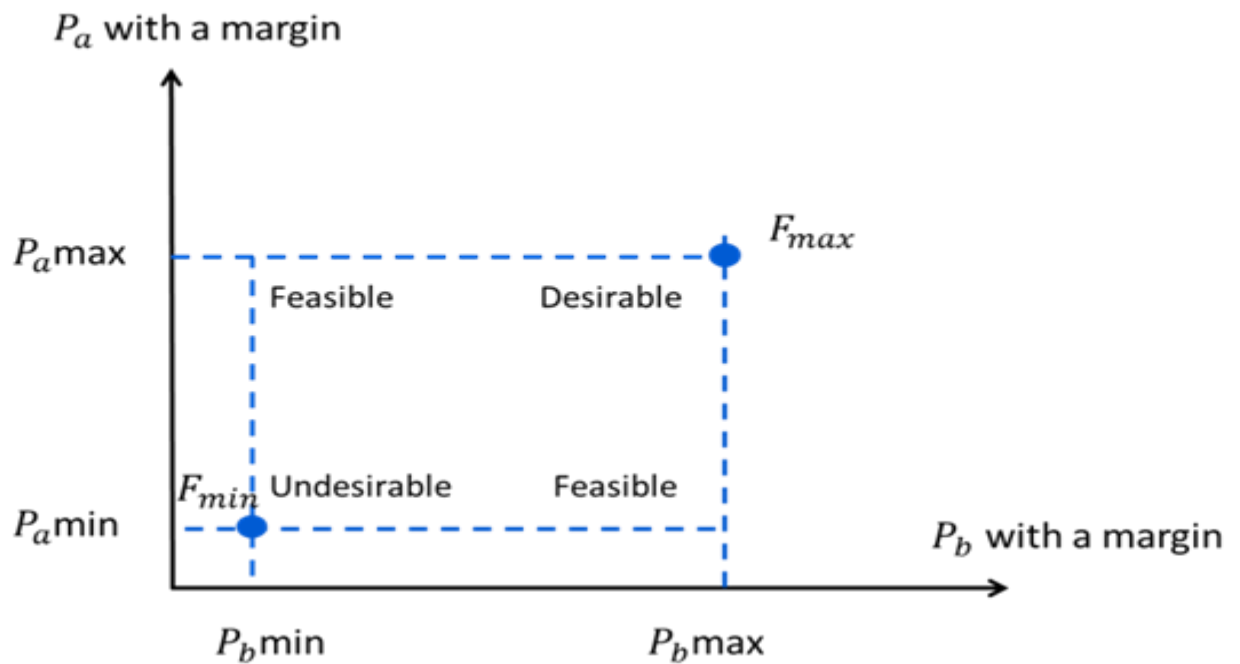
Figure 5-12 Trade-off between two parameters, P_a and P_b with regards to their margins

The parameter pair $\{P_a min, P_b min\}$ represents designs where the values for both parameters are at the minimum, that meets the requirements but has no margin. Solutions near or below these parameters are not considered desirable by designers. The parameter pairs $\{P_b min, P_a max\}$ and $\{P_b max, P_a min\}$ represent situations where parameters $P_a \ and \ P_b$ are traded-off against each other and represent feasible design solutions. The pair $\{P_a max, P_b max\}$ represents situations where the values for both parameters are at their maximum. Design requirements are achieved and the solution is considered desirable. Therefore, the performance function F is maximised. However, if the objective is to optimise a performance function by minimising some parameters, then $\{P_a min, P_b min\}$ would indicate the desirable design space and $\{P_a max, P_b max\}$ the undesirable one. The overall value might also be a constraint, for example when there is a weight limit on a board with a given area. This approach of trading off

parameters that have margins, offers designers and decision makers the possibility to explore different areas where the design could be feasible as well as judging the appropriate criteria for selecting a specific design solution.

In order to identify an optimal design conflicting objectives are typically considered simultaneously. Mattson and Messac (2005) argues that "one of the most powerful tools for resolving such objectives, in a computational setting, is multi-objective optimisation. Generally, there are many potential solutions to multi-objective optimisation problems; a particular set of optimal solutions is referred to as the Pareto optimal set or Pareto frontier". By definition, Pareto solutions are considered optimal because there are no other designs that are superior in all objectives.

A general multi-objective optimisation problem attempts to find the design variables **x** that optimise a vector objective function f (**x**) over the feasible design space S. The formulation of a multi-objective optimisation problem is defined as follows:

Minimise x $\mathbf{f(x, p)}=[\ f_1, f_2, \ldots . f_n]$ (1a)

Subject to: $g_j(x,p) \leq 0$; j=1,....,J   (1b)

$$X_L \leq x \leq X_U$$ (1c)

Here, **x** are the component design variables (factors controlled by the designer), **p** are the component design parameters (factors kept constant by the designer), **f** is the component objective functions, g_j is the inequality constraint. The design variables **x** are bounded by their lower and upper bounds X_L and X_U, respectively.

Because of trade-offs among the objectives, there is generally a set of optimum solutions to (1a). This set is called a Pareto set, and the design solutions in this set are called the Pareto designs. Extensive reviews of multi-objective optimisation concepts and methods are given by Deb *et al.* (2000) and Gunawan and Azarm (2005). However, the applications of this type of approaches

by industry tend to limit the scope of optimising a design. More often the main objective is to minimise the cost for some design attributes A and B such as A>B, A<B or A=B, without actually quantifying the capacity of A and B. On the other hand, methods that deal with the computational behaviour of different design objectives require a number of iterations and runs. Therefore, this involves a need to consider what systems and components can do and how their parameters define capability.

In practice the relationship of the parameters is often not linear as in Figure 5-13. For example, a beam which has a load capacity depending on its length and its diameter, can be optimised through a Pareto optimisation. The actual solution is the red point, which is at a distance from the optimal solution. Therefore, there is a margin compared to the Pareto curve on the length and the diameter. The existence of these margins will help the designers make trade-offs between the length against diameter and select the optimal solution that meets the requirement.
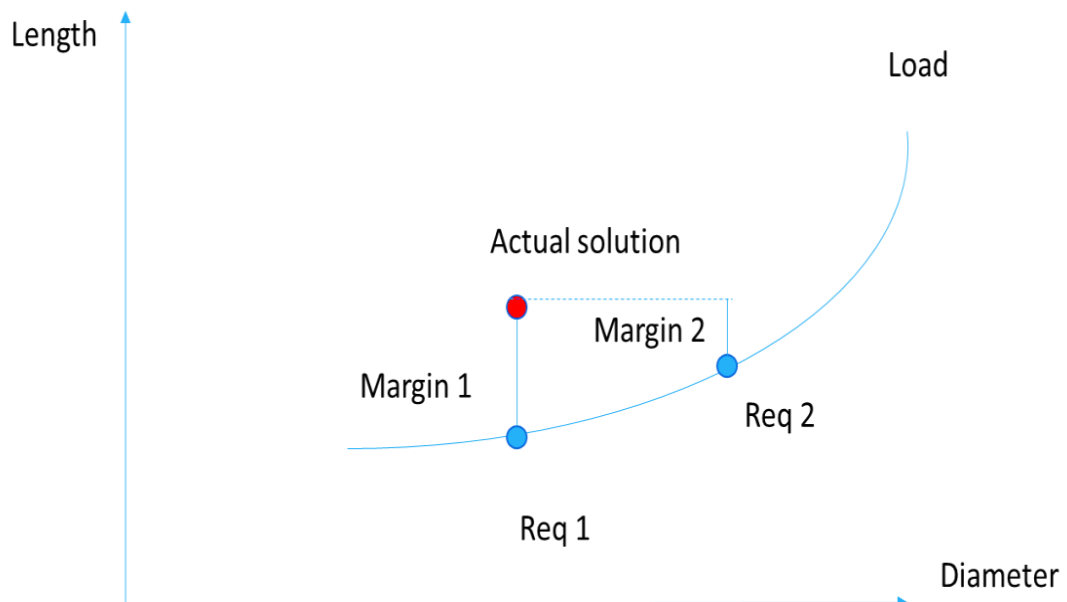
Figure 5-13 Margins on different parameters

In industrial applications, the relationships are far more complex than in these simple examples. Engineers should find how much they need to give up of a certain objective in order to improve another one to a certain quantity. Therefore, they build in the "margins" in the non-linear constraints, that is then reflected in different levels of margins for each of the objectives or parameters. For example, when calibrating an engine, the levels of emissions are deliberately set to a below-legal limit). This can be used to approximate how many units the value of some objective function changes if we alter the value of some other objective function by one unit.

5.7.1   Application: truck cooling system
a.   Truck design

The relationship between margins and trade-offs is now illustrated through an industrial example from our truck case study. Trucks are incremental designs. Every 10 to 15 years the company launches a new product generation, such as a new heavy weight truck, which sees a substantial number of newly designed components and systems. In between these large product development cycles, new versions are developed for particular classes of needs. For example, after launching a basic version, the company later embarked in developing trucks that can be used as fire engines. The automotive industry also needs to meet different and changing emission legislations for different markets. The product generation changes are linked to the emission legislations, but engines are modified throughout the life cycle of a product generation. The automotive industry faces a number of technological challenges in terms of meeting different legislations, developing highly customised products to satisfy customer needs, as well as particular operating conditions. There are also challenges in terms of the lead time, and the trade-offs between cost, the overall product development and performance.

To illustrate this, the cooling system of the truck was selected. The cooling system needs to be modified, as the engine temperature increases for whatever reason. This could either be a different engine, the truck could be operated in a different environment or on a different duty cycle. In some driving conditions, the air flow crossing the radiator is not enough to cool the coolant. This happens in hot climates, or when the engine is running for a long time without moving the vehicle. For example, a truck operating in open mines in the desert requires substantially more cooling than a truck running on European motorways and would operate the fan most of the time. These challenges force companies to find an efficient way to make these trade-offs. Design margins are important for many trade-offs that engineers can make, as they represent a room for manoeuvre. Design margins can accommodate new requirements; therefore, engineers can avoid redesigning their existing components and systems, which ultimately will result in decreasing the development time and cost.

b. The cooling system

For most use scenarios, the heat that is produced in the engine needs to be actively cooled. This is performed by the cooling package which consists of the radiator and the fan. The cooling system's main function is to cool the engine to stop it from overheating. When the engine coolant temperature rises to a threshold level, this will activate a valve, which will in turn send air pressure from the truck's air reservoir to the fan drive and engage the clutch on the fan. When engaged, the fan drive activates the fan through a clutch, to cool the engine by pulling air through the radiator. The amount of cooling provided is dependent on the airflow generated by the fan. The coolant system also can be used for heating. The heat transferred from the engine to the coolant is for example used in the cab heat exchanger in order to give the driver a comfortable temperature inside the cab. The cooling system (Figure 5-14) has tight geometrical constraints. It has the cab flooring on the top, on the sides of the chassis frame, the grille in the front, at the

bottom the front underrun protection (FUP) and the engine in the back, as illustrated in Figure 5.14. To increase cooling the airflow needs to be increase.
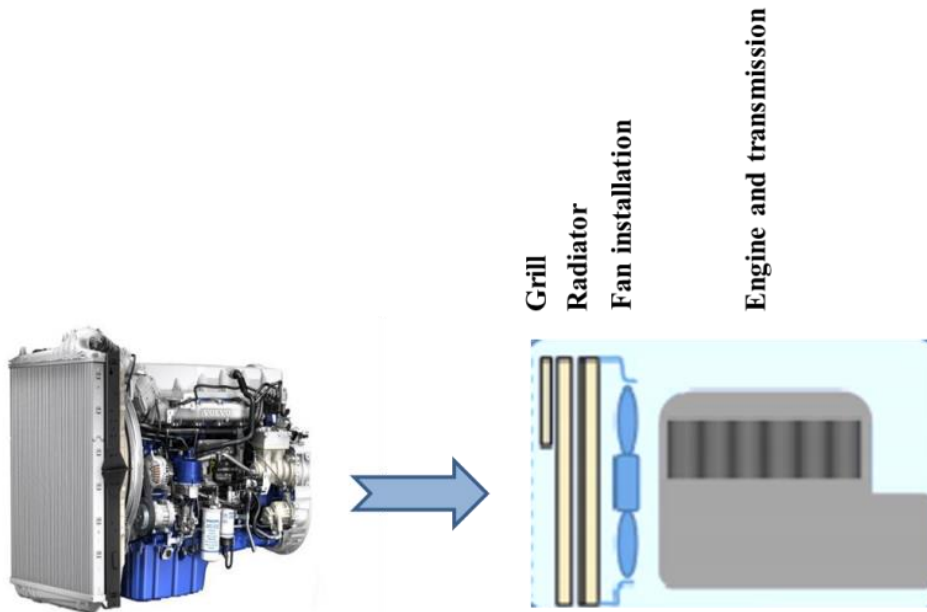
Figure 5-14 A cooling system layout

Different engine specifications have different cooling needs, according to the size of the engine and the load on it. The company offers a wide range of truck variations and configurations. Specific trucks are built from a product platform, which aims to meet the widest possible range of application with the minimal number of components and systems. This means that some components have large margins in performance with regards to the requirements of a particular configuration. The fan is one of these critical components that are shared across several configurations.

c. Margins on a fan

Fans are usually selected from a range of models and sizes, rather than being designed specifically for a particular application. Fan selection is mainly based on calculating the airflow and pressure requirements of a system, then finding a fan of the right design to meet these requirements. Considering that the company only uses a small number of sizes of fan it is effectively the rotational speed that is varied in practice.

As the company needs to be sure that they can meet the requirements under all the given scenarios they calculate the size of the fan and the fan speed they would like and use this as an input to select the right fan with a suitable fan speed.

The fan overall performance is determined by the fan capacity, pressure, speed and power, which follow the following fan laws (Gullberg and Sengupta, 2011), which address the change required compared to an already existing baseline design which has been tried and tested for a given set of operating conditions.

$$q_2 = q_1 \times \left(\frac{n_2}{n_1}\right) \times (\frac{d_2}{d_1})^3 \tag{1}$$

$$p_2 = p_1 \times (\frac{n_2}{n_1})^2 \times (\frac{d_2}{d_1})^2 \times \left(\frac{\rho_2}{\rho_1}\right) \tag{2}$$

$$P_{R2} = P_{R1} \times (\frac{n_2}{n_1})^3 \times (\frac{d_2}{d_1})^5 \times \left(\frac{\rho_2}{\rho_1}\right) \tag{3}$$

The design parameters are: d for Diameter [m]; n for Rotational speed [rpm]; P_R for Power [rpmkW]; p for Pressure [Pa]; q_v for Volumetric flow rate [m^3/s] and ρ for Density of air [kg/m^3]. Subscript 1 refers to the existing conditions and subscript 2 refers to the required conditions.

Higher airflow usually means better cooling. Consider a design requirement regarding the airflow that the cooling system must create for a particular engine and operating conditions.

From the first fan law (1) we know that the airflow varies in direct proportion to the rotational speed. Therefore, the design requirement can be met by two design parameters which are the rotational speed of the fan and the fan diameter (size).

There are existing designs which meet these requirements, but since most of the fans are generally overdesigned, the solution exceeds the initial requirement for this particular design. For example an existing airflow of q_1 = 1.3 CFM (that is normal litre (at 0°C and 1.013 bar)) per minute) can be achieved with a fan diameter d_1 = 680mm, and a rotational speed n_1 = 1.06 RPM. Whereas, the needed air flow is only q_2 = 1 CFM. In order to evaluate what is the actual needed fan diameter d_2 and the rotational speed n_2, we apply the first law (1):

$$q_2 = q_1 \times \frac{n_2}{n_1} \times (\frac{d_2}{d_1})^3$$

Then,

$$d_2 = d_1 \times \sqrt[3]{\frac{q_2}{q_1} * \frac{n_1}{n_2}}$$

Figure 5-15 shows the variation of the fan diameter with the rotational speed. The Pareto curve obtained for this installation shows that at the fan speed ratio 1.06 RPM, the fan diameter would be 623.057mm. On the other hand, for a fan diameter of 680mm the fan speed ratio is 0.80 RPM. But in reality, the installation is using a fan that operates at a diameter of 680mm at a speed ratio of 1.06RPM. Therefore, there is a margin on *d* the diameter of the fan and a margin on *n* the rotational speed of the fan.
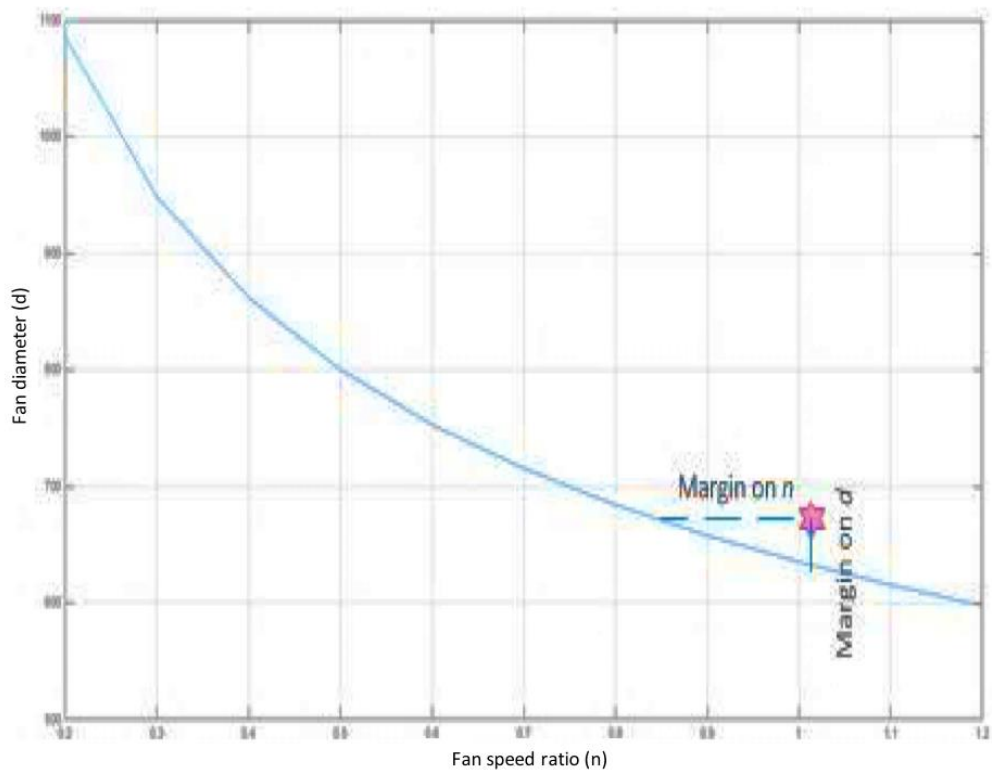
Figure 5-15 Different margins in different parameters

If we choose another design that gives the same flow rate, but with a design margin (18% of the air flow), it will give us another margin on *d* the fan diameter and another margin on *n* the rotational speed of the fan (Figure 5-16).
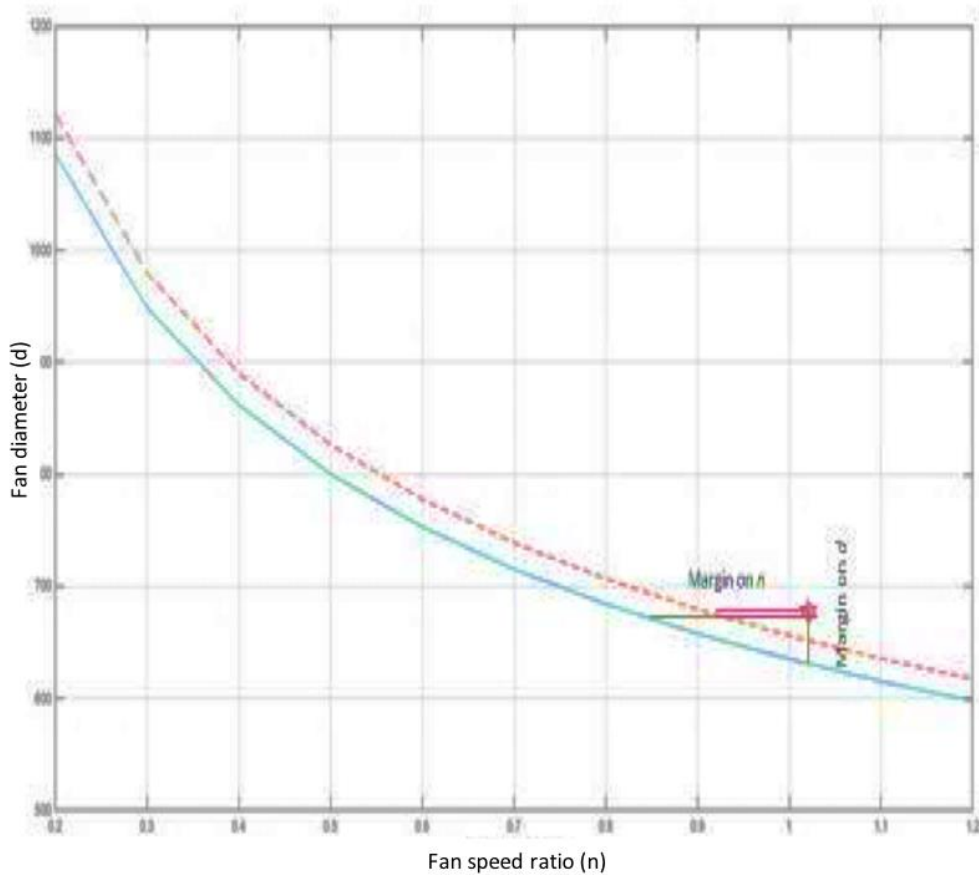
Figure 5-16 Relationship between margins in the design requirement and design parameters

The airflow depends on the volume of air that the fan can push and the speed with which it rotates. However, both larger fans and higher rotation speed have drawbacks for the design of the truck. A larger fan takes up more space and is potentially heavier, which ultimately affects the engine efficiency. The fan rotation is generated by taking energy from the engine and therefore directly affects engine efficiency. Therefore, the designers need to find the optimal balance between fan size and speed.

In practice, the company uses only a small number of different fans, with different diameters, in an attempt to minimise the number of parts in their product platform. The fans are long lead time components. A new fan design would require the production of expensive new moulds. It would potentially also be possible to modify the geometry of the fan blades, however this would require considerable design effort from their fan supplier. The rotational speed is also not freely variable. Therefore, the designer will generally have a margin on the fan capacity.

The selection of the fan and the rotation speed is not only determined by the airflow, but also by other constraints. In particular, as the fan is directly underneath the cab, noise and noise regulations are an issue. A bigger fan would potentially generate more noise. These parameters might themselves have margins that need to be considered when making changes.

The designers might also deliberately select a solution which has a certain margin on it, as this would give them additional room for growth in case the requirements are exceeded. Theoretically the requirements ought to be defined so that they cover these eventualities. This is the case for the particular application that they were set for. The designer however knows that another variant might have similar, but slightly higher requirements. Understanding the margins on their solutions enables the designers to reuse by adapting this solution for another application saving themselves considerable design effort.

This example illustrates how much effort designers are putting into understanding the optimal solution for each variant, even if they are constrained by the platform. One reason is that they need to be absolutely sure that the components that they have selected will be working reliably under all circumstances. In this particular problem, a team of engineers works largely on design analysis. They occasionally make small changes to a component or a part of the component. However, they try to minimise these as well, as every change to a platform component requires

rechecking in each combination through analysis and simulation as well as retesting the physical components.

Therefore, the management of margins is also a means of managing the design effort, even at the cost that individual components or systems are overdesigned for a particular application. While there is a certain cost, in terms of added fuel consumption due to increased weight, associated with an overdesigned fan, there are safety and reliability risks associated with an under-designed fan. A greater number of fan variants would result in a greater part cost and a greater design effort.

5.8 Summary

It was identified that the changing terminology and the lack of communication around margins is one of the key issues in the case study company. This makes it difficult to capture the knowledge about margins which is not explicitly documented.

Also, it was demonstrated that margins on components or systems profoundly affect how a design process is carried out. Engineers and designers look for components or subsystems with margins, to accommodate potential changes and analyse design alternatives.

Moreover, due to the fact that there are shortcomings in tracking margins and capturing the knowledge related to these margins in industry, the management of margins relies heavily on the experience of engineers and designers. There are no specific tools to assist with the evaluation of margins. When questioned, a large number of engineers and managers felt that there was a need for more support especially with gaining an effective overview of how margins can be flagged up at the different stages of the product development process. This thesis suggests a model which can help investigating and managing design margins.

6 Development of a Conceptual framework to Investigate and Manage Design Margins

The empirical study has shown that tracking design margins is complex and can be difficult to manage, mainly because margins are not explicitly communicated across the organisation. Although some designers and engineers are aware of the margins they have on some components, this knowledge is not recorded precisely. Thus, there is a clear industrial need for support with the way design margins are managed throughout the product development process. This chapter describes a conceptual framework that was developed to investigate and manage margins. The framework was developed based on well-known methods used in the industrial sector.

6.1 Background to the conceptual framework development

This research initially focused on understanding the concept of design margins and how there are communicated. Work was carried out both to identify the terminology around the concept (Chapter 5) and to develop a conceptual framework that could help in managing design margins. The empirical study at Volvo GTT highlighted the need for a basic overview or model that could help to identify why and how design margins are added and used. Therefore, the focus of the research was to bring insights on how to manage design margins and to develop a framework that could be used to elicit the data required by the company to shape the entire design process. It was important for the success of this research that the framework is taken up by industry. To this end, many discussions were held with engineers and designers to identify why certain tools and methods were used in industry whilst others were not. During this investigation, it became clear that tools and methods that are accepted and used in companies are techniques like Quality Function Deployment (QFD), Failure Mode and Effects Analysis (FMEA), and Design Structure Matrix (DSM). These methods can be implemented in stages and do not require significant initial input or learning from the engineers in order to begin, yet can provide structured guidance to difficult engineering problems.

The core intent of quality functional deployment (QFD) is to quantify the relationship between design decisions and product quality. These relationships are documented in a series of matrices, or "houses" to produce quantifiable relationships. The first of these houses is the house of quality (HoQ), which relates customer requirements with the associated technical requirements. The required input to the HoQ is an unambiguous statement of the customer requirements (CRs) and their associated importance weighting (IW).

Based on these CRs, which are often subjective, the designer defines a series of measurable technical requirements (TRs), and their preferred sense, i.e., to maximise, to minimise , or target

a certain value. Correlations between the CRs and TRs are identified in the relationship matrix (Leary and Burvill, 2007). One of the interviewed engineers said: "*Function Deployment method. The sort of house of quality stuff. Where you would take user requirements and then relate them to proper functions, and then in the next step relate the functions to components, and then you work your way through from... requirements to... essentially manufacturing*" *(PL).* However, with regards to design margins identification this method can give an extra layer of difficulty, because it provided a limited comprehension of how the importance of each requirement is weighted.

The process of carrying out an FMEA can be divided into several steps. Basically, each failure mode considered in the FMEA technique is evaluated by three factors as severity (S), likelihood of occurrence (O), and the difficulty of detection (D). A number between 1 and 10 (with 1 being the best and 10 being the worst case) is given for each of the three factors, and a risk-priority-number (RPN) is obtained. Although FMEA is probably the most popular tool for reliability and failure mode analysis in the automotive industry, several limitations are associated with its support to identify or manage design margins. First, the failure data gathered from suppliers, engineers, and testing is often missing or unreliable. Hence, the assessment information of three risk factors (severity, occurrence, and detection) is mainly based on experts' knowledge and experience. Second, in the traditional FMEA methodology, the three risk factors are assumed to have the same importance (Braglia, 2000). However, it is observed that engineers give more preference to the fault detection factor (based on discussion with test experts at Volvo).

One key recommendation was that any model should be simple enough to be outlined in a matter of minutes, yet if required, extra layers of complexity could be added in the future.

In this research, it was argued that the complexity of large development projects, the availability of limited data regarding design margins and the time required to follow these projects, make

the explorative methods to elicit the margins data and how they shape the company's processes an appropriate methodology. It appears that alternative methodologies have difficulties in addressing the goals of this research and its associated research questions. Regardless of many limitations and the caution that is necessary in the interpretation of results arising from "exploratory-based" models, this thesis claims that it provides ways to investigate design margins from which qualitative and quantitative insights can be obtained about product development processes. These insights can then support product planners, engineers and designers analysing different scenarios and making more informed decisions about product development.

6.2   Outline of product and process modelling

The design of complex products usually involves the coordination of many activities over multiples sites before getting the final product. Thus, there is a large amount of connectivity between the products that a company produces and the processes that are used (Earl *et al.* 2001). A key issue in any proposed method or tool that supports the modelling of products and design processes is the development of an appropriate underlying model. However, the modelling of facets of design is a large area and will be discussed briefly in this chapter. The main focus will be on methods and tools that were used in this research. A detailed review of modelling and the design process is given by Wynn *et al.* (2007) and Engel and Browning (2008) who reviewed the key aspects of product models.

In the literature related to this area, models for product development adopt approaches which emphasise the following two main aspects:

Design-focused, which supports the generation of better products by the application of prescriptive models and methods to the design process (Pahl and Beitz 2013)

Project-focused, which advocates approaches to support or improve the management of the design project, project portfolio, etc. (Hales, 2011).

In industry, the main focus of product modelling is from a development perspective with models used to examine how key systems and components can be manufactured and assembled to create the final product. The importance and the difficulty of planning complex systems development has been recognised by many authors in the literature. For instance, Eckert and Clarkson (2010) have explained that complexity and uncertainty in such products forces industrial organisations to produce and manage a multitude of plans in parallel during projects: product plans focusing on cost, on the bill of materials and in procurement issues, process plans targeting the control of milestones, lead-times or project activities; resource plans; and quality plans.

A greater part of the modelling activity occurs during the early stages of the development process, mainly at the design phase where a range of models may be used as different concepts are investigated and evaluated. Conventionally, product models and especially process models have provided a basis for planning and managing projects. By listing the activities, deliverables (often generated from a product breakdown) and their interconnection, product planners can get an idea of several key aspects of a project, including project duration, cost and the critical path for project activities.

6.3   Challenges for modelling

The design and development process of large and complex systems and products is itself complex. Understanding and predicting the way design is carried out is a difficult task for both researchers and industry. The design process can be viewed as a "system of interrelated activities" (Wynn *et al.* 2011), which are performed with the objective of reducing uncertainties surrounding the design solution or, in other words, as a system of design activities organised

around the goal of gaining knowledge and confidence that the solution will function and perform according to the specified requirements.

A distinguishable characteristic of complex design processes is the presence of many sources of uncertainty that need to be resolved through the interrelation of different kind of design activities. De Weck *et al.* (2007) mentioned both exogenous (such as changes in operational environments, in customer demands or in regulations) and endogenous (such as those arising from the maturation of technologies and corporate strategies) sources of uncertainty.

On the other hand, the design and product development process has been recognised as a "social and collaborative process" (Shai and Reich 2004), where many aspects of collaborative behaviour have been found. This thesis takes the view of the dimensions of design iteration adopted from Wynn *et al.* (2007) where it is described as an *adaptive* decision making behaviour (Figure 6-1).
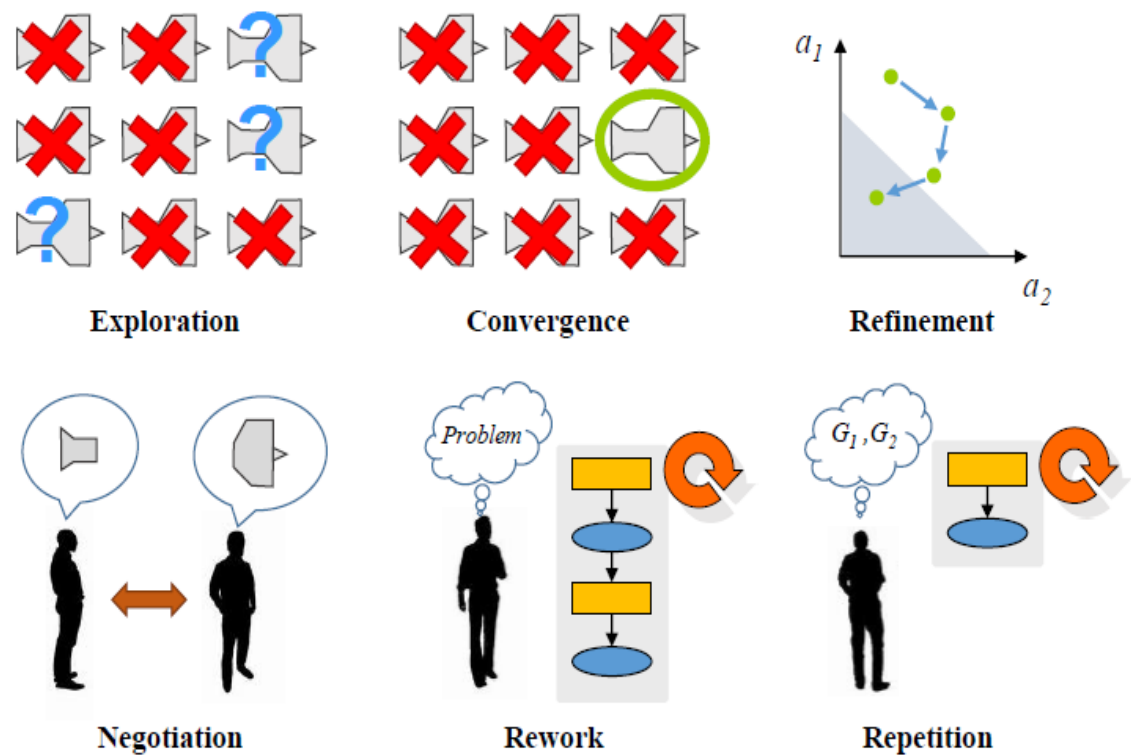
Figure 6-1 Dimensions of design iteration proposed by Wynn *et al*. (2007) in the context of gas turbine design

Wynn *et al*. (2007) argued that design is different from repeatable processes which can be defined *a priori*, since uncertainty and complexity forces engineers to accommodate evolving requirements, explore opportunities, oversee continuous changes, perform complicated trade-offs and solve design problems which always exhibit, to some extent, a degree of novelty.

For the reasons mentioned above, capturing knowledge about margins becomes difficult. Margin knowledge can be hidden at different stages of the product development process, or the knowledge about some of these margins can get lost when the company moves from developing one generation of products to another one. Although designers and engineers, might know about

the margins that key components or systems have, this knowledge is generally tacit. It is not modeled or documented explicitly.

Considering that the majority of models, especially the process models, are a combination between the 'as-is' and 'to-be', the most important issues involved in the modelling of products and processes are the level of granularity and the level of abstraction. The challenge is to find the right balance between the amount of effort required to elicit the model and the level of information required. Overall, one of the key requirements of a useful product or process model is to be flexible to quick and easy modification and improvement. The method used to model design margins which is described in this thesis aims at satisfying these key requirements while combining different methods and approaches.

6.4   Modelling approaches

This section discusses the modelling approaches that were used to investigate the concept of design margins throughout the product development process. These are the elicitation and representation aspects of DSMs coupled with the Change Propagation Matrix. Both of these will be briefly discussed before the process of implementing these methods is outlined. Then the application of these methods will be illustrated with an example.

6.4.1   Design Structure Matrix

Among the methods and tools used in capturing the complex interaction of design activities, Design Structure Matrix (DSM) is considered to be a "popular representation and analysis tool for system modelling, especially for purposes of decomposition and integration" (Browning 2001). There has been a large interest in DSMs over the past decade. Many authors and industrials have acknowledged the utility of this method. The main aspect of DSM is that it displays the interaction between sub-systems and the relationship between components.

DSM is a binary matrix, where the rows and columns are named and ordered identically (Figure 6-2). All the elements of the domain of analysis are assigned along rows and corresponding columns. The dependencies of elements with others are represented by placing entities (such as 0, 1, X, etc.) within the matrix.
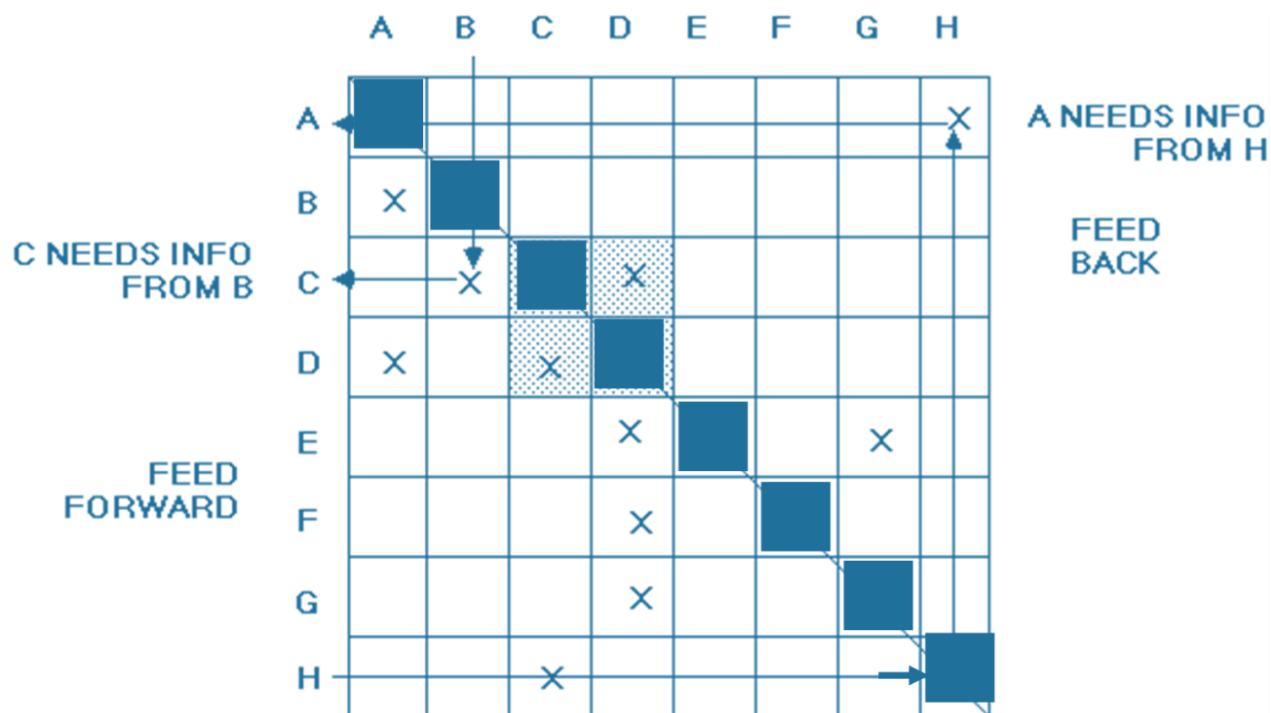
Figure 6-2 Design structure matrix

The entities in a single row represent all the elements whose output are required to perform the task corresponding to that row. Similarly, reading down a specific column reveals which element receives information/dependency from the element corresponding to that column. Marks above the diagonal show information fed back to earlier listed elements (i.e. Feedback mark) and indicates that an upstream task is dependent on a downstream task.

Browning (2001) identified four types of DSM in product development: the Activity-Based (or Schedule) DSM, to model the information ow between design process activities; the Parameter-Based DSM, to model design parameter interdependencies; the Component Based (or Architecture) DSM, useful for modelling system component relationships and investigate architectural decomposition; and the Team-Based (or Organisation) DSM, aiming to capture the interactions between people or organisational structures.

Design Structure Matrices were selected as one of the main approaches for the modelling method for the following reasons:

- In comparison with other modelling methods (examined in another work) like GRAI method (Graph with Results and Actions Inter-related) or IDEF (function modelling method), a DSM clearly displays the relationships between components of a system, in a way that is easy to comprehend and one that supports analysis of the system.

- DSMs provide a precise framework within which models can be elicited. This is because the matrix format means that every single possible connection must be addressed. By examining each cell of a matrix in turn, every possible connection has to be considered.

- DSMs are the basis of the CPM tool which was used to generate these matrices and evaluate the change propagation.

- Last, but not least, DSM was used (section 6.5.2) to focus on key components and capture where the margins could be.

6.4.2 Change Propagation Matrix

Based on the DSM that allows the visualisation of direct linkages (parts, subsystems..), Clarkson *et al*. (2004) developed the Change Prediction Method (CPM), to show how change propagation data can be visualised in the context of change propagation and how multiple Figure 6-3 shows the main features of the Change Prediction Method.
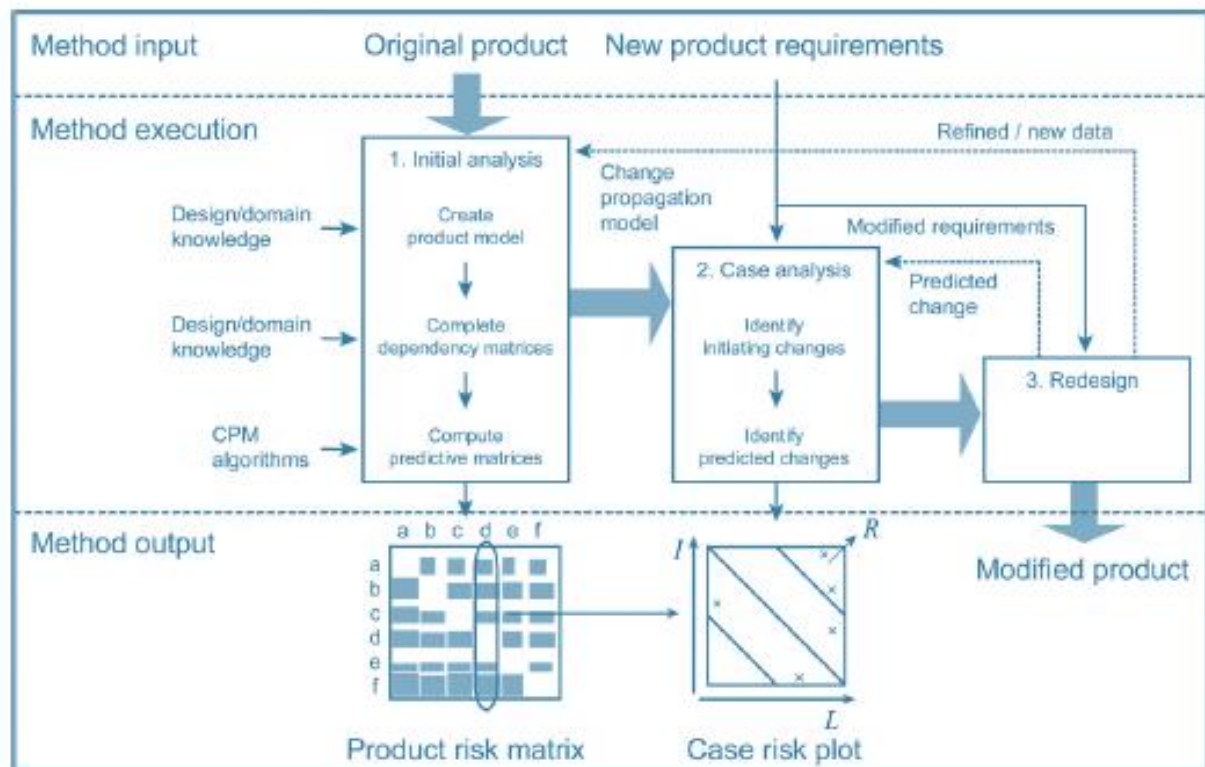
Figure 6-3 Change Prediction Method proposed by Clarkson et al. (2004)

The method has been applied in many industrial studies, including change impact prediction in helicopter design (Clarkson *et al.* 2001) diesel engine (Jarratt *et al.* 2004) and jet engine fan design (Koh and Clarkson, 2009) to estimate the impact of engineering changes defined as "alterations made to parts, drawings or software that have already been released" (Jarratt *et al.*, 2011). Clarkson *et al.* (2001) method generates two types of DSMs: a direct likelihood matrix, representing the probability of a change in one component leading to a change in another; and a direct impact matrix, representing the amount of rework needed to implement that change. Then the algorithm developed is used to predict the total impact of the change from the whole propagation tree.

CPM shows how change propagation data can be visualised in the context of change propagation and how multiple views are used in this context. The Change Prediction Method uses architectural DSMs to model the connectivity between the components and sub-systems that make up the product. Numerical values are used to weight the relationships in terms of impact and likelihood of change propagating between the two components (Keller *et al.* 2005). Matrices for likelihood and impact are generated by replacing the crosses (×) of the component DSM with values between 0 and 1. Likelihood is defined as the average probability that a change in the design of one component will lead to a design change in another by propagation across their common interface. Impact is defined as the average proportion of the redesign that will need to be redone if the change propagates. The two matrices can then be combined to create a direct risk matrix. This stage of the process is shown in Figure 6-4.
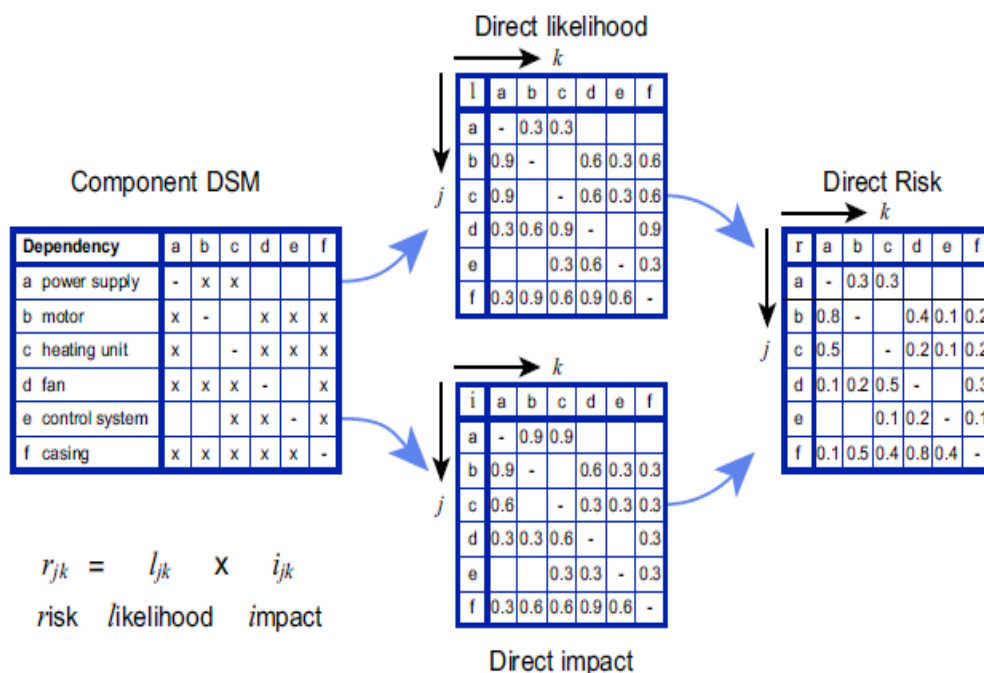
Figure 6-4 Generation of component DSM followed by the likelihood and impact DESMs from Clarkson et al. (2001)

This method has been turned into a software tool (CAM) that supports engineering change management in various ways, from model building to visualisation of change data (Keller, Eckert *et al*. 2005). The tool was used to develop the DSMs and CPMs.

The CPM method was applied to analyse the change impact and the possible propagation paths in the cooling system. The outcome of this analysis was to study the role design margins play in shaping the design process. This was initially motivated by the argument that if a component or a system is able to absorb some degree of change, it means that component or system has some margins that allow for the change to be absorbed and not propagating.

These two methods were the basis for developing a model to illustrate the importance of considering design margins, especially at the early phases of the product development and to bring the focus more on what the component can do rather than what it has to do.

The key strength of both models is its cost-effectiveness to model moderate size and well-structured development processes. Because of that and their intuitive graphical notation, they have been applied in industrial practice and support well process visualisation, planning and execution monitoring and control. Its limitations include the difficulty to include various forms of iteration and to account for collaboration and adaptive behaviours often observed during development projects.

6.5 The process of building a design margins model

The design margins model was defined as a simple four step process, which is illustrated in Figure 6-5. This process uses a combination of the DSM and CPM construction methods as the basis of the model development.
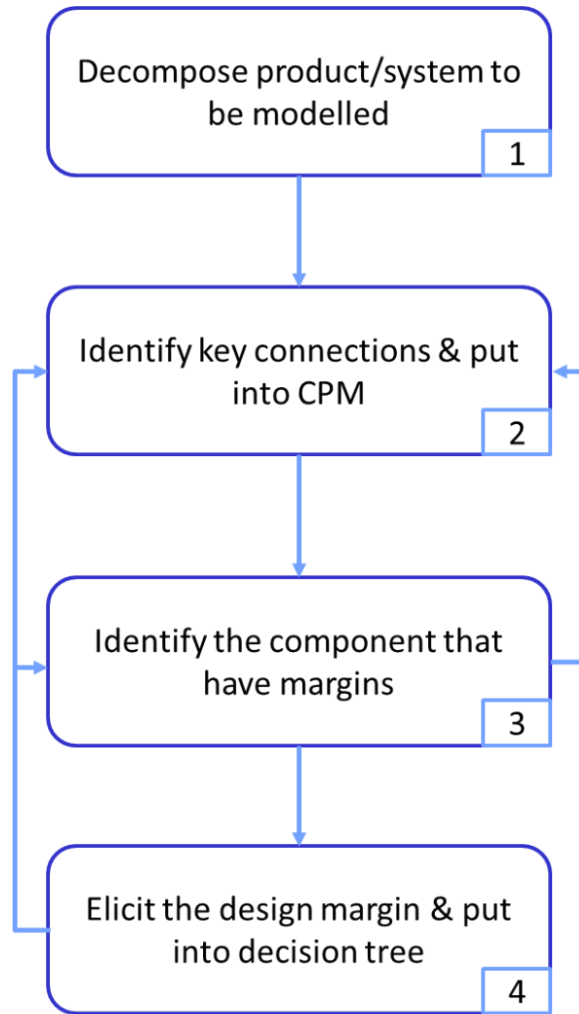
Figure 6-5 Overview of margins investigation method

The four steps of the method are as follows:

Selecting the product or the system to be modelled and identifying a suitable level of decomposition depending on the purpose of use of the model and at which stage during the product development process the model is generated. As discussed above, identifying the level of granularity is important when building a model. A precise model could follow a specific product or system throughout its life cycle. Hence, the model could be used to evaluate where

there remain margins to accommodate potential changes and then can be updated as changes are implemented.

Identifying types of connections. These can be selected from a list of key connections between systems or components common to most products (e.g. mechanical and spatial). (Keller *et al.* 2005) has developed a method to identify key linkages and argues that there are four main questions that must be considered.

Is there a connection (linkage) between these parts of the product?

If so, what type of connection is it? Two parts of the product may be connected by more than one linkage type.

Considering the linkages between the two parts, what is the likelihood of a change to one of the parts propagating to the other?

If a change was to propagate between the two parts, what would the impact of it be?

The CPM tool can be then used to assess the overall connection between two components and therefore evaluate the potential change behaviour.

Knowing the different connections between the components gives the opportunity to design engineers to have a better understanding of how a system or a product works. It also allows them to identify what are the critical components and obtain the change probabilities and impact for use in the Change Propagation Method (CPM). Therefore, they can identify the components that have margins. If a component is able to absorb some degree of change it means that it has margins.

The elicitation stage requires a further analysis of the state of the margins in terms of buffer and excess over the product development process. When there is a margin either engineers do not make a change or they might change something where there is still some margin. To make a decision, engineers need to consider the two aspects of design margins which are the buffer and

excess. The buffer is a range of uncertainties associated with the component and its use. The excess represents the range that engineers can make use of to redesign or make a change. Therefore, if they can do anything to reduce uncertainty they can shift some of the uncertainty buffer to excess (see chapter 5).

The development of the model in the company was carried out in collaboration with the cooling system team as mentioned in chapter 4. This section follows each of the steps described above, using one of the cooling systems modules produced by the company. The identification of a suitable decomposition of the system and the types of connection was made with the cooling system team manager and carried out over a period of a few months. The coolant system's main functionality is to cool the engine to prevent it from overheating. However, the coolant system also can be used for heating; the heat transferred from the engine to the coolant is, for example, used in the cab heat exchanger in order to provide the driver with a comfortable temperature inside the cab.

6.5.1   Decompose the system to be modelled – Step 1

The cooling system (Figure 6-6) has tight geometrical constraints. It has the cab flooring on the top, on the sides the chassis frame, the grille in the front, at the bottom the front underrun protection (FUP) and the engine in the back.

Figure 6-6 A truck cooling system package at the front of the whole engine assembly

This system was selected as a case study because it is one of the systems that are subject to various constraints from different features and therefore a number of trade-offs were present. One of the most challenging tasks for the coolant system engineer is to make sure that all components in the system get enough flow. Depending on the different components' resistance, pipes dimensions and where the different components are connected in the system, the resulting performance can be significantly different.

6.5.2   Identification of system decomposition and key connections – Step 2
General functionality

Figure 6-7 illustrates a typical flow schematic of the cooling system in a heavy-duty truck. After the pump, the flow enters the oil cooler which is a heat exchanger that sits behind the coolant duct cover. From the coolant duct cover the main flow goes through the engine.
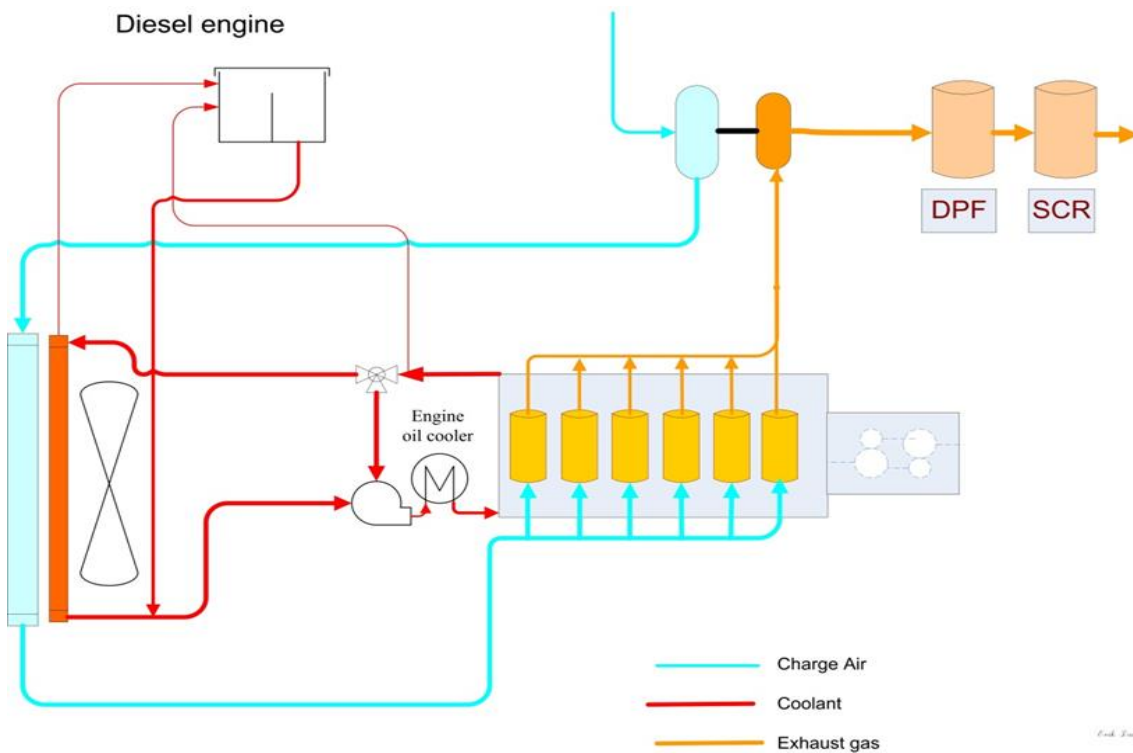
Figure 6-7 Schematic cooling flow of a heavy duty truck

At the engine outlet, a thermostat is located. When the coolant is warm, the thermostat is open and the coolant will be cooled in the vehicle radiator before the coolant goes back to the pump. During the start engine, when the coolant still is cold, the thermostat is closed and the coolant bypasses the radiator and goes directly to the pump.

System decomposition and key connections

The identification of a suitable decomposition and the key connections was a long process, which involved several stages. Several meetings were conducted with the cooling system team. The result of these discussions was an overview of the system functionality and a system decomposition.

The first stage was to break down the cooling system illustrated in Figure 6-7 into subsystems (charge air, coolant and coolant air):

Charge air subsystem (shown in blue Figure 6-7): the ambient air is taken through the air intake, via the air filter to the turbo compressor (shown in the Figure 6-8). When the air is compressed, it gets hot, so before entering the engine it is cooled in the Charge Air Cooler (CAC), as illustrated in Figure 6.8
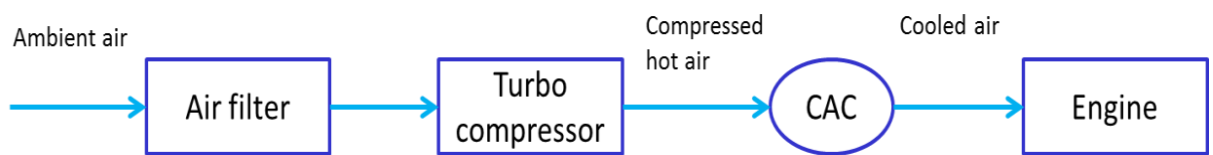
Figure 6-8 Charge air flow

Coolant subsytem (shown in red Figure 6-7): The coolant flow is driven by the coolant pump. After the pump the coolant cools the engine oil and then the engine itself via coolant channels. At the outlet of the engine the thermostat (Th in Figure 6-9) "decides" how much coolant that should be cooled in the radiator. The expansion tank is connected to the radiator and engine outlet. The tank allows the coolant to expand when heated up, and is also used for level detection, filling and reservoir in case of leakage (Figure 6-9).
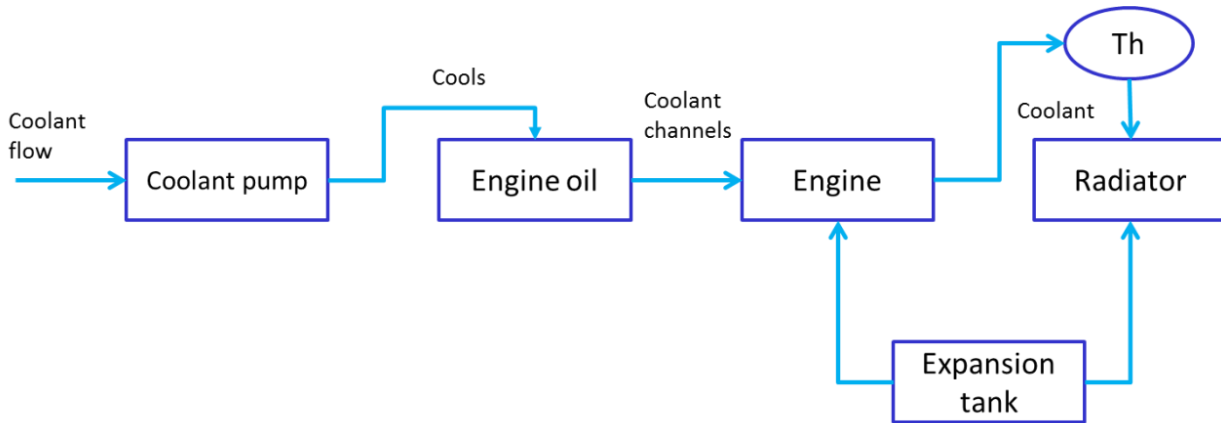
Figure 6-9 Coolant flow

Cooling air subsystem: The cooling air is pushed through the grille openings by the forward motion of the vehicle. As illustrated in Figure 6-7, when the coolant temperature is high the fan starts engaging, to suck more air through the CAC and radiator. Recirculation shields are installed around the heat exchangers, in order to make sure the air is directed effectively.

After the system decomposition we (the author and the cooling system team manager) identified the system's key components listed below:

Coolant pump

Engine

Radiator

Expansion tank

CAC (Charge Air Cooler)

Turbo

Grille

Fan module

Thermostat

Engine oil cooler

Recirculation shield

Connection pipes

Bypass line

After defining the main components, we then identified three main linkage types; see (Keller *et al.* 2005) :

S: Spatial connection when components are adjacent or they are in close proximity and therefore might be affected by changes to each other without necessarily having a physical or functional link

M: Mechanical connection when components are physically, joined or held together.

F: Flow connection when there is a flow between two components. The most evident flow connection is how the flow is transmitted between the different parts of the cooling system. In the case of the flow connection the case study identified five specific types of linkage:

CAF: Cooling Air Flow

CF: Coolant Flow

ChAF: Charge Air Flow

OF: Oil Flow

ExF: Exhaust Flow

Once the decomposition and connections were identified, an initial model was created in DSM form with the help of the cooling system team manager. A specific DSM was created for each type of connection (Figure 6-10) and these were combined into a single matrix (Figure 6-11).
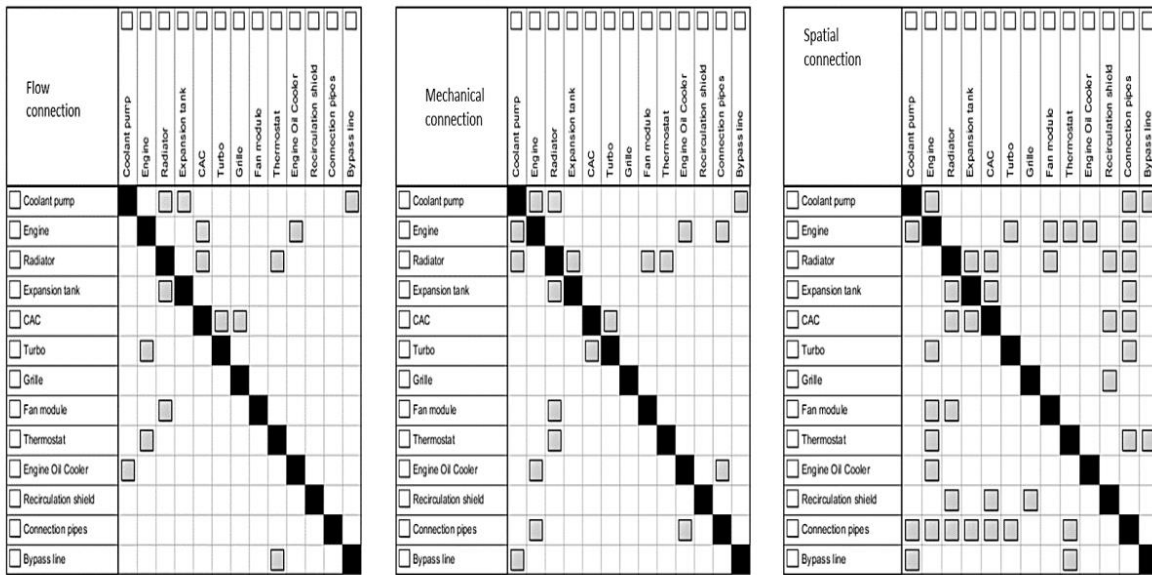
Figure 6-10 DSMs for flow, mechanical and spatial connections in the cooling system

However, since mechanical links can be seen as a special type of spatial connection, it was decided that for the analysis to consider only the flow connections (CAF, CF, ChAF, OF, ExF) and spatial connection (S) as shown in the combined matrix in Figure 6.11.

	Coolant pump	Engine	Radiator	Expansion tank	CAC	Turbo	Grille	Fan module	Thermostat	Engine oil cooler	Recirculation shield	Connection poipes	Bypass line
Coolant pump	■	S	CF	CF								S	S CF
Engine	S	■			CFChA	S		S	S	S OF		S	
Radiator			■	S	S CF CAF			S	CF		S	S	
Expansion tank			S CF	■	S							S	
CAC			S	S	■	ChA	CAF				S	S	
Turbo		S ExF				■						S	
Grille							■				S		
Fan module		S	CAF S					■					
Thermostat		S CF							■			S	S
Engine oil cooler	CF	S								■			
Recirculation shield			S		S		S				■		
Connection poipes	S	S	S	S	S	S			S			■	
Bypass line	S								CF				■

Figure 6-11 DSM for the flow connections and spatial connection in the cooling system.

Once the DSM was completed, it was decided to run an exercise involving two engineers and one manager from the cooling system team to verify whether this decomposition was suitable and to build the Change Propagation Matrix (CPM). For that, the engineers and the manager were asked to evaluate by grading high, low and medium the likelihood and the impact of a potential change. It was suggested that they consider two scenarios; when they have major changes (new big project) and when they have minor changes. They had to build a CPM for

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each scenario. The likelihood and impact data was converted to rating values: high= 0.8, medium=0.5 and low=0.1. The values were then put into the algorithm from the CPM tool. The output, illustrated in Figure 6-12, shows the components that are most susceptible to change and those that are most likely to influence a change. The highest risk elements are in red, medium in yellow and low in green. For the analysis, we considered the scenario where they need to make major changes and evaluated how design margins can guide that process.
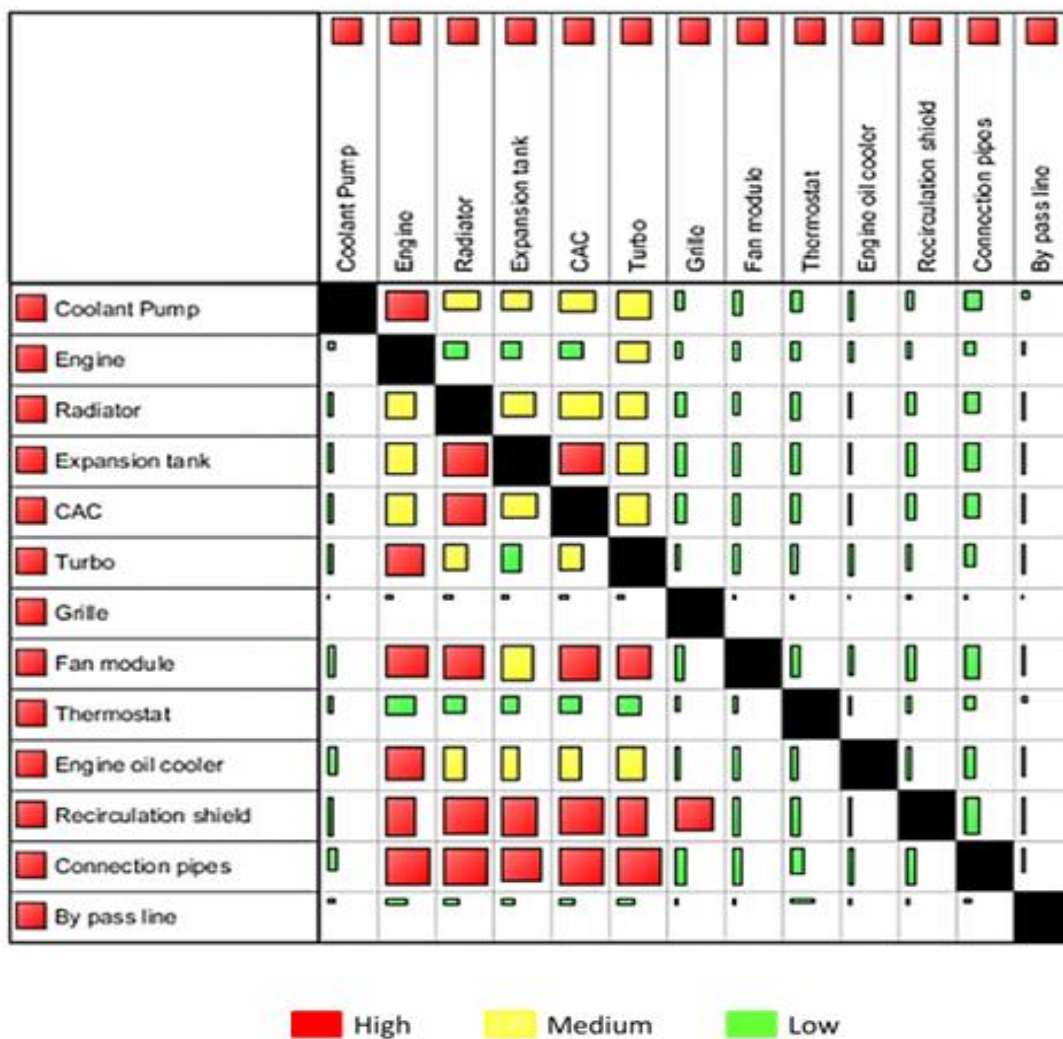
Figure 6-12 Change Propagation Matrix for Major changes

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The participants in the exercise completed it separately, and different questions were raised during the exercise. However, they all acknowledged the importance of such models and found the exercise interesting and potentially useful.

The findings from this exercise were quite different in terms of how engineers thought about change, and the events and features that could trigger a change. Further the differences extended to how they evaluated the impact of a potential change. However, all of them showed relatively good agreement on the mechanical connections between components, besides some divergent interpretations of component assemblies (fan). Spatial connections led to slightly more divergence between the engineers, yet, the flow connections were easier to agree on.

The filling of the matrix was strongly influenced by what the engineers knew about the design and how much they were involved in it. For example, the fan specialist (P.G) knew most about flow links, because they fell into his area of expertise.

6.5.3 Identifying components which have margins – Step 3

Design margins are planned as soon as the requirements are known. During the design a component or system is discussion of margins is wrapped up in assessing engineering change and the risk of change propagation. Designers are also taking active steps to avoid changes by designing flexibility into the details of the systems.

The output reordered in Figure 6.12, can help engineers to identify the components most likely to influence a change (i.e. cause it to propagate) and the components most likely to be susceptible to a change (i.e. be affected by change propagation). From the matrix, it can be seen that the engine is the component that causes potentially the most changes; i.e. it is a change multiplier (chapter 2). The engine is an expensive component with a long lead time, and it is not changed in response to other components changing. Therefore, the engineers need to look for

alternative components that either have margins which absorb the change, or can be readily changed.

6.5.4   Elicit design margins and put into a decision tree – Step 4

As chapter 5 argues, margins can be seen to have an element of buffer and an element of excess or contingency. The concepts mentioned in the interviews also can be thought of as either buffer or excess concepts, but the division is not always clear. Safety margins and tolerances are both buffers which are added to deal with uncertainty. Safety margins deal with uncertainty in use and, in particular, uncertainty arising from misuse of products. Tolerances are catering for uncertainty arising from manufacturing variability. In trucks an element of buffer is already incorporated in the requirements, as they include the variability in ordinary and intended use that will be covered by a system or component.

Room for growth is an explicit excess concept, which allows the designers to meet higher requirements in the future. Overdesign can be seen as a both an excess and a buffer, as the designers see their colleagues raising requirements as an uncertainty against which they protect themselves through overdesigning a component. Once the uncertainty of knock-on effects of changes is removed the overdesign moves from a buffer into an excess. Later in the process overdesign is seen as a form of costly waste, i.e. a form of excess that can be eliminated.

Given the fact that the engineers' decision regarding the design margins may vary, depending at which stage of the process the decision is made, it was decided to use a decision tree to model a specific situation that a designer or an engineer might have to deal with. Decision trees are a simple, yet powerful form of multiple variable analysis. They are produced to identify various ways of splitting a data set into branch-like segments (chapter 2). Decision trees attempt to find a strong relationship between inputs and targets in a group of observations that form a data set.

A strong input-target relationship is formed when knowledge of the value of an input improves the ability to predict the value of the target. For example, if designers have to select a material, knowing its strength improves the ability to predict how much load the material can carry. The general form of this modelling approach which was used to build the decision tree is shown in Figure 6-13.
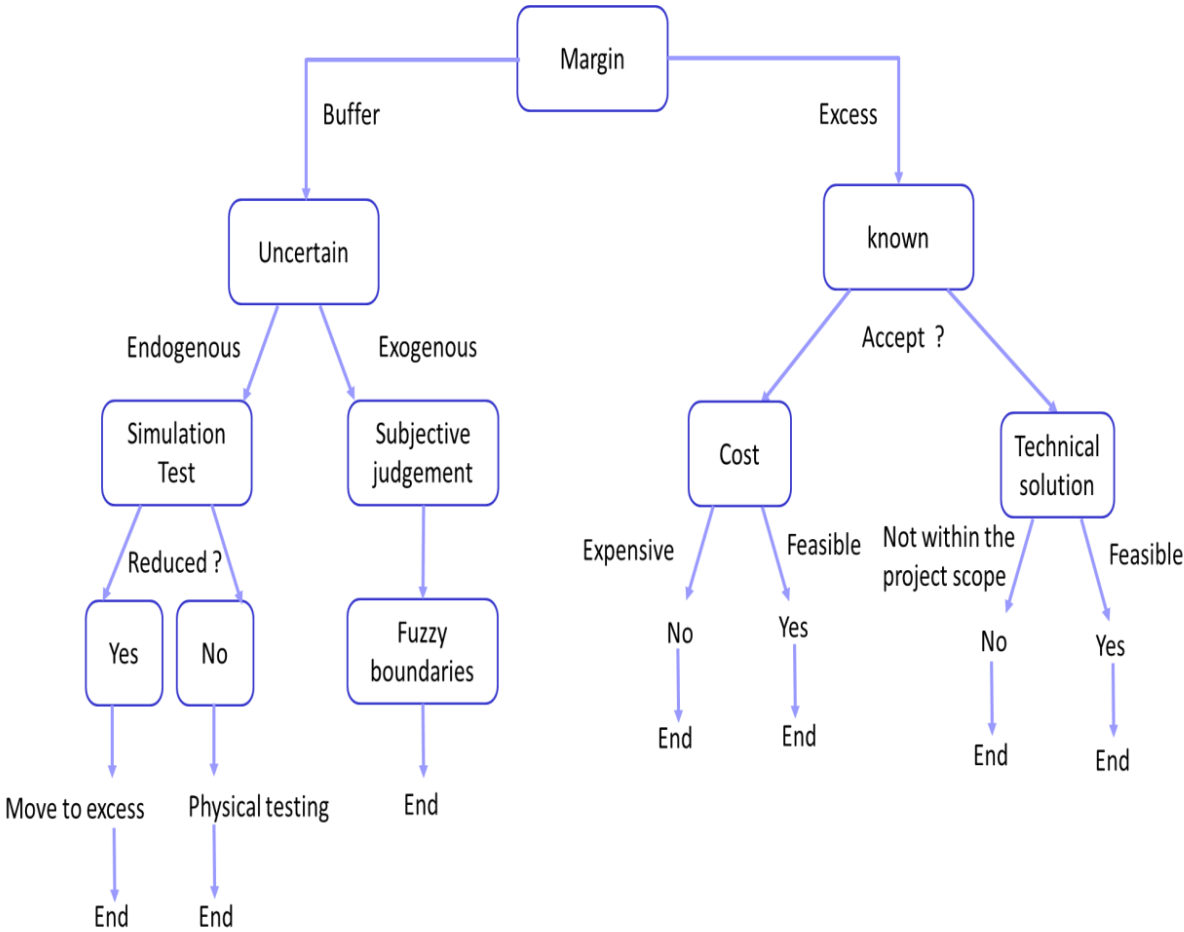
Figure 6-13 Design strategies based on margins state

Once the margin is known, the analysis moves to identifying how much of that design margin is considered as a buffer and how much of it is considered as excess. Then the investigation

starts by evaluating different possibilities (inputs for each node) and considers the decision actions that need to be taken (target), as shown in Figure 6-13.

The left hand branch in Figure 6-13 considers when the margin is a buffer. When he uncertainty is very high, engineers consider a range of parameter values to compensate for those uncertainties. However, engineers want to have control over those uncertainties and be able to predict their probability of occurrence. As described in Chapter 2, the uncertainty can be endogenous or exogenous. If the uncertainty is endogenous, it means that engineers gave some control over the probabilities they are facing. Therefore, they can conduct further tests and simulations and try to reduce the buffer. If the buffer is reduced then that part moves into excess, otherwise the engineers can wait until they get more feedback from the physical test. In both cases, the decision made at this level regarding the design margin is more accurate. Even if there are buffers which are not immediately usable in design but offer the potential that they can be reduced and release tangible and usable margins. These offer options for meeting higher levels of functional requirement or optimising product parameters against existing functional requirements.

The right hand branch of the decision tree in figure 6.13 considers when the margin is excess. When the value of the margin is known and clearly exceeds requirements, it is an excess. The excess part of a margin provides design flexibility; it is the part that designers can make use of, for example to deal with changes or increasing requirements. In this case designers need to decide whether or not to design with that excess (surplus). As soon as the requirements are known the role of design margins is to reduce uncertainty in the design process. At the early phases of the development process design margin are seen as a positive way of managing design effort. However, as soon the product reaches the production stage, design margins are seen as a source of extra cost and engineers look for excess to remove. Yet, if engineers have a global

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view over the design margin state throughout the PDP, they can see that for specific scenarios, introducing design margins as a form of deliberate planning for a number of potential changes, can reduce the cost of making changes from scratch. For these reasons it is important to follow and update the model of design margins across all phases of the product development and update the design strategies based on the margin state.

6.6   Eliciting, collecting and documenting design margins

The work presented in this research suggests that the company needs to change their protocol or the way they are carrying design, and propose to investigate design margins at the early phases of the product development.

Margins can be related to several aspects of the product including capability, requirements, performance, and quality. Given these, the proposed framework will analyse, transform, and integrate design margins into design process. Once the new requirements are assessed and high-level concept definitions are completed, the next step is to elicit, collect, analyse and identify design margins on key component parameters. At the early stages, margins on key components and / or parameters can be elicited and analysed by using the CPM, because if a component is able to absorb some degree of change it means it has some margins. The stakeholders then need to agree which margins they want to consider. Later in the process, the actual margin can be quantified using simulations and / or tests. At this stage stakeholders, can decide which part of the margin they can make use of, so they can incorporate some excess into a system or a component. Therefore, the changes that need to be made to the new design can be done without consequent changes propagating across the design. One aspect of this elicitation process is to maintain a documentation of how and when margins were flagged up, so that this knowledge can be used when developing other products or making changes.
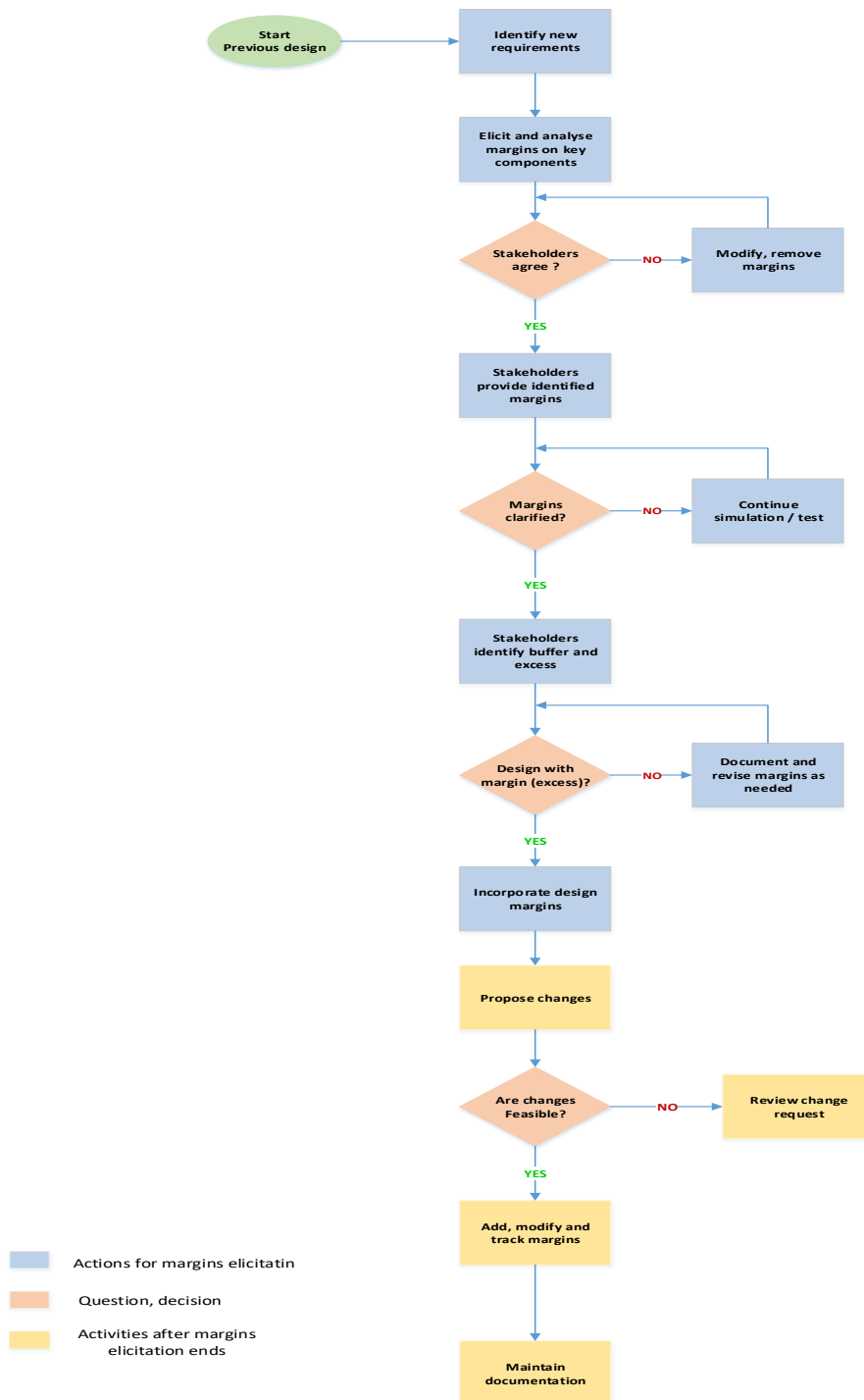
Figure 6-14 Eliciting, collecting and documenting margins

Figure 6-14 highlights the process of collecting and evaluating margins. The framework shows

activities and milestones that need to be considered for margins collection and management.

Each step within the margin elicitation sequence is completed before moving on to the next step. Activities may be added, modified, deleted, and their sequences changed, depending on the scope and type of the project or the task. Generally, subtasks within a larger project focus on fewer activities and may have different stakeholders and finer grained criteria for success than the project itself.

Margins need to be communicated explicitly across the organisation, because they are part of the discourse in informal negotiations. Some critical margins are flagged up as part of concerns for the safety of the product, but large margins are often left uncommented. As designers are often aware of the state of the margins of their own components, they often try to protect components with critical margin in the design process from changes.

The overall framework implies that elicitation and a good documentation of margins would help decision makers implementing changes more efficiently.

6.7   Evaluation of the model, application to the cooling system

The model was evaluated in two ways. Firstly, with regards to the change propagation matrix, by setting up, together with engineers from the cooling system team, two scenarios and evaluating how the knowledge about margins informs the change behaviour. Secondly by presenting the decision tree (shown in Figure 6-13) and the model (shown in Figure 6-14) to top managers who have a global overview of the product development strategies in the company, to investigate whether the elicitation of margins was of benefit in its own right (i.e. the margin's elicitation model could act as a guide to engineers evaluating engineering change).

6.7.1   CPM Analysis

As was stated earlier in this chapter, the cooling system design manager and the cooling system engineer were requested to participate in this phase of the model building exercise. They were

asked to build a Change Propagation Matrix (CPM) considering two scenarios; when they have major changes (new big project) and when they have minor changes. For the evaluation phase the first scenario when they have major changes is considered for its relevance.

Scenario 1: New project

Based on the linkages identified in a previous exercise (see section 6.5.2) the participants were asked to build a CPM in case they have major changes. Each participant did the exercise alone, in a separate session, and was guided through the exercise by the author. After the initial model, a refinement iteration was undertaken. The author reviewed the model to check that the linkages which should be symmetrical (i.e. spatial and mechanical connection) were symmetrical in the model.

Once the linkage model is created for the system, the participants were asked to assess the likelihood and the impact of change propagating.

The impact and likelihood values from the model were scale between 0 and 1, then run through the CPM tool (Figure 6-15)
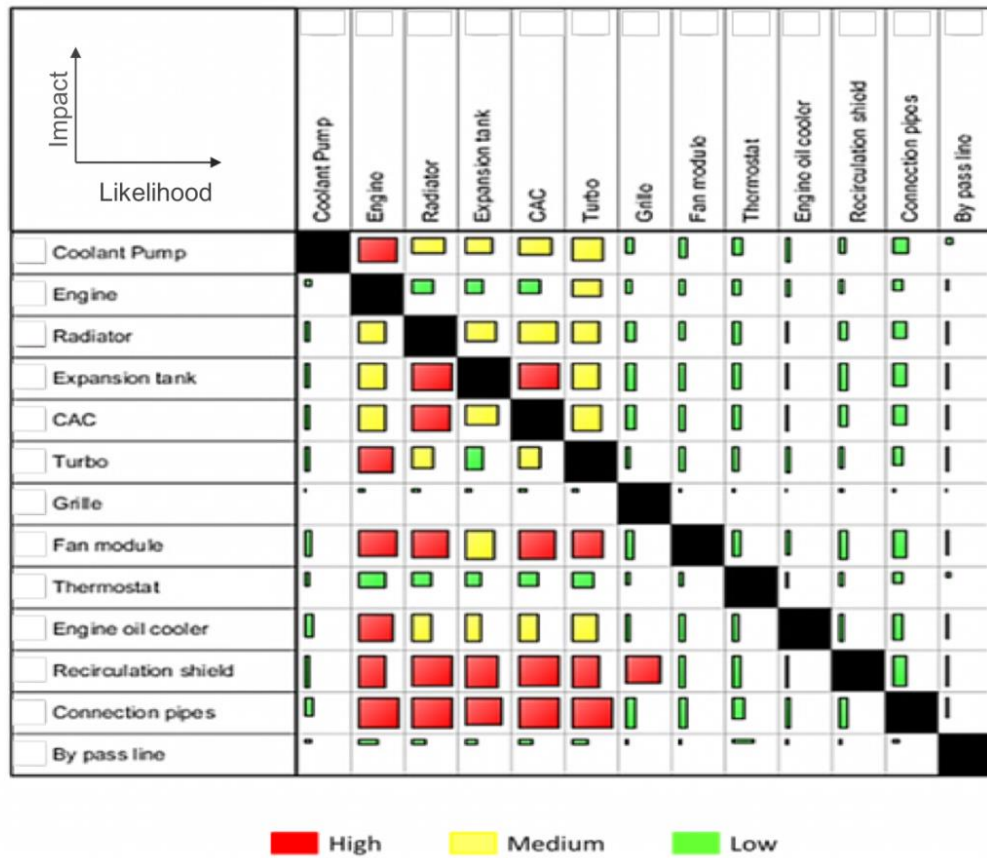
Figure 6-15 Results from the CPM tool for the cooling system

The results were recorded to identify the components most likely to influence change (cause it to propagate) and the components most likely to be susceptible to change (affected by change propagation).

These lists were discussed with the cooling system design manager and the cooling system engineer; they were also presented at a meeting to the other engineers working in the cooling system team.

Overall the results from the evaluation exercise appear good, as there were no major contradictions. However, this scenario highlights an interesting point: the fact that the fan case assembly is likely to be affected by change, but unlikely to be redesigned as a result of a change.

This means that margins would have been built into it in the first place to avoid a re-design. The fan case assembly has a long lead-time for design and assembly. As a result, it is designed with enough margins in the components around it to allow it to absorb changes. The cooling system manager and the cooling system engineer had different thoughts on this. After discussion, it was decided to consider the fan as a module to simplify the exercise. Some discussion was carried out between the sessions to identify how the knowledge about margins can inform the engineering change. The outcome of this exercise helped in developing the process shown in Figure 6-14.

It appeared from this aspect of the evaluation that the data from the CPM tool was a useful basis for eliciting margins and implementing changes.

6.7.2   Model Visualisation: decision tree and elicitation process

Designers can take active design steps to generate margins within a product. The obvious example is to overdesign a system or component and thereby generating an excess that can be used up in future changes. This does not mean that all parts of a system are overdesigned, rather than that designers design or redesign specific components so that the overall system has a greater flexibility. For example, if a system is getting too heavy, it might be enough to redesign one component to make it substantially lighter in order to give the whole system a weight margin that can be used for future changes. Usually this can only be justified if there is an immediate benefit for the current system. This was the basis of the discussion with two senior managers and a senior engineer who visited The Open University to discuss the findings and evaluate the proposed model.

During the evaluation exercise the need for visualisation techniques arose frequently. The managers and the engineer involved felt that the ability to manipulate the model to focus on the areas of interest raised by a particular scenario are valuable.

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During the first session, the decision tree was presented to demonstrate how the knowledge about the margin state can inform the design strategies. The model was useful because it helps "*distinguish different states of margins*" and "*structure our thinking in terms of buffer and excess before taking any decision about the margins*" (O.I senior manager).

Afterwards, in the second session the elicitation process was discussed and refined based on the participants insights. Overall, the model was relevant as it gives a whole system perspective. This is particularly important in a big company such as Volvo, where components are often geographically dispersed in major projects and therefore the opportunity to view the system and the product as a whole is extremely helpful.

6.8 Summary

It is important to capture the knowledge about margins throughout the product development process. This can help the company to manage the development process more efficiently, since margins have obvious benefits for design processes in accommodating changes and reducing the risk of additional iteration loops.

A conceptual framework was developed to investigate and capture margins. The overall framework indicates that a clear elicitation and an explicit documentation of margins can help decision makers implement more efficiently the necessary changes involved in product development.

The exercise can be summarised as:

i.   Although DSM looks like a simple for dependency modelling but it is not as simple as it appears. Deep understanding of the studied system is required for the modelling. There is a tendency to put too much information in a link (for example to put two types of connection

for a link between two parts). But to make it understandable and transferable, it is recommended to identify just a single type of information in a link.

ii.   Case studies revealed that the approach used in this research forces engineers to examine products from a different perspective and that building the models themselves is a valuable exercise in its own right. A key point about the conceptual framework is that it gives engineers a global product overview and also make them think over the uncertainties they face during the design process; such as the evolving precision in requirements, emerging constraints or changes. This perspective helps people appreciate the complexity of their products and it makes them view design margins in different terms. Design margins are seen as an important aspect of product design.

7 Discussion

This chapter provides a general discussion to the thesis. It also discusses margins from two different perspectives.

7.1 General Discussion

This thesis argued that margins play an important role across the entire design process. However, margins are not recognised as a unified concept which is clearly communicated and tracked throughout the design process. Rather different people have different notions of margins and do not disclose the rationale behind adding margins or the amount that they have added. This can ultimately lead to products which are more costly to develop than necessary. However, margins also enable designers to avoid design changes as they know the extent to which existing components and systems can accommodate new requirements and thereby saving significant design time. Hence, having a clear picture of the state of the margins on component parameters, together with managing the ways that requirements are met as a product is developed, are important aspects of product development. Understanding margins will be of a great benefit to the company to cope with product optimisation without compromising the platform strategy. Therefore, how well a manufacturing company is able to understand the margins of their design concepts is crucial in successfully dealing with changes that occurs throughout the development process.

Margins are a combination of buffers built into a design to cater for uncertainty and excess which is a genuine surplus in a component, system or design. While different notions of margins favour one or other aspects, it becomes clear that both aspects have to be looked together. As the excess part of a margin provides design flexibility, designers can try to reduce uncertainty, for example by reducing the variability in use, to move parts of the buffer element of the margin into a useable excess.

At a general level, the work presented in this thesis has helped define the concept of design margins. As was described in Chapter 2, there are relatively few publications on the topic and what has been published is usually unlinked and only focuses on specific aspect of margins such

as performance margins. There are very limit references in the available literature that have examined design margins in companies in detail or addressed the concept from a process view. This thesis redresses this by reporting upon an empirical study carried out in Volvo GTT. One of the findings from this study was that there is a clear industrial need for support with design margins and how they are communicated in teams or across teams. An explorative process method grounded in the needs of industry has been proposed to model design margins. The method focused on understanding the product and the connections among different parts in order to capture margins and the role they play throughout the product development process. Without understanding the details of a product, it is difficult to predict its exact behaviour or understand the margins associated to key components or systems.

Margins on key parameters can apply to the whole system, such as the engine design temperature, or as margins for specific parameters, like the temperature a material can handle. Another important group of margins to capture are those on critical components where a company knows that they will not be able to absorb change. However, if they are aware they might be able to compensate through making fundamentally different design choices. These design considerations are highly relevant where alternative configurations and variants are considered, with princely different margins behaviour. This critical margin information can be flagged up and shared across an organisation.

7.2   Knowing and communicating margins

Generally, designers have a sense of the margins some key components have, rather than knowing an explicit value of margins they had a sense of whether their component would be able to absorb more change or be able to be changed easily without requiring a major redesign.

However, this knowledge is usually not recorded explicitly. The product planners and designers in the early phases of a new product did not know to which extent a component could still be changed. The designers in later stages where usually not aware that margins have been added to the requirement or had little sense of how much margin was added.

Margins are not communicated explicitly across the organisation, but become part of the discourse in informal negotiations within the company. Some critical margins are flagged up as part of concerns for the longevity of the product, but large margins are often left uncommented. As designers are often aware of the state of the margins of their own components, they often try to protect components with critical margin in the design process from changes. One way of doing this by embedding the parameter values deeply in the sequence in which dependent decisions are being made, so that they parameters and their components cannot be changed without undoing a large part of the design process. For example much of a product in the case study is designed around the harmonic frequencies. If these are changed most components would need to be altered, therefore values from which the harmonic frequencies are derived usually remain unchanged.

7.3 Designing margins into the product

Some major systems are designed explicitly so that a system does not have to be redesigned in the next product generation. For example, the truck company recently redesigned their wiring harness and created a new harness with several unused ports in the expectation of needing them in a future product generation. In this example, the margins are clearly visible to everybody including the customers, as the additional cost is minimal for the current generation but with a clear advantage in the future.

Designers can take active design act steps to generate margins within a product. The obvious one is to overdesign a system or component and thereby generating an excess that can be used up in future changes. This does not mean that all parts of a system are overdesigned, rather than that an engineer designs or redesigns specific components so that the overall system has a greater flexibility. For example, if a system is getting too heavy, it might be enough to redesign one component to make it substantially lighter to a give the whole system a weight margin that they can use for future changes. Usually this can only be justified if there is an immediate benefit for the current system.

Sometimes the design itself can be flexible so that it can be used in different contexts without requiring a change. A simple example is that the engineers designed a fixing where screws where screwed into slides rather can holes, so that they could be moved around without needing to add additional holes. Similar decisions can be taken about far more complex components. In fact, some of the motivation between a move from hardware to software comes from a need for increased flexibility.

8 Conclusions

This chapter concludes the thesis. It includes the main conclusions, the research contribution made by this work and reviews the research questions. Limitations of the work are discussed along with suggestions for future work.

As stated in the introduction (Chapter 1), the aim of the project is to investigate the concept of design margins and how the industry is handling that in the current practice. The principal objective in this thesis is to describe design margins in a suitable language and propose a method to model margins in a way that can be linked to the existing product representations.

8.1 Answering the Research Questions

The three main research questions of this thesis have been supported by the findings of the literature review (Chapter 2) and the empirical study (Chapter 4). A number of sub-questions, which were outlined in Chapter 1, arose from the main research questions. Although some have partially been answered in the previous chapters, each will now be addressed in turn.

The first question is aimed at defining design margins:

RQ1 : How can margins be defined?

The case study conducted at the company showed that margins can be referred to by many terms. Margins are considered by different teams in the organisation, who use different terminology and are not necessarily aware of the margins other teams have added. Margins are added both to the requirements that are given to the product planners and the design itself by the designers. Chapter 4 discusses the different terms used for margins and the motivations behind adding these margins.

During the product definition phase, the customer needs are analysed in order to generate requirements for the design team. At this stage a safety margin might be added to the customer requirements to anticipate changes in the use conditions. For example, if a truck is designed to carry a certain load, the company can't control or prevent customers from overloading the truck. Therefore, they plan in a safety margin. The design team used the specified requirements to generate their design definition, in which they add a design margin to cope with uncertainty (buffer). Towards the end of the design process the tolerances are added to assure a reliable manufacturing process. Both the product definition team and the design team might add a margin as a room for growth to allow for future changes in requirements.

This thesis proposes a definition to margins which covers all these terms. A margin is: "*the value a parameter has above and beyond what it needs to meet its functional requirements regardless of the motivation for which it was included*" (Eckert, Earl et al. 2013).

The second research question concerns the way design margins are handled.

RQ2 : How margins are handled in the PDP ?

This research has studied the way margins are handled in the company. A distinction between two elements; buffer and excess, was proposed to help understanding the concept of margins in order to manage them.

As argued in Chapter 5, margins can be seen as an element of buffer and an element of excess. The terms mentioned in the interviews also can be thought of as either buffer or excess concepts, but the division is not always straightforward. Safety margins and tolerances are both buffers that can be added to deal with uncertainty. Safety margins deal with uncertainty in use and in particular uncertainty arising from misuse of products. Tolerances are catering for uncertainty arising from manufacturing variability. In trucks an element of buffer is already incorporated in the requirements, as they include the variability in the use conditions.

Room for growth is an explicit excess concept which is aimed at generating an excess to allow designers to meet higher requirements in the future. Overdesign can be seen as a both an excess and a buffer. At the early stages, overdesign is considered as a buffer to cater for uncertainty or changes in the requirements. Once the uncertainty of knock on effects of changes is removed the overdesign moves from a buffer into an excess. Later in the process overdesign is seen as a form of costly waste, i.e. a form of excess that can be eliminated. However, the designers think of overdesign as a buffer against future changes either through new versions or in the next product generation and do not wish to drop out their overdesign.

From this study, it become clear that design margins are added or used up across the entire product development process. Also, margins can potentially be accumulated throughout the design without other parties necessarily being aware of this occurring, which makes tracking margins difficult. However, throughout this thesis and particularly in Chapter 5 we demonstrated how design margins shape the whole product development process.

The third question looked at the possible ways to explore and model margins to manage the engineering change;

<u>RQ3 : How margins can be modelled to manage the engineering change?</u>

Design Structure Matrix (DSM) method was used to capture the relationships among components and dependencies between components. Further an activity based on Change Prediction Method (CPM) was used to analyse the change propagation among components (Chapter 6). The understanding of these relations provided useful insights for a better way to model margins. Needing to have an overview of the product goes beyond being able to predict the performance of a part and the impact of a change to it. It is vital for managing the design and development process.

The work described in this thesis aims at improving the understanding of design margins and proposes a method to investigate the concept. The objective of this research is to bring new knowledge in the area of engineering design that would be of benefit to industry and academia.

8.2   Research Conclusions and Contributions

The notion of margins, consisting of buffer and excess and the transition from buffer to excess throughout the design process give designers a rich way to express and communicate information about the forthcoming design. These design considerations are highly relevant

where alternative configurations and variants are considered. This critical margin information can be flagged up and shared across an organisation.

On the other hand, a company, has to consider margin across a particular the design process and also across multiple products. As components and systems are deployed in different applications, there might be huge margins with regards to one application and be optimal for another, so that cost of creating an optimal product has to be traded off against the cost of creating a bigger platform and less communality across applications.

8.2.1   Main conclusions

- Design margins have always been an important part of the product design and development process, but today they are a critical aspect.

- The knowledge about design margins is tacit. Most of this knowledge is present in the minds of some engineers. It was found that there was no formal way to capture and communicate margins in teams or across teams. Sharing this knowledge is vital to the company success.

- Design margins were identified as being a way to respond to uncertainty in the product development.

- Design margins shape the entire product development. When known, design margins can enable designers to avoid unnecessary design changes as existing components and systems can accommodate new requirements and thereby saving significant design time.

- Design margins are a core element in the trade-off between the product cost and the process cost (the cost of designing with margins vs the cost of designing new components for each application).

- Design margins allow the trade-off between the optimisation and customisation.

8.2.2 Contributions to knowledge

- The case study provides evidence that margins are added by different stakeholders for different reasons without using an accurate method of documenting them or communicating them in teams or across teams.

- Design margins can be seen as a combination of two elements; a buffer built into a design to cater for uncertainty and an excess which is a genuine surplus in a component, system or design.

- When the margins in the product are known they guide the engineers in their actions or decisions that they make in the process.

- As most of the design activity is constrained by the lead-time, knowing the margins helps the designers to design quicker. Design margins set out options and possibilities.

- This research proposes a conceptual framework for exploring the concept of design margins. It tracks the margins through stages of a process, particularly in the transfers between buffer and excess and using up excess in meeting new requirements

- This research highlights the potential application of design margins such as in; change prediction and management, knowledge management and cross functional team support.

8.2.3 Contributions to the company

- Comparison between the company terminology and literature on the topic of design margins.

- The company obtained external views and different insights on issues related to the product development, the used terminology and the need to explicitly document the knowledge about design margins.

8.3 Limitations and Future work

Alongside the contributions described above, the research has several limitations. This section attempts to cover some of these possible limitations.

One of the limitations is that findings are based mainly on a single case study. Although it was planned to study another system or consider another case study from aerospace industry, it wasn't possible to carry out another in depth study within the three years of the PhD. Therefore, analysis of another system or other products would be recommended to generalise the research findings.

Designers need a variety of different visualisations of the data to be guided to important information. The method proposed in this thesis tried to combine well known methods used in industry to draw conclusions on how margins can be managed. However, the models are only as good as the knowledge that is put into them. Who is in the team creating the model will depend upon the purpose to which it will be put. For example, a team of novice designers will produce a very different model from a group of experienced engineers, but the act of building the representation itself might be a useful learning process.

One of the important limitations of this method is how it currently links with the Change Prediction Method (CPM). In this thesis, the CPM was only used to examine a single connection between two parts and the potential change behaviour. Understanding margins is the key to carrying out engineering change processes efficiently. The concept of margin can therefore inform more accurate change prediction.

Future work will further develop the understanding on how margins aggregate. Detailed studies in this sense will enable to link back the concept of margins to the Change Prediction Method (CPM). This could potentially be incorporate to Cambridge Advanced Modeller (CAM) the software used to model DSMs and CPM.

Another important aspect of future work is to examine other modelling methods especially mathematical ones. During this research, we were confronted with many complex aspects related to design and product development such as, multi-objective optimisation, uncertainty, controllable uncertainty and it would be very important to consider these aspects in more details. This will offer significant potential for supporting product planners and senior managers with potential product offers and configurations.

Analysis and reflection over the previous research contributions have led to the author to identify some opportunities for future research arising from this thesis. These opportunities are:

Investigation of the relationship between design margins and probability

Chapter 5 analysed and discussed margins as crisp values versus margins as a range of possible values. This has led to the conclusion that there is no systematic way to accurately determine the value a margin could have. Further investigation of the relationship between design margins and probability will serve to help identify how to quantify and calculate margins and how this information can be used in design.

Empirical research on the cost of design margins

Chapter 5 discussed that there is a cost associated to design margins. The question that arises from this point is the trade-off that needs to be made between the costs of developing a new component versus the cost of designing with margins (i.e. what excess is acceptable). Performing further empirical study to quantify the actual cost of designing components with margins and make comparison with the total cost of developing new components for projects that are subject to major changes, is an opportunity for future research arising from findings reported in chapter 5.

8.4 Summary

Throughout this thesis we have been arguing that margins occur during most phases of the design process and have a big effect on the working of many engineers, however they are surprisingly unaware of margins and do little to communicate them explicitly. Design processes are subject to many uncertainties coming both from the outside and the design process itself, which affect requirements and design implementations. Any change to the product at any point affects the margins on other components, which either have to be changed and operate under different conditions. However, the effects are cumulative and not tracked throughout the design process. The thesis presents a model of margins allowing them to be tracked through the stages of the design process. The motivation, development and validation of this model took place in collaboration with the Volvo Trucks who provided access to design engineers and their data. This access to data and personnel covered the general design processes in the company enabling an examination of the role and potential for margins at several stages in the design lifecycle. The collaboration facilitated the investigation of a detailed case study on a truck cooling system which provided a testing ground for the proposed method.

9 Appendix

Questions asked during the interview with the durability manager

1. Can you please tell us about you work?

2. What does durability mean? How does it differ from reliability or robustness? Is that covered by other features?

3. What areas of the truck cause durability issues?

4. How does this differ with use scenarios?

5. How do you account for them?

6. What happens when you raise a concerns about an element of the truck?

7. How do you estimate risks associated with durability.

8. How do you measure durability/reliability?

9. How do you test the components for durability? Do you consider the worst case scenario and you test accordingly?

10. Are your tests integrated with other tests?

11. What are the failure mechanisms?

12. Do you use any specific tools or methods like FMEA?

13. How do you make sure that you maximise the reliability during service life?

14. How do you insure that a level of reliability is maintained when some components are too optimised or overdesigned?

15. I guess you can collect data from the field by looking at the product performance and identify any systematic faults that can be fixed in the current product generation or future one. How do you do that?

Interviewer: So how easy is it to get people to accept the new process at Volvo?

Respondent: It's depending on how the process is evolved. If it's a top down command it's very difficult, but if it's coming from beneath up then I don't think it's difficult. There is a tendency that it will come from above or from the side more, from people who have not maybe enough knowledge of how we work today so therefore there is a big gap between how we judge the current situation and therefore it could be some difficulties.

Interviewer: So you don't like consultants coming in and telling you how to do your processes.

Respondent: No, no, it doesn't work very well but we do it.

Interviewer: Why doesn't it work? What is the problem?

Respondent: The problem is the obvious, quite complicated and the people coming from outside have a tendency to simplify it a bit and then come with advice that fits this simplified world but it doesn't cover the daily work for the engineers because we have very complex product here. People can see we do trucks but it's better to say that we do parts that you can put together in a million different trucks, like Lego toys. Of course this part must fit together and it must be a decent truck, not always a complete optimised truck because then we need to look at those million different combinations that is possible.

There is a big gap between those who come outside and they look at the car industry and come with advice. A car, it's complicated in some way but

compared to the truck chassis it's not in the same category at all. The complexity we have on a car we have on the cab, you can say, different styling, different colour, different interior but the chassis is more special, more unique or different.

Interviewer: So where does this added complexity come from, in your opinion ?

Respondent: First of all there is a natural complexity because if you look on a truck outside that they use for various purposes, you have long timber trucks, there's short tractors as we call them and you have different loads, you need to carry a different amount of load. Some are doubled rear axle because they carry more load and some have one because they are…and they are very tailored for the legal requirement of how long and how heavy a truck can be. Then we have all the timber trucks, construction trucks, trucks for garbage, rosary. They are all different so therefore the chassis has a natural big variation.

Then we have the sales organisation who want to have as few mutations as possible. They don't like gaps in door frame so it's not necessarily that they sell a lot of it and that they earn a lot of money on those variants, but it's a culture or a company…they want us to provide a lot and we can by the way we are working provide a lot. It's from two sides, partly we have learnt how to handle them so therefore there's no break or block and then the sales organisation and they want a lot because the customer came in and said, "I want this truck but I want another fuel tank size." It could be any small changes, that they want a different tyre brand or big changes that they want.

So they see this on the market, this demand of various, I think I can call it tailored trucks and we try to do them as serial trucks and not as unique trucks.

Interviewer: Is there anything where Volvo would say, "No we're not going to develop that" or "that's not where we're going to go to"?

Respondent: Yes sometimes and of course there are technical problems sometimes to do it. Then of course it will cause the restrictions. They are this gap in the doorframe and then of course there are some combinations that are ridiculous, that you don't do a high feature from them and a low feature robust rear ends it's no use or a very heavy truck with a very small engine. There are of course natural limitations but if it's requested and if it's possible and product planning can present a business case and we estimate that we will sell 100 of these, then we do it.

Interviewer: Then it becomes a small project and you do it.

Respondent: Yeah. Now we have in the base product we have a lot already and then if it becomes a new project we take all the variants we can do into the new project and then only add something.

Interviewer: How easy is it for you to judge whether it's feasible to do something if it comes from sales and they say, "We're going to need 100 of those"? Do you know whether you can do it or at what cost you need to do it?

Respondent: We have a certain process that we follow. Normally this will change, request goes out in the organisation and we estimate. First we try to figure out what do we need to do? Then we estimate the cost of that and then it goes to a

decision [inaudible 00:10:57] and they do this, if it's a business case or not. They have a way to calculate the payback time for such an investment. So that is the regular process. Every week I think they have…there's a lot of these small changes and then sometimes it's big, like a new truck that you saw maybe on the job here.

Interviewer: But can you always estimate that you're not having to do big changes because of these relatively small projects?

Respondent: Sometimes we get into surprises because this pre-study, as we call it, had not been done properly and then of course they have to reconsider. There are these gates, I don't know how much you know about the process but there is a checkpoint at each, so at those you should update your cost estimate and if you figure out, I guess, 100 hours but we need 1,000 then that goes into the next steering committee and then they have to consider should we close this or should we do it? So it happens of course. Normally of course there is a tendency to underestimate work. You do a full investigation of everything before you answer, it's a little bit simplified but if the right people are involved they are fairly accurate, but easy. Nowadays it's where there are more and more software in the truck it's more complicated. Mechanically I think we are quite skilled in seeing what we need to do but it's more complicated because the software is connected to all these variants and loaded on the truck, so each truck you need to know exactly how many axles and everything

A part of the cooling system engineer interview transcription

[Markus] …..We then translate those into... design briefs. And we give those to the, ah what we call the engineering systems organisation, which is made up of the CPPD teams focused on engine systems, cooling, you know, lubrication, erm performance, emissions and so on. And ah then the deliverables. So we're the requirements gatherers, the they actually deliver the product. OK. I'm te, I'm moving out of the talk-about-it organisation and into the doing organisation, to run what we call the systems engineering group. And the systems engineering group model total machines, and, trade off the requirements at an engine level, decide what's feasible and what's not, so yeah our customers might say they want ah the smallest engine in the world at the cheapest price, putting out the most power. Mmm. Which is sort of mutually exclusive.

[Markus] Mmm.

And somebody's got to arbitrate between what do we give the customers, what would be competitive, and what have we got the capability to deliver. And umm, that's where the the requirements are brought in, and then expectations are set by the systems engineering group to... trade those off. So, here's the "what", here's the "how", the "how much", we don't know until the systems engineering have really looked at, OK if you want this fuel consumption you realise you need this heat breeze????, you need this packing size, you need this power and so on. So that's, that's the way it goes.

[Claudia] So essentially you have to check whether that all adds up to some extent?

[Markus] Yes, it's, it's, within our... product objectives. What we've done differently…as you may know is we've mapped the voice of the customer down through the business…So umm, we now have tools which we've developed to do that, so we can look at this highly complex interactions, it's a bit like an SDM

[Claudia] Yeah.

[Markus] But it's now done against requirements, and in fact we've complemented it by using the SDM-type approach. So we've now mapped...

[Safaa] Sorry, what do you mean by SDM?

Sorry, yeah. Structural...

[Claudia] Do you mean DSM?

[Markus] DSM, sorry, right, OK. (Laughter) Little bit of a mix-up in letters, you'll notice that with me. It's always names, ????. So yeah, the SDM side of it, the structural... matrices, it's all about mapping and how much detail you want go in to.

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