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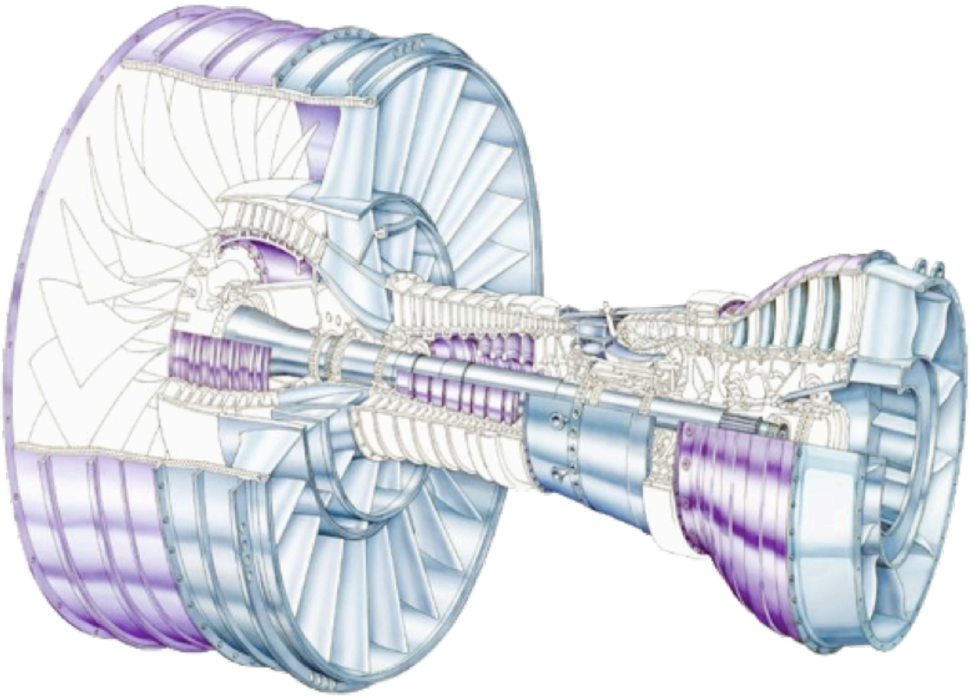

Design for Robustness as a natural way of working within projects at Volvo Aero Corporation

Master of Science Thesis in the Master Degree Program, Product Development

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Göteborg, Sweden, 2011

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Cover: Generic picture of an aero engine. Volvo Aero Corporation is specialized in the components highlighted in blue and purple.

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Abstract

Volvo Aero Corporation has during the last two decades gone from producing both complete aero-engines and components for aero-engines based on designs licensed from others, to engaging as partners in most of the worlds large engines programs with responsibility for development, production and service. This shift has required Volvo Aero Corporation to initiate, train and develop an organization that is capable of taking that responsibility. With the increasing production volumes that follows the engagement in world-wide engines programs – serving the largest aircraft manufacturers in the world – the capability of designing components that can be produced in a reliable way so that they meet requirements in a reliable way is crucial.

As a way to create this capability Volvo Aero Corporation has introduced the concept of Design for Robustness. Design for Robustness is a mindset that is adapted to ensure that components are designed in such a way that they are insensitive to unwanted variation; variation that cause the products to not meet requirements through variation in production, variation during use, etc. To manage this initiative Volvo Aero Corporation has founded a Centre of Excellence for Design for Robustness (CoE DfR) who's purpose it is to develop and supervise the methods and practices related to Design for Robustness. This thesis has been performed together with CoE DfR to investigate how they can improve their impact within Volvo Aero Corporation. This has been done through the analysis of how they are perceived today, mainly through nineteen qualitative interviews with employees at Volvo Aero Corporation. This has then been compared to how research on the subject describes good robustness work. From this analysis, recommendations for Volvo Aero Corporation have been elicited.

The major findings from this work include the notions that the knowledge about Design for Robustness is at an overall basic level and unconsolidated and that the knowledge of CoE DfR is insufficient at Volvo Aero Corporation. This has resulted in recommendations to define Design for Robustness at Volvo Aero Corporation and to define CoE DfR, to be able to educate the personnel. Findings also identify a need to introduce system support for Design for Robustness, a need to increase the knowledge about the production processes in the development work and a need for increased cooperation between departments. Those findings have led to recommendations concerning more analysis of the operational systems, design practices and the concept of a robustness mentor, all to find ways to address the identified needs. Finally, suggestions have been brought up during the course of this work for a robustness measure – a way to measure robustness so it can be more easily assessed. The findings in this study has though only confirmed the need for a measurement in the design work and not how it should look, this has been suggested for future research to find out. Though, one recommendation has been made regarding measuring robustness and that is to set up a database were robustness indicators could be recorded so that the results from working with Design for Robustness can be evaluated over time.

Key Words: *Design for Robustness, Robust Design, Volvo Aero, Product Development*

Design for Robustness som ett naturligt arbetssätt inom projekt på Volvo Aero

NICKLAS BRAGSJÖ

Sammanfattning

Volvo Aero har under de senaste två årtiondena gått från att producera både hela flygmotorer och delar av flygmotorer på licens, till att vara partners i de flesta av världens stora flygmotorprogram, med ansvar för utveckling, produktion och service. Denna förändring har krävt av Volvo Aero att starta, utbilda och utveckla en organisation som kan hantera det ansvaret. Med de ökade produktionsvolymer som följer på deltagande i världsomspännande flygmotorprogram – som levererar till de största flygplanstillverkarna i världen – är kapaciteten att kunna konstruera komponenter som kan produceras på ett tillförlitligt sätt, så att de möter ställda krav på ett tillförlitligt sätt, avgörande.

Som ett led i att skapa den kapaciteten har Volvo Aero introducerat konceptet Design for Robustness. Design for Robustness är ett tankesätt som används för att försäkra att komponenter konstrueras på ett sådant sätt att de är okänsliga mot variation; variation som gör att produkterna inte möter ställda krav genom produktionsvariation, variation under användning, etcetera. För att hantera detta initiativ har Volvo Aero skapat Kompetens Centret Design for Robustness (KC DfR) vars syfte det är att utveckla och övervaka metoderna och bruket av Design for Robustness. Det här examensarbetet har genomförts tillsammans med KC DfR för att undersöka hur de kan förbättra sin genomslagskraft inom Volvo Aero. Detta har gjorts genom att analysera hur de uppfattas idag, huvudsakligen genom nitton kvalitativa intervjuer med anställda på Volvo Aero. Detta har sedan jämförts med hur forskning inom området beskriver bra robusthetsarbete. Från denna analys har sedan rekommendationer till Volvo Aero utvecklats.

De huvudsakliga resultaten från det här arbetet inkluderar insikten att kunskapen om Design for Robustness är på en övergripande grundläggande nivå, men osammanhängande, och att kunskapen om KC DfR är otillräcklig på Volvo Aero. Detta har lett till rekommendationer om att definiera vad Design for Robustness innebär för Volvo Aero och att definiera vad KC DfR ska göra, för att kunna utbilda personalen i dessa ämnen. Resultaten identifierar också ett behov av systemstöd för Design for Robustness, ett behov av ökad kunskap i konstruktionsarbetet om produktionsprocesserna och ett behov av ökat samarbete mellan avdelningar. Dessa resultat har lett till rekommendationer om att inleda fler undersökningar av ledningssystem, konstruktionsanvisningar och innebörden av en robusthetsmentor. Detta för att hitta sätt att adressera de identifierade behoven. Slutligen så har förslag identifierats under arbetets gång som handlar om ett robusthetsmått – ett sätt att mäta robusthet så att den kan utvärderas lättare. Resultaten från den här studien har dock bara bekräftat behovet av ett robusthetsmått i konstruktionsarbetet, inte hur det kan se ut. Detta har föreslagits för framtida forskning att utreda. En rekommendation angående mätning av robusthet har dock kunnat göras: att skapa en databas där

robusthetsindikatorer kan sparas för att bekräfta att resultaten från att arbeta med Design for Robustness kan utvärderas med tiden.

Nyckelord: *Robust design, Volvo Aero, produktutveckling*

Contents

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To all the people at Volvo Aero Corporation who have been a part of the interview study I would like to say: I couldn't have done this without you!

To my wife, who has encouraged me tremendously and supported me all the way, I would like to direct my sincere love.

Nicklas Bragsjö, Göteborg 2011-02-06

1 Introduction

1.1 Why is Volvo Aero Corporation interesting from a Design for Robustness perspective?

The history of Volvo Aero Corporation (VAC) dates back to the 1930's when the Swedish Board of Aviation ordered 40 aircraft engines intended for the future Swedish Air Force from the locomotive manufacturing company (Nydqvist & Holm in Trollhättan, Sweden) that seven decades later should have transformed to VAC. The engines that they made were manufactured on license from international companies such as Rolls Royce Ltd. and Pratt & Whitney with adaptations made to fit the Swedish planes. Engines from the early VAC have been used in all the Swedish fighter jets. (Volvo Aero Corporation, 2007)

To increase the market opportunities an initiative was launched in the 70's to market VAC as an engine producer with capabilities of producing for the commercial market. This initiative led to partnerships with Garrett, GE and Pratt & Whitney and today VAC is a partner in almost all engines programs and have specialized in shafts, spools and cases. The focus at VAC is to develop lightweight solutions to reduce the fuel consumption. (Volvo Aero Corporation, 2007)

From the early 90's VAC has taken an increased responsibility for the development of the components they produce for the engines programs where they are partners. This has led to VAC going through organizational changes that include the creation of a development organization. As partners in programs that develop engines for aircraft manufacturers such as Boeing and Airbus, owners of some of the most expensive industrial projects ever, the importance for VAC to develop components that can be produced and delivered on time, and at the right quality, has become crucial. (Vega Galvez, 2010)

In the aero-industry today there are large efforts put into making products lighter. The main reason for this is to reduce the fuel consumption of the aircrafts to reduce their environmental impact. With the aim of developing lightweight solutions VAC has introduced the concept of fabrication – instead of producing large castings, smaller casted, forged and sheet metal formed parts are assembled. The use of this concept put high demands on geometric accuracy to assure that the components can be produced to meet requirements: the designs need to be robust. (Vega Galvez, 2010)

With the participation in large commercial engines programs, today VAC is facing increased production volumes. To handle those increased volumes while fabricating components is a challenge that put even higher demands on the robustness of the products. When the volumes increase, the cost of correcting recurring deviations becomes too high. (Vega Galvez, 2010)

1.1.1 The Centre of Excellence Design for Robustness

As a means to manage the issues of producibility and reliability VAC has implemented Design for Robustness (DfR). DfR is a mindset that is adapted to ensure that components are designed in such a way that they are insensitive to unwanted variation. (Bergman & Klefsjö, 2010, p. 195) As a way to implement and develop the initiative a centre of excellence for DfR (CoE DfR) was created. The purpose of this centre of excellence is to develop practices for VAC to work with tools connected to DfR and to do this they have defined five areas that they work with: probabilistic design, risk management, requirements management, producibility and concept selection. (Wendel, 2010)

1.1.2 The issue

The perception at CoE DfR is that their impact on how VAC works today isn't what it could and should be. To reach out to everybody in the organization has proved hard. There is also a thought from CoE DfR that the employees at VAC don't share their understanding of what DfR is and that this is a reason for their lack of impact.

1.2 Purpose of study

The purpose of this thesis is to investigate means for getting awareness and an acceptance of the need for robust design within VAC. Since the need is already established by the organization the main issue will be to diffuse that knowledge throughout the company. In the long run this is done in order to make VAC's products less sensitive to natural variation.

1.3 Aim

In order to meet the purpose with this thesis a mapping of the perception of DfR at VAC will be done. This mapping will be the building ground for an analysis that aims to propose recommendations on how VAC can increase the acceptance of DfR. In the scope of the thesis will also be to investigate the need for a robustness measurement and depending on the results from that investigation the development of that robustness measurement will be initiated. The idea of a robustness measurement is that it can make the evaluation of the robustness in a design easier hence increasing the usability of the methods. In the development of this measurement the focus will be on validating the need of it and verifying that it can be used at VAC.

The aim of this thesis will be to answer the following research questions:

> RQ1: How do the engineers at Volvo Aero Corporation perceive Design for Robustness?
>
> RQ2: What is the need for Design for Robustness within Volvo Aero Corporation?
>
> RQ3: What can Volvo Aero Corporation do to increase the use of Robust Design Methodologies?
>
> RQ4: How can robustness be measured and how can it help Volvo Aero Corporation?

Depending on the answer to research question four, the overall research aim is initially:

> RA: To develop a robustness measurement.

1.4 Scope

In this thesis there will be no deeper examination of explicit methods for robust design. The issues that will be dealt with are in the range of principles and practices for robust design. To some extent the significance of themes in the analysis will be assessed using statistics but overall the collected data will not be subjected to statistical analysis since the population sampled is too diverse and too small. Rather, the analysis will be qualitative and a sense of the situation will be sought after.

1.5 Structure of the report

To start with the report will, in Chapter 2, describe the chosen research methodology and what implications this will have on the study. Chapter 3 will present the theories and methods related to robust design that will constitute the frame of reference for the study. In the following chapters where the findings from the study are presented (Chapter 4), analysed and synthesized (Chapter 5) the report will be structured according to the research questions. The idea is to, in each chapter, describe and analyze what have been found concerning each research question and to funnel down the information from raw data via answers to the research questions to eventually end up in tangible recommendations grounded in the theoretical frame of reference. Through a discussion at the end (Chapter 6) the whole report will be tied together and will eventually lead to conclusions and recommendations for VAC, both on how to deal with the issues raised as a foundation for the thesis (Chapter 7) and for further research (Chapter 8).

2 Methodology and Research strategy

In order to produce a scientifically valid result the need for a well-justified research strategy is crucial. It is also important to thoroughly describe what methods and strategy that has been used in order to give the reader a possibility to assess the results from the study with this description as a context. In this chapter a presentation of how the work has been conducted during this thesis is given.

2.1 Research methods

Given the nature of the research questions – open ended, explorative and qualitative – the choice of focusing on qualitative research methods came natural. Qualitative research is used when the topic of study concerns social interactions and interpretations of words rather than numbers to gain understanding: an inductive view between theory and research is held, with the former generated by the latter. (Bryman, 2004)

The initial research on different methods to use when performing this kind of study comprised of over-viewing relevant literature on the subject. The focus in this study was on case-study research because of the nature of the research questions. As Yin (1994, p. 1) state: “case studies are the preferred strategy when ‘how’ or ‘why’ questions are being posed, when the investigator has little control over events, and when the focus is on a contemporary phenomenon within some real-life context.” The research questions for this study fit very well in to the above description: they are all in a sense asking ‘how’ or ‘why’, the researcher is an outsider to the organization without any ability to control the events studied and the focus is very much on a contemporary phenomenon within a real-life context. Case study research, and how it is used will be closer described in section 2.1.1.

When setting out for this thesis other research methods were considered, especially Action research. Action research is a social research method that emphasizes the participation of the researcher in the studied event (Sagor, 1993, p. 7). The research sets out to solve a problem and to contribute to science (Ottosson, 1996).

Action research often focus on three related stages of action:

1. Initiating action, such as, adopting a text, choosing an alternative assessment strategy.

2. Monitoring and adjusting action, such as, seeing how a pilot project is proceeding, assessing the early progress of a new program, improving a current practice.

3. Evaluating action, such as, preparing a final report on a completed project.

(Sagor, 1993, p. 8)

The use of this kind of method would be highly interesting, to find answers to some of the research questions: to initiate alternative practices of robustness in a pilot project and evaluate the results to assess improvements. Given the circumstances at VAC though, this was hardly possible. Both because the researcher wasn't a part of the organization, and because pilot projects regarding those issues would need to stretch over a longer time then was available. And above all, an approach like that would be very expensive and involve a lot of resources at VAC. VAC Would not be willing to make the necessary investments to perform this type of study at this stage.

2.1.1 Case study research

As a research strategy, the case study is well suited when performing organizational and management studies. (Yin, 1994) A case study investigates a contemporary phenomenon within its real-life context (Yin, 1994) and in the case of this thesis the contemporary phenomenon is robust design and the real-life context is the product development organization at VAC. When conducting a case study it is important to rely on multiple sources of evidence (Yin, 1994, p. 13). This is needed to triangulate – support a statement by converging data from multiple sources – the results. It is also important to develop theoretical propositions to guide data collection and analysis (Yin, 1994, p. 13). According to Yin (1994, p. 18) a guide to lead the study – a research design – is needed. The research design should describe how the research is planned to be conducted and should function as a "road map" to create a link from the initial questions of study to the conclusions to be drawn.

For this study, the available sources of information were literature on robust design, internal documents at VAC – describing e.g. the organizational systems – and information collected from the employees at VAC. Since the research were aimed at investigating individuals understanding of issues and events an approach with personal interviews were chosen to collect the information from the employees (Bryman, 2004, p. 321). Two different types of interviews were conducted. The main contribution was from systematic, semi-structured interviews with a representative sample of employees at VAC and the second type of interviews were informal discussions with the thesis supervisor from VAC and other members of CoE DfR.

To guide the work the "road-map" in figure 1 was developed. This leads from the identification of problems at CoE DfR via the study of internal documents and literature to select suitable interviewees, state research questions and create an interview template, to the collection of data through interviews. With the help of the internal documents and the literature the data from the interviews was analyzed to describe the situation at VAC. From this description, recommendations for the continued work with DfR were elicited.

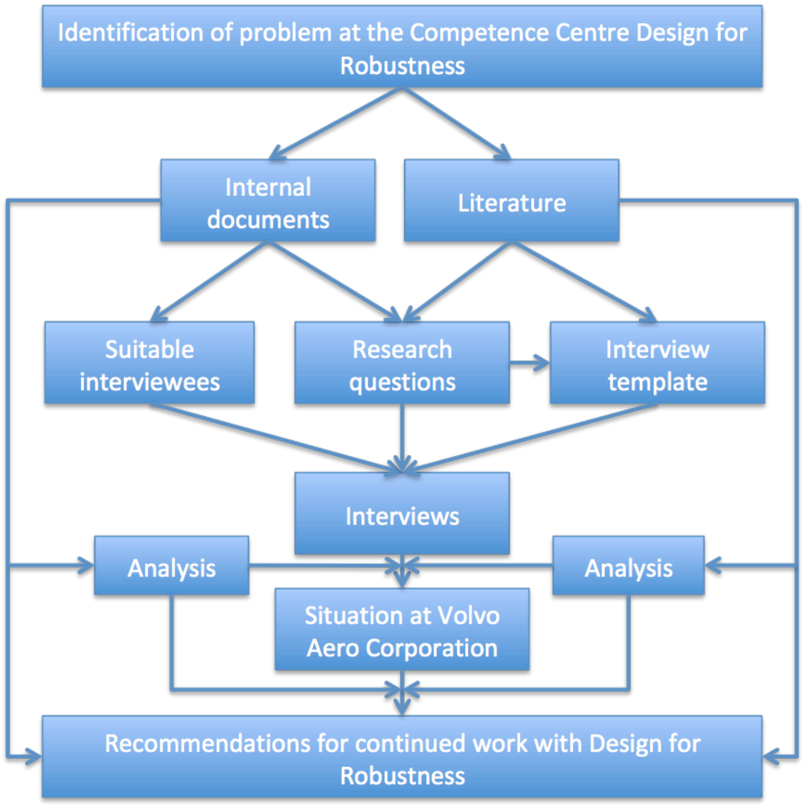

Figure 1 Case study design

2.1.2 Qualitative interviews

When performing the interview study that constitutes the majority of the empirical data in this thesis, semi-structured interviews were used. In a semi-structured interview the researcher has a list of open-ended questions that are asked during the interview. They are not necessarily asked in the same order, but circumstances of the interview guides the interviewer. During the interview questions that are not included in the guide can be asked, either to develop a path of reasoning or to probe deeper into an answer. (Bryman, 2004, p. 321)

The reason for using this technique is to emphasize and understand how the interviewees relate to and understands the topics that are studied (Bryman, 2004, p. 321). Since the research to a great extent is about understanding the individuals' perception of the research question this approach was good to reduce bias from the researcher.

One important issue when performing an interview study is the sampling. In order to achieve a representative sample, from which generalization to the level of VAC could be done, the aim was to have representatives from all affected departments and all the different roles in VAC's development organization. To do this a survey of the VAC internal system was conducted to produce knowledge about what parts of the development organization at VAC that was affected by DfR. From this description a number of persons, representing different roles in the organization (Design Engineers, Department Managers, Project Managers, Method Specialists etcetera) were randomly selected from the departments where the potential from using DfR was high as participants in the interview study.

This approach to sampling is described in literature as purposive sampling, meaning that a good correspondence between research questions and sampling has been the goal. The aim was to interview people who are relevant to the research questions. (Bryman, 2004, pp. 333-334)

Another important issue when performing interview studies is the interview guide. To guide this work the literature on robust design and how the research questions are formulated was considered. A checklist for preparations of an interview guide was adapted from Bryman (2004, p. 324):

- Create order based on the topic areas
- Formulate interview questions in a way that will help answer the research questions (but without being too specific)
- Use relevant and comprehensible language
- Do not ask leading questions
- Do not forget questions about both general (name, age etc.) and specific (position in company, number of years employed etc.) information about the interviewees

The interview guide that was used can be found in Appendix A.

2.1.3 Literature study

The literature study performed to serve as a foundation for this thesis mainly focused on the topics of robust design and product development. To get a good picture of what work that had been done before this thesis was initiated, articles, thesis reports, dissertations and books on the topics were surveyed. With this knowledge a deeper examination of relevant sources, mainly dissertations and books, was conducted. The main sources that were used to produce the theoretical frame of reference in Chapter 3 were the dissertations by Gremyr (2005) and Hasenkamp (2009) and the textbook by Bergman & Klefsjö (2010). Also, to incorporate general knowledge about product development in the study the work of Ulrich and Eppinger (2008) has been used as reference concerning the product development process.

2.1.4 Internal documents

At VAC the Global Development Process (GDP – a generic stage-gate process developed and used by companies within the Volvo Group), the Operational Management System (OMS – description of the operational processes at VAC) and Violin (the Volvo Group intranet) were surveyed to create knowledge about the organization.

2.2 The analysis

To analyze the amount of data that the interviews generated put a lot of demands on holding a very systematic approach to handle the data. The data need to be systematized in such a way that it can be coded – the process of reviewing transcripts and/or field notes and giving labels to component parts that seem to be of potential theoretical significance (Bryman, 2004, p. 402). When each interview was finished the researcher produced a transcript of the interview. The process of transcription served not only as a way to make the data manageable and searchable but also to give the researcher a first thorough recapitulation of the interview to get acquainted with the data. With the interviews transcribed it was possible to read them several times to identify pieces of data: words, sentences or paragraphs (codes) that somehow related to the research questions. Into each unit of data a theme was interpreted: the reason for why e.g. a sentence was of interest. When all the transcripts had been coded in this way the identified themes were summarized and ranked according to the number of interviews they were mentioned in. Having a quite large number of themes they were reduced through assigning significance to the themes based on the ranking: if a theme had been mentioned in more interviews than another it was deemed more significant. Based on the themes and the theoretical frame of reference answers were produced to each research question. From those answers recommendations to VAC was then elicited. This result in a somewhat semi-quantitative analysis approach with a quantification of qualitative data to base recommendations on. The analysis strategy used in this thesis is visualized in figure 2.

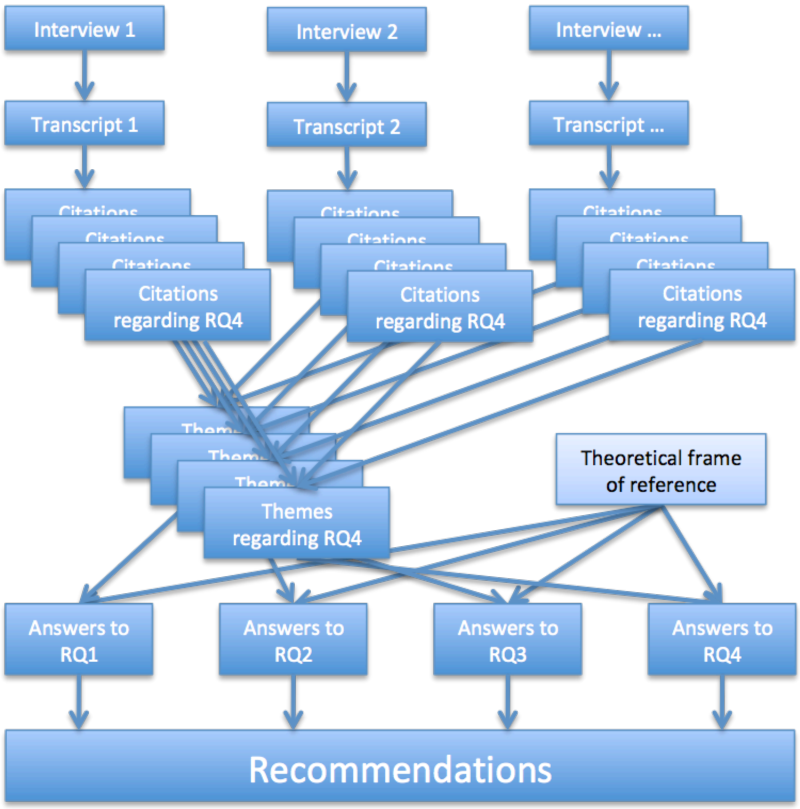

Figure 2 Analysis strategy

2.3 Reliability and validity

To validate the results from a research like this means to confirm that what the researcher observes, identifies or "measures" is what he say he is (Bryman, 2004, p. 273). The importance of achieving valid and reliable results is natural since it is a prerequisite for having useful results. In Bryman (2004, p. 273) reliability and validity is described in two dimensions: internal and external. This gives the following four concepts:

- External reliability – Concerning the degree to which a study can be replicated
- Internal reliability – Concerning whether, when there is more than one observer, members of the research team agree about what they see and hear
- External validity – Concerning the degree to which findings can be generalized across social settings
- Internal validity – Concerning whether there is a good match between researchers' observations and the theoretical ideas they develop

Adapted from Bryman (2004, p. 273)

Since it is impossible to "freeze" a social setting the criterions for reaching external reliability is difficult when conducting qualitative research (Bryman, 2004, p. 273). It is also difficult to achieve external validity in a qualitative research setting since case studies and small samples often are employed (Bryman, 2004, p. 273). However, of more importance is to assure that the internal validity and reliability is achieved. Since the research aims to answer questions about VAC and to produce recommendations based on those answers the internal validity need to be high. One way to achieve this that has been to apply respondent validation. This means that corroboration is sought through the act of providing the participants in the study with accounts of the findings (Bryman, 2004, p. 274). The goal is to seek confirmation that the researcher's findings and impressions are congruent with the views of those on whom the research was conducted (Bryman, 2004, p. 274). The respondent validation was achieved through providing the interviewees first with the transcripts of their interview so that they could reflect on what they actually had said. This was to give them the possibility to correct or clarify any reasoning. When the results had been reached a presentation at VAC was made. To this presentation all the interviewees were invited and with the invitation a summary of the findings was attached. The interviewees were asked to provide feedback during the presentation to start a discussion about the validity and reliability.

The result from the respondent validation was useful but could have been better. All the interviewees were presented with the transcripts from their interview but only one third had comments on what had been said. For the validation of the results, half of the interviewees contributed to a discussion; either by participating in the presentation or by commenting on the results via email. Not only interviewees were present at the seminar. A total of 31 persons from VAC participated and contributed by commenting on both the results from the interviews and the conclusions and recommendations.

3 Theory on Robust Design and Product Development

As a foundation for this study, both an initial and continuous search and examination of relevant theory and methods was performed. The reason for this was to give a deeper understanding of the subject studied and to give a theoretical frame of reference toward which the issues in the study could be related. This frame of reference was then used in the synthesis with the results from the interview study as a basis for comparisons with the actual state in VAC. In this way a picture of where discrepancies exist could be established.

In this literature study the subject of Robust Design was the main topic to examine. Its principles and practices were studied to find a proper way to define it. Also, the general topic product development was studied. Focus was there on the product development process, and the purpose was to have a foundation for evaluating the work at VAC with regards of their product development process.

The major findings from those two subjects are presented in this section of the report.

3.1 Design for Robustness

In the literature on the topic of robustness the term Design for Robustness (DfR) is not used very much. Instead the general terms are Robust Design and Robust Design Methodology. The reason for VAC to use the term DfR is that they consider it to be their variant of Robust Design, in the meaning that they want to have the possibility to take a larger scope on robustness and have the familiarity of a DfX notion (Wendel, 2010). In this thesis Robust Design and Design for Robustness has been used as equals, and Robust Design Methodology is used as a reference to methods to work with DfR.

3.1.1 What is meant by robustness?

Robustness in the terms of product quality relates to insensitivity to sources of variation during a product or systems manufacturing, assembly, usage, maintenance and recycling (Bergman & Klefsjö, 2010, p. 195). When looking at it, all products are exposed to variation e.g. variation in use environment and variation in production processes, and during its lifetime there are a large number of sources of variation, called noise factors, that affect it (Bergman & Klefsjö, 2010, p. 195). Variation can be divided in five different categories:

- Unit-to-unit variation
- Variation due to wear
- Variation depending on the customer's usage
- Variation depending on the environment of the system
- Variation due to system interactions of different kinds

Bergman & Klefsjö (2010, p. 200)

3.1.2 What is Robust Design?

To handle the variations that make a product "non-robust" can be done in several ways. To some extent the noise factors can be eliminated or controlled during manufacturing and operation. The nature of noise is though such that it is often hard, impossible or too expensive to be eliminated or controlled. A third way to counteract noise is to design the product in a way that makes it insensitive to noise factors. (Hasenkamp, 2009)

A common example to illustrate how design factors can affect the robustness of a product is a pendulum. To the characteristics of a pendulum belongs a non-linear relationship between the length and the period, as can be seen in figure 3.

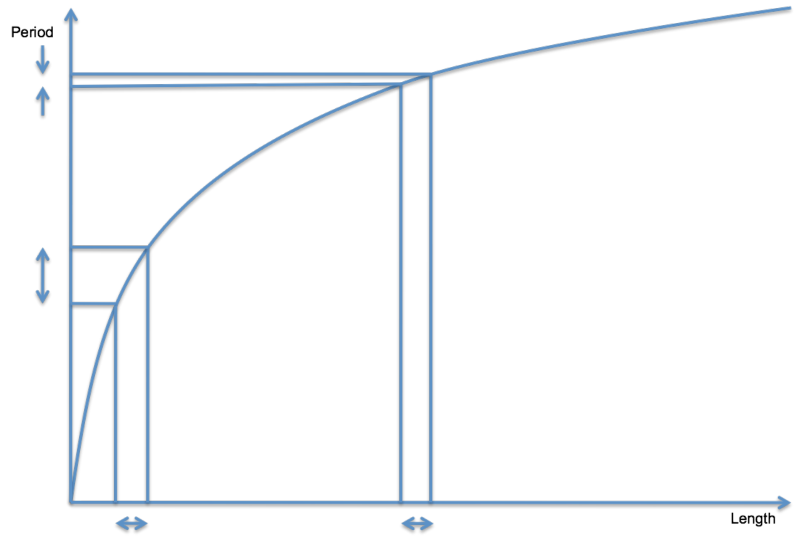

Figure 3 The relation between the length of the pendulum and its period (From Bergman & Klefsjö, 2010 p. 198)

With a longer pendulum a unit disturbance of the length has smaller effect on the period than a shorter pendulum. If non-linearities like this can be utilized a more robust product can be achieved. (Bergman & Klefsjö, 2010, p. 198)

Awareness of this variation is a cornerstone of robust design to be able to create insensitivity to this variation. The use of methods to achieve robustness through design, Robust Design Methodology, should be used in a systematic way in all phases of product development, from concept generation to the production of a product. (Arvidsson & Gremyr, 2009, p. 39)

Arvidsson & Gremyr (2009, p.39) summarizes their definition of Robust Design Methodology as:

> *Robust Design Methodology means systematic efforts to achieve insensitivity to noise factors. These efforts are founded on an awareness of variation and can be applied in all stages of product design.*

This is the definition of robust design that has been used in this thesis.

3.1.3 How should a company work with robust design?

Since the efforts by the Centre of Excellence Design for Robustness (CoE DfR) at Volvo Aero Corporation (VAC) are directed at introducing new ways of working, it is important to consider the aspect of change. Hasenkamp (2009, p. 48) state that it can't be assumed that a methodology like DfR can be implemented via a one-time effort. Hasenkamp (2009, p. 48) refers to Mellby (2006, p. 142) who concludes that it is important to:

> *... design and implement a methodology that supports the emergence of a culture, characterized by the values, infrastructure and usage of tools etc. appropriate for the robust design concept.*

With this background Hasenkamp concludes that the creation of awareness of variation is the start of an approach to designing for robustness. This is needed to create a foundation for understanding and appreciating subsequent efforts. Focus should be on principles of robust design, and everybody involved in the development work, including management, should be taught about this. In the next phase the practices – what needs to be done – should be introduced at all levels and finally the concerned engineers should be trained on available tools to achieve robustness. (Hasenkamp, 2009, p. 49)

3.2 The Product Development process

To guide the work in a company that develops products a common way is to consider the activities as parts of a process:

> *A product development process is the sequence of steps or activities which an enterprise employs to conceive, design and commercialize a product.*

(Ulrich & Eppinger, 2008, p. 12)

The design of this process varies between companies, both in level of abstraction and regarding what phases are included. Ulrich and Eppinger (2008) identify six phases that are considered common to a lot of processes and are described in a generic product development process. The six phases are:

Planning: Includes an assessment of technology developments and market objectives. Should result in a project mission statement.

Concept Development: Alternative concepts are generated based on the needs from target markets. One or more concepts are selected for further development and testing.

System-Level Design: Decomposition of the product into subsystems and components. Should result in a geometric layout of the product and a functional specification of the product's subsystems.

Detail Design: Complete specification of geometry, materials and tolerances of all parts in the product. Critical issues to be addressed are production cost and robust performance.

Testing and Refining: Involves construction and evaluation of multiple preproduction versions of the product. The goal of the evaluations is to answer questions about performance and reliability.

Production Ramp-up: The product is made using the intended production system. The purpose is to work out remaining problems in the production process.

Ulrich & Eppinger (2008, pp. 13-15)

To each of those phases certain activities can be connected from each function involved in the development work. Ulrich & Eppinger (2008) connects the activities by three main functions – marketing, design and manufacturing – to the process. The relevance in this thesis falls mainly on the activities from design. Those are illustrated in figure 4.

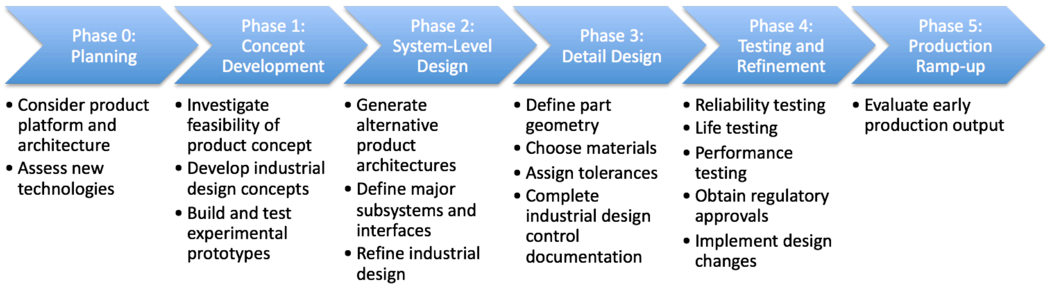

Figure 4 Generic Product Development Process with related design activities

Adapted from Ulrich & Eppinger (2008, p. 14)

4 Findings from the empirical study

The major part of this study comprises a set of nineteen methodically conducted qualitative interviews with personnel at VAC to elicit information that will be the foundation for answering the research questions. How the interview study was set up and performed is thoroughly described in Chapter 2. In this chapter the results from the interviews will be presented and the structure of the chapter follows the four research questions. From the interview data themes regarding each research question was identified and the themes were ranked according to the number of interviews they were mentioned in. This ranking served as an indicator of importance of the themes with more mentioning's indicating a higher importance. From this ranking a division of the themes was made to make them manageable, dividing them into three classes were the most important are described in depth, the medium important are described on an overall level and the less important can be found in appendices for reference. Since the number of themes and the number of interviews they have been mentioned in differs between the research questions, there have not been a pre-defined number of themes that should be given a certain classification. But, to make it manageable an aim has been to keep the most and medium important from exceeding five each. The strive has been to make the division according to the nature of the set of themes. Citations to illustrate the themes are in most cases free translations by the author from Swedish since the majority of the interviews were conducted in this language. The system used to identify citations is based on a five digit number where the first two positions indicate interview number, the third position indicate which research question the citation is related to and the fourth and fifth position indicate sequential number in the transcript: citation I05312 is citation twelve related to research question three in interview five. With this system it is easy to trace the origin of the citation to be able to put it in the context of the interview.

4.1 How do the engineers at Volvo Aero Corporation perceive Design for Robustness?

In the interviews seventeen different themes could be identified that somehow relates to the first research question. Those can be found in their entirety in Appendix B along with references to in which interviews they can be found. When the findings on research question one were analyzed it was relevant to separate the responses from members of CoE DfR from the rest of the interviewees. This was necessary since their understanding of DfR is more comprehensive and already established why their presence in the data imposed an unwanted bias. What this led to was mainly that three themes lost their significance and was not treated as equally important in the following analysis. Regarding research question one, three themes were mentioned in at least 25 percent of the interviews and are classified as being more important.

The three most important themes are:

T1.1 DfR should be used in all phases of PD with the aim of producibility

T1.2 Knowledge about CoE DfR is based on contact with individuals

T1.3 DfR is about insensitivity to noise and variation awareness

In the following sections an elaboration on those four themes will be presented and after that a summary of important findings among the other themes will be found.

4.1.1 Design for Robustness should be used in all phases of Product Development with the aim of producibility

Almost half of the interviewees explicitly talked about DfR as a means for achieving producibility in the products through efforts in the product development work. The general impression from all the interviews was that everybody in the sample sees producibility as a big issue at VAC today and that working with DfR has been mentioned as an effort to increase the producibility.

The following statements are examples on data connected to the theme that illustrates how interviewees' reason about DfR connected to producibility:

> "And that the production process isn't stable doesn't only depend on problems from the manufacturing processes but can also be because we've designed it in such a way…"
>
> **I15101**

> "I'm not entirely sure about what they (CoE DfR) want with this (DfR). What I think is that production… to make it possible to… improve for production. That's what I think."
>
> **I16104**

4.1.2 Knowledge about the Centre of Excellence Design for Robustness is based on contact with individuals

On the question about what knowledge the interviewees had about CoE DfR and the work that they do a lot of the answers indicated that the knowledge was restricted to what they had learned from encounters with individual members of CoE DfR in project contexts or from relations to managers related to CoE DfR. Often the interviewees have worked with one or more members from CoE DfR with issues related to DfR but don't know that they are from CoE DfR. The interviews showed no evidence of a systematic approach from CoE DfR to increase the awareness about either them self or the work they do. Overall the knowledge about CoE DfR was scarce among the interviewees, except from those who work or have worked at the department.

The following statements are examples on data connected to the theme that illustrates how interviewees reason about their knowledge about CoE DfR:

> "Not very much to be honest. We've had some contact with Alejandro (member of CoE DfR). For the GEnx TRF."
>
> **I17105**

"Well, it was when we worked in the GEnx project that Tor Wendel (former member of CoE DfR) was pulling very much in some parts. That's the only thing."

I19104

4.1.3 Design for Robustness is about insensitivity to noise and variation awareness

The perception of DfR as a way to improve the sensitivity to noise and that variation awareness is important to achieve this was identified with a majority of the interviewees. With seven out of seventeen interviewees specifically relating to this theme it is the second most mentioned.

The following statements are examples on data connected to the theme that illustrates how interviewees' reason about DfR connected to noise insensitivity and variation awareness:

"As for me, I think that one should work proactively to be able to handle disturbances on the product in production."

I05101

"And it's about trying to make sure that if we change something in a geometry it will still be OK. And that's what I try to do. It is to alter the geometry to check if it meets the requirement."

I12102

4.1.4 Summary of important findings among the rest of the themes

When the rest of the themes are considered they can be divided in two groups based on the number of interviews they have been explicitly mentioned in: one or two interviews or more than two interviews. With a classification of the themes in relevance, according to the device that more mentioning indicates a higher relevance, this division gives that the following themes are the most relevant:

T1.4 DfR methods should be applied early

T1.5 DfR is about basing design decisions on facts (e.g. capability)

T1.6 DfR is about geometry assurance and fixturing

T1.6 is directly related to the knowledge about what DfR is and implicitly relates to the knowledge about CoE DfR and what they do. **T1.6** is a theme that, when taking into account who has emphasized it, increase the perception that the knowledge about DfR and CoE DfR is connected to whom the interviewee has been working with.

The facts that DfR methods should be applied early (**T1.4**) has been seen in the interviews as two-sided. Either the interviewee talks about the application of methods seen within e.g. Six Sigma efforts already in the design phase instead of when the product has reached production or pre-production. A more specific meaning of early is to be early in the design process; that the concept and methods of DfR needs to be applied already in the beginning of the design phase.

> "And measure very early, in early phases, to understand that this is were we will have problems if we don't change already now. But unfortunately, today we react afterwards instead; ok, it went wrong, why is that?"
>
> **I03109**

T1.5 is a theme that strengthens the connection of DfR to producibility but also that gives it a meaning as a means for strengthening the argumentation when making design decisions.

4.2 What is the need for Design for Robustness within Volvo Aero Corporation?

In the interviews ten different themes could be identified that somehow relates to the second research question. Those can be found in their entirety in Appendix C along with references to in which interviews they can be found. Regarding research question two four themes were mentioned in at least 50 percent of the interviews and are classified as being more important.

The four most important themes are:

T2.1 DfR can improve producibility

T2.2 VAC needs to improve their PD process due to the change to a design organization

T2.3 There's good experience from working with DfR

T2.4 To reduce cost in PD

In the following sections an elaboration on those four themes will be presented and after that a summary of important findings among the other themes will be found.

4.2.1 Design for Robustness can improve producibility

Producibility has been identified as one of the major issues for VAC to handle and more than 75 percent of the interviewees sees DfR as way to improve the producibility. It is a problem that VAC has to deal with and that affects many departments and can be seen as the major reason for why VAC should work with DfR.

The following statements are examples on data connected to the theme that illustrates how interviewees' reason about DfR connected to producibility:

> "… when we look at our history, our products haven't been very producible so to speak."
>
> **I07201**

> "Initially our developed products are related to flaws. They aren't simply robust enough. We get deviations in production."

I17201

4.2.2 Volvo Aero Corporation needs to improve their Product Development process due to the change to a design organization

During the last fifteen years VAC has gone from a make-to-print company, producing engines on license from developers, to having full responsibility for design and production of components for OEM customers. This shift has led to a need at VAC to learn how to manage this process and that learning is very much in progress right now. Almost 75 percent of the interviewees mention this as a reason for implementing DfR as a support for improving the design work.

The following statements are examples on data connected to the theme that illustrates how interviewees' reason about the change to a design organization:

> "…we are going to be a new… a design organization and manage our self's, and then you need to understand… to be able to analyze things when they go wrong and preferably act pro-actively and follow-up and measure."

I03207

> "GEnx is one… have been one of the first projects… that is where we really discovered the lack of robustness."

I13201

4.2.3 There's good experience from working with Design for Robustness

Many of the interviewees have been in contact with DfR methods either at VAC or at customers or former employers. In ten of the interviews those experiences was mentioned with positive words, indicating an acceptance of the methods as a way to improve design work.

The following statements are examples on data connected to the theme that illustrates how interviewees' reason about the experiences from working with DfR:

> "But we have had a great use of the geometry assurance team there. I think they have been very inspiring when we developed the concept."

I09203

> "Then we had to accept a design that we didn't feel really comfortable with. The customer had worked on it before. And we could then in the… in the predecessor make our own design. Then we had used some DfR methodology so to speak. It became… it became better. Most people think so, and even the customer thinks it's better."

I11207

4.2.4 To reduce cost in Product Development

Almost half of the interviewees mentioned cost reductions as a reason for using DfR. This was mainly connected to the possibility of reducing deviations and increasing producibility through DfR. One interviewee discussed the cost of one deviation and related it to the actual number of deviations in one of VAC's projects and stated that deviations in that amount could be the issue that makes the product unprofitable.

The following statements are examples on data connected to the theme that illustrates how interviewees' reason about cost reduction in PD through use of DfR:

> "I think the intention is very straightforward. We can't afford to handle all the problems that emerge during the development of products; it's almost a demand that we do it right from the beginning. It's very expensive to correct flaws so it's quite obvious that we need a good way of thinking."
>
> **I02201**

> "You spend less money on making dumb changes and non-conformances handling. Especially non-conformances handling."
>
> **I06106**

4.2.5 Summary of important findings among the rest of the themes

When the rest of the themes are considered they can be divided in two groups based on the number of interviews they have been explicitly mentioned in: one or two interviews or more than two interviews. With a classification of the themes in relevance, according to the device that more mentioning indicates a higher relevance, this division gives that the following themes are the most relevant:

T2.5 VAC needs to handle new, demanding production processes

T2.6 Design decisions needs to be based on facts

T2.7 DfR is demanded by customers

T2.8 VAC must be able to meet increased volumes in production

T2.5 mainly relates to the introduction of fabrication at VAC as a means for achieving lightweight products. Since fabrication implies welding of multiple parts the geometrical variation due to e.g. welding distortions becomes increasingly important to handle. This implies on CoE DfR to learn more about the results from different production processes. More then one third of the interviewees mentioned this theme as a reason for working with DfR and this citation is an example on how they reasoned:

> "It's the same thing. Very high level of fabrication. And then it is… how shall I put it? Basically it's all the welding that is the big problem. Welding that generates deformations."
>
> **I15202**

This theme is also connected to the theme **T2.8** since increased volumes gives leverage to the problems with the new production processes. With low volumes it's manageable to have deviations on components that are corrected as they emerge from production, but when the volumes increase that approach would lead to cost levels that are to high. The following citation describes how a member of CoE DfR reasons about the increased production volumes:

> "The purpose, as I see it, is that we (CoE DfR) Should be involved to work more pro-actively to… because of increased production volumes we want to eliminate sources of variation or noise factors."
>
> **I05201**

The theme **T2.6** is sensed in many of the interviews and explicitly mentioned in almost one third of them. It expresses a desire that is best displayed by the following citation:

> "…an analysis that I even showed the company executives and that has been met with positive eyes and smiling faces saying: oh good, we rely on facts. So there's a great expectation for that to be what we are, but we aren't really there."
>
> **I10207**

The fact that **T2.7** is notated by citations like the following:

> "As far as I understand this initiative started because GE wanted to… Wanted us to work with it."
>
> **I01201**

4.3 What can Volvo Aero Corporation do to increase the use of Robust Design Methodologies?

In the interviews 27 different themes could be identified that somehow relates to the third research question. Those can be found in their entirety in Appendix D along with references to in which interviews they can be found. Regarding research question three six themes were mentioned in more than 50 percent of the interviews and are classified as being more important.

The six most important themes are:

T3.1 Knowledge about the production processes

T3.2 A system support for controlling that DfR is used

T3.3 Awareness of CoE DfR at VAC

T3.4 Cooperation between departments

T3.5 Defined methods to work with DfR

T3.6 Defined place in the projects for CoE DfR

In the following sections an elaboration on those six themes will be presented and after that a summary of important findings among the other themes will be found.

4.3.1 Knowledge about the production processes

In more than half of the interviews the importance of increasing the knowledge about the production processes was discussed and related to the use of DfR. Many of the interviews indicate that process knowledge is important to be able to apply RDM's and that this knowledge is lacking today at VAC. Important to notice is that the knowledge about the production processes from a DfR perspective concerns the results from production. DfR is not seen as a means for improving the production processes, but to understand what they are capable of and to incorporate that knowledge in the design work.

The following statements are examples on data connected to the theme that illustrates how interviewees' reason about the importance of increased knowledge about the production processes:

> ”The thing is to gather the knowledge in a good way. And that… the knowledge gathering… that's important. To quantify it.”
>
> **I07303**

> “And then we have to feed it back: how did it turn out? To the design organization. And I think that we are probably really bad at that today. That's something we can be a lot better at.”
>
> **I08301**

4.3.2 A system support for controlling that Design for Robustness is used

Half of the interviewees mentioned the introduction of a system support as a way to increase the use of RDM's. Among those there were different ideas on what type of support the system should give. One denotation was that the system in some way should force the engineers to perform and consult lessons learned. Another denotation suggested checklists for evaluating robustness during the design phase incorporated to the system. For that kind of support the importance of keeping it on a practical level was urged.

The following statements are examples on data connected to the theme that illustrates how interviewees' reason about what a system support for controlling that DfR is used can mean:

> “A checklist might be good to make. A simple checklist, I don't know, before you release a drawing or before we release a drawing maybe you can have, e.g. in the system, some checklist for DfR.”
>
> **I03320**

> “That's probably the only thing I miss, this practical application support.”
>
> **I13313**

"It's not documented, there's nothing in our operational system that tell us to take into account the experiences from earlier projects."

I15311

4.3.3 Awareness of Centre of Excellence Design for Robustness at Volvo Aero Corporation

The awareness of CoE DfR at VAC is perceived as poor among the interviewees. Everybody seems to have some knowledge about who they are but they are often mixed up with other departments or only related to the individuals working with DfR. The interviews with members of CoE DfR have showed that the awareness is important for the impact of their efforts.

The following statements are examples on data connected to the theme that illustrates how interviewees' reason about the importance of awareness of CoE DfR at VAC and how the lack of knowledge and mixing up can manifest:

"It's very much like that. If you are known you have a much better impact. So… where they know about me I have a decent impact."

I02310

"**I9:** I don't know exactly who those people are that sits there… it is geometry assurance and welding simulation that I think of on this floor and the EMS's (Engineering Method Specialist) if you look at… from those departments. Because I guess that they belong to some of the departments that sit here? **NB:** Up there, Design and Configuration management. **I9:** Oh, is it that department?"

I09306

"Like all competence based ventures it takes time. You only reach it when you had a cultural impact."

I11309

4.3.4 Cooperation between departments

The theme concerning cooperation between departments mainly focused on the lack of it. The specific cooperation's that were asked for regarded design departments and production but also between those two and all departments that work to increase producibility. This concerns e.g. CoE DfR, Manufacturing verification and Quality. CoE DfR was seen by some as the facilitators of this cooperation. If they could be present early in the projects they could identify areas to work with to handle robustness.

The following statements are examples on data connected to the theme that illustrates how interviewees' reason about cooperation between departments:

"I think it's also matter of cooperating with other departments, that are developing methods. That might be not directly … Design for Robustness or Robust Design but that are working for example with producibility or that are working with liability or aero performance or different issues. So I think cooperation… It's lacking somehow."

I01317

"And then I think there could be a very strong cooperation between my department and DfR. Really, it's different areas of responsibility, but everything strive for producibility."

I20308

4.3.5 Defined methods to work with Design for Robustness

To have well defined methods to work with DfR is seen as an important step towards increasing the use of RDM's. For the engineers at VAC to actually use them they need to be well defined in terms of how they should be used, when they should be used, who should use them and where support can be find to use them. CoE DfR is seen as the unit that should handle this type of issues.

The following statements are examples on data connected to the theme that illustrates how interviewees' reason about having defined methods to work with DfR:

"Of course we should establish methods that many should use… … One thing is that you should have methods that many can use, that they (CoE DfR) own. That is every-mans rulebook. Methods, systems etc. That they manage and own. If we incorporate IT-tools I expect them to own, manage and develop methods in that tool."

I11306

"Practically, what they need is an infrastructure in the shape of methods and tools. That's also an important part. As I mentioned before… it's the motive for the work right now. That this infrastructure is in place."

I18305

4.3.6 Defined place in the projects for Centre of Excellence Design for Robustness

The importance of having a defined place in the projects for CoE DfR is indicated as a facilitator for other themes. With a defined place in the projects the awareness of CoE DfR will increase and the idea is that it also will facilitate cooperation between different departments through the establishment of a robustness plan for the project that concern all other project members.

The following statements are examples on data connected to the theme that illustrates how interviewees' reason about the importance of a defined place in the projects for CoE DfR:

> “Our process description isn’t really like that, so it’s partly that the process… we have described a lot of activities but not really how they are connected completely in a process.”

I04308

> “I would want CoE DfR to grow and created the ability to go into the projects in the start and act DfR mentors. So that they can set up a plan for how to work with those questions.”

I17313

4.3.7 Summary of important findings among the rest of the themes

When the rest of the themes are considered they can be divided in two groups based on the number of interviews they have been explicitly mentioned in: six or more interviews or less than six interviews. With a classification of the themes in relevance, according to the device that more mentioning indicates a higher relevance, this division gives that the following themes are the most relevant:

T3.7 Awareness of DfR methods

T3.8 Defined scope of CoE DfR

T3.9 Early involvement

T3.10 Educate the personnel

T3.11 Improved usability of KPS

All of those are somehow related to the six most important themes but represent some difference. When there are defined methods to work with DfR **T3.7** is important to get an acceptance and to ensure that they are used. The interviews also indicate that different levels of knowledge are necessary for different persons but that everybody need to have a basic understanding of what can be done with DfR. The following citation illustrates how a manager at VAC reasons:

> “You need to have a feeling about; what kind of task is performed? If nothing else to be able chose sometimes: we do this, but we don’t do this.”

I10304

T3.8 is related to the need to have a defined place in the projects but is also related to what they should do. There are indications that the work description for CoE DfR is under construction and somewhat insufficient. There are also indications that it’s not entirely clear who is responsible at VAC for e.g. producibility, requirements management and robustness. The following citation from a member of CoE DfR illustrates this:

> "It's a bit loose so far, the shape of DfR and what competences we have right now."
>
> **I05301**

When the interviewees reason about **T3.9** it is connected to the importance of a defined place in the projects but emphasising the importance of being early to be able to affect the products when the pre-requisites are set. A member of CoE DfR reflects on it in this way:

> "We aren't involved when the pre-requisites are set, instead we come in with some kind of Six Sigma role."
>
> **I02302**

To **T3.10** is seen as a way to achieve awareness of both CoE DfR and methods for working with DfR. Almost half of the interviewees ask for CoE DfR to facilitate training and education for both method specific knowledge and to create awareness about them self's and what they can do. One example is a manager at VAC that says:

> "I don't see it as my role to know that. I want to know things to the limit that I understand what it's all about. And then it's up to each CoE to apply it in practice"
>
> **I18314**

One theme that was brought up by more than 25 percent of the interviewees related to increased knowledge about the production processes was to achieve **T3.11.** KPS is a system for storing data about the components from the control measurements during and after production. This system is seen as a possible source for data that can be used when working with DfR and a member of CoE DfR uses it today to support the evaluation of designs from a robustness perspective. A number of flaws in the KPS system are though present, the biggest one being that VAC's production sites don't have a uniform system and that one site doesn't even have a system. Another problem with the KPS is that it was originally set up for production purposes, which makes it struggling to use for design:

> "KPS as far as I know was designed for production needs. But it was not adapted to Product Development purposes. So it's very hard for a designer to go through all that steps for just getting a standard deviation or a Cpk value."
>
> **I01311**

4.4 How can robustness be measured and how can it help Volvo Aero Corporation?

In the interviews 21 different themes could be identified that somehow relates to the fourth research question. Those can be found in their entirety in Appendix E along with references to in which interviews they can be found. Regarding research question four three themes were mentioned in more than 25 percent of the interviews and are classified as being more important.

The three most important themes are:

T4.1 Setting up a database for confirming robustness (deviations, reliability, # tool changes, # fixturing changes etc.)

T4.2 Measuring number of deviations

T4.3 Tolerance analysis connected to capability.

In the following sections an elaboration on those three themes will be presented and after that a summary of important findings among the other themes will be found.

4.4.1 Setting up a data base for confirming robustness (deviations, reliability, # tool changes, # fixture changes etc.)

The most important reason for measuring robustness has been identified to be the possibility to prove that the work with DfR has given a result. With a measurement that indicates robustness a design can be evaluated and compared against both alternatives and old products and based on that evaluations the effect of working with DfR can assessed. A number of indicators for robustness has been identified such as number of deviations, reliability (measured in probability of failure), number of tool changes and number of fixture changes.

The following statements are examples on data connected to the theme that illustrates how interviewees' reason about need for a data base for confirming robustness:

> "What can be done is that we can compare for example a component today… how we developed, in terms of deviations or in terms of reliability or in terms of different things. And then, lets see, ten or twenty year later we can analyze another component and see how we developed."

I01406

> "And then we have to say like this: well, when we produce by this design we will have this amount less deviations. And that's a tricky thing to prove. And it's tricky to say that yes, we usually do it wrong, now we are going to do a little less wrong. It's bit of a strange argumentation."

I04402

4.4.2 Measuring number of deviations

To measure the number of deviations in production is suggested by more than one fourth of the interviewees as a way to assess robustness. It is connected with the understanding of robustness as being insensitive variation and the fact that deviations are the result of uncontrollable variation. To somehow show that a certain design leads to fewer deviations from production would increase the quality of design decisions.

The following statements are examples on data connected to the theme that illustrates how interviewees' reason about measuring number of deviations over time:

"When you produce it's the number of NCR that is… your 'receipt' that you have reached the target. So, the number of NCR is a good measure."

I02402

"For us it is when the deviation curves goes down. Because we use it (DfR) very much to fight deviations."

I13403

4.4.3 Tolerance analysis connected to capability.

One way that was suggested for measuring robustness was to evaluate tolerances connected to capability. It is seen as a way of quantifying an important indicator of robustness. An important aspect of this theme is that it relates not only to producibility but also to fulfilment of functional requirements since tolerances are set in a certain way to ensure that requirements are fulfilled.

The following statements are examples on data connected to the theme that illustrates how interviewees' reason about performing tolerance analysis connected to capability:

"Well, I would say process capability. That's the big thing"

I06401

"The easiest would be to look at this, the requirements in relation to our processes and the capability. And that… the answer… a lot of it is in our loads of deviations.

I17405

4.4.4 Summary of important findings among the rest of the themes

When the rest of the themes are considered they can be divided in two groups based on the number of interviews they have been explicitly mentioned in: one or two interviews or more than two interviews. With a classification of the themes in relevance, according to the device that more mentioning indicates a higher relevance, this division gives that the following themes are the most relevant:

T4.4 Measure and predict reliability

T4.5 Connect robustness indicators to cost

T4.4 is suggested to be done e.g. by using p-FMEA to produce probabilities as a quantitative measure. It's illustrated by the following citation by a manager at VAC:

"But in some way, if you should make predictions, you need to know how to do with the help of risk analyses and process FMEA and to assess the probability that problems arise in all different stages."

I20403

With the theme **T4.5** the interviewees indicates that a closer connection to cost would increase the usability of the DfR methods. This comes from the fact that the development is very driven by cost and if it can be shown that a method helps reduce cost or that a certain design reduce cost it will be more likely to be accepted. An engineer at VAC exemplifies it like this:

> "You should need a… like a chart from production that show e.g. price vs. tolerances. That say that if we increase tolerances, the price will go down to a certain point maybe."

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5 Analysis

In this chapter the results from the interview study are analysed with the theoretical frame of reference as a background. The idea is to relate the situation at VAC, as found from the interviews, to what research on the topic suggest as a good way of working. This is done to identify areas where VAC need to improve and what they need to do to achieve that improvement. The structure of the chapter is in such a way that it deals with each research question separately to eventually produce answers to each question.

5.1 How do the engineers at Volvo Aero Corporation perceive Design for Robustness?

Two of the three first most important themes regarding this research question (**T1.1** and **T1.3**) relates very well to the definition of robust design by Arvidsson and Gremyr (2009, p. 39). This indicates that the understanding of robust design at VAC at least is at a level where the employees know what DfR is about. With **T1.1** and **T1.3** being explicitly mentioned in only 25 to 50 percent of the interviews the knowledge seem to be unevenly distributed among the interviewees. If all the themes that suggest some knowledge about DfR that is in line with what Arvidsson and Gremyr (2009) defines (**T1.1**, **T1.3** and **T1.4 – T1.6**) are considered, all interviews but one have explicitly mentioned one or more of them. This supports the interpretation that the knowledge among the engineers at VAC about DfR at least is at a basic level but also that it is not very unison.

Table 1

T1.1	DfR should be used in all phases of PD with the aim of producibility
T1.2	Knowledge about CoE DfR is based on contact with individuals
T1.3	DfR is about insensitivity to noise and variation awareness
T1.4	DfR methods should be applied early
T1.5	DfR is about basing design decisions on facts (e.g. capability)
T1.6	DfR is about geometry assurance and fixturing

T1.2 is an indicator that the knowledge about CoE DfR is weak. Without an understanding of who CoE DfR are and what they do it is hard to get a good impact on the operations and since CoE DfR is meant to be a driving force for robustness at VAC it's important to formulate their scope based on the principles of robust design to avoid rejection of the initiative by the organization (Mellby, 2006, p. 142).

5.2 What is the need for Design for Robustness within Volvo Aero Corporation?

Table 2

T2.1	DfR can improve producibility
T2.2	VAC needs to improve their PD process due to the change to a design organization
T2.3	There's good experience from working with DfR
T2.4	To reduce cost in PD
T2.5	VAC needs to handle new, demanding production processes
T2.6	Design decisions needs to be based on facts
T2.7	DfR is demanded by customers
T2.8	VAC must be able to meet increased volumes in production

Within VAC there has been a change during the last fifteen years from building licensed engines designed by large engine manufacturers like Rolls Royce and GE to having full responsibility for the design, production and support of components that are part of large engine projects that are intended to be used at the world's largest and most widely used airplanes (Galvez, 2010). This has meant not only that VAC has had to learn how to cope with those tasks but also to a severely increased production volume. With this change still in full progress VAC especially try to find methods to improve producibility since that is a problem that have emerged during the last years as a result from the change. This is a problem at VAC today and many of the interviews reflect this as a reason for why VAC should work with DfR. **T2.1** and **T2.2**, the two most mentioned themes regarding RQ2, both emphasize the issues with producibility and the organizational change at VAC respectively. The idea is that the producibility can be improved through the development of products that are less sensitive to variation. With this decreased sensitivity fewer deviations will occur. Since VAC is relatively new to product development the introduction of DfR can help support both their process of learning to make good designs and their pursuit of producibility. **T2.8** also support the fact that the increasing production volume is an issue that VAC needs to manage. With the notion of **T2.3** stating that there has been good experience from working with DfR it can be suggested that DfR can be a good way for VAC to manage those issues. The experiences can be from earlier work at VAC or from other companies where the methods are more widely used. All this can be seen in the light of **T2.4** since cost reduction always is of great importance to stay competitive and DfR is seen as a way to achieve this. By improving the designs with respect to robustness fever deviations in production are expected with the result of less loop-backs to product development and hence lower cost. With VAC management identifying producibility as a key element to reach business success (Volvo Aero Corporation, 2010) this is a good reason for using DfR.

As **T2.5** indicate, not only is VAC facing challenges in the design work and with increasing production volumes, but they are also incorporating new, highly demanding, production processes. The concept of fabrication is undeniably increasing the importance of robust designs. To understand the capabilities of the new production processes is of great importance to produce designs that are producible in a way so that they meet requirements.

The two themes **T2.6** and **T2.7** can be seen as related. Since VAC today produce components for OEM customers they need to prove their capability of delivering in a robust way. If GE, for example, is supposed to deliver their engine to Boeing at a certain date they need to know that the components VAC supply meet requirements and are delivered on time. To assure this they require VAC to work with methods to improve producibility because bad producibility puts risk on the complete supply chain. And with this external pressure it becomes increasingly important to base design decisions on facts so that VAC can prove that they are working in a successful way with those issues.

5.3 What can Volvo Aero Corporation do to increase the use of Robust Design Methodologies?

T3.3 and **T3.5** – **T3.10** relates to creating awareness of CoE DfR, defining methods for DfR, how CoE DfR should work and that the engineers at VAC needs to be educated. This is very much in line with what Hasenkamp (2009, p. 49) concludes. Hasenkamp (2009) emphasize the importance of variation awareness, education of all employees that are involved in development work on the principles and practices of RDM and to train engineers on available tools to counteract noise factors. With CoE DfR present as a driving force for facilitating DfR it could be argued that they should provide the necessary education to meet this demand and to be able to do this they need to state what they do, where they do it and how they do it. The importance of being involved early (**T3.9**) is crucial to be able to influence the work in the right direction already from the start. If CoE DfR is used only as a support when troubles arise the intended pro-activeness with DfR is lost.

Table 3

T3.1	Knowledge about the production processes
T3.2	A system support for controlling that DfR is used
T3.3	Awareness of CoE DfR at VAC
T3.4	Cooperation between departments
T3.5	Defined methods to work with DfR
T3.6	Defined place in the projects for CoE DfR
T3.7	Awareness of DfR methods
T3.8	Defined scope of CoE DfR
T3.9	Early involvement
T3.10	Educate the personnel
T3.11	Improved usability of KPS

To introduce a system support for controlling that DfR is used has been suggested by several interviewees (**T3.2**). As seen from the results this can mean introducing checklists for evaluating robustness during the design phase. An available system at VAC for this is the OMS (Operational Management System) where all the processes that constitute VAC's operations are described and related to each other. In this context appropriate Design Practices can be suggested to secure the robustness of a design. If the general product development process formulated by Ulrich & Eppinger (2008) is viewed, one can conclude that this kind of support ought to be suitable in almost all phases: concept development, system-level design, detail design and testing & refinement. Also the importance of incorporating lessons learned in the system is noted. An effort towards this is made as a part of the development of a "Capability & new content analysis" performed at CoE DfR (Knuts, 2010).

T3.1 and **T3.11** are both indicating a need for increased knowledge about the production processes. The awareness of variation is emphasized by Arvidsson & Gremyr (2009), and this awareness should be a foundation for collecting knowledge about the production processes. This knowledge is important to confirm that a design is producible before it is handed over to production. The process knowledge is not in itself a way to achieve robust designs but is really about reducing unnecessary iterations between production and design. With the possibility to model and predict producibility a lot of expensive efforts can be avoided. Using the KPS (**T3.11**) to design with process knowledge is a way to achieve the more general aim of **T3.1** and the work that is done today by CoE DfR using the KPS can serve as a starting point for improvements.

The importance of cooperation between departments (**T3.4**) is supported by Hasenkamp (2009), in the meaning that all employees involved in development work should be educated on RDM's. Since every department is affected by variation they should try and work together to reach the common goal of robustness. From this aspect CoE DfR can function as robustness mentors in the projects and through early involvement in the projects set up a plan for the robustness work that affects all departments.

5.4 How can robustness be measured and how can it help Volvo Aero Corporation?

In the interviews there could be established one big reason for measuring robustness: to prove that the methods to achieve robustness have effect. The main instrument to do this is suggested to be the set-up of a database over robustness indicators so they can be monitored over time to confirm that robustness is achieved (**T4.1**). Since robustness is viewed as strongly connected to producibility the suggestions of number of deviations (**T4.2**), capability based tolerances (**T4.3**) and probability-based reliability (**T4.4**) as measurements for robustness are natural. If they can be connected in a relevant way to cost (**T4.5**) the practical usability of those measurements can be increased.

Table 4

T4.1	Setting up a data base for confirming robustness (deviations, reliability, # tool changes, # fixturing changes etc.)
T4.2	Measuring number of deviations
T4.3	Tolerance analysis connected to capability
T4.4	Measure and predict reliability
T4.5	Connect robustness indicators to cost

6 Discussion of the results

One big issue that was identified during the interview study was the problem of getting relevant answers to the fourth research question – How can robustness be measured and how can it help Volvo Aero Corporation? The interviewees were not soon to confirm the relevance of a robustness measure, but when it came to how this should be achieved the answers were more floating. There are of course some natural ways of evaluating for example producibility through the number of deviations or reliability through probability, but those are all post-design measures. In literature regarding robust design the issue of measuring robustness was also scarce. So, it was concluded that, to develop a measurement that can be used to support the design work in a pro-active way, even more research than could be fitted into this thesis need to be done. Hence the research aim stated in the beginning of the work was abandoned and left for future efforts to tackle.

An idea that a participant at the seminar presented about robustness is that it's not something that IS but it's something that BECOMES. The meaning of this was that robustness depends on so many factors from so many different parts of the company that it in the early stages can't be measured because it's not there yet. An interesting but maybe somewhat discouraging thought for someone that searches for a robustness measurement. It is though important to keep this in mind since it can be deceitful to trust numbers too much. If a measurement is found and used the risk is that important aspects are missed when relying too much on that.

A great deal of thought has been given to the validity of the results. Is the way the findings have been used relevant? Can significance really be assigned in the way it is done in this thesis? When it comes to the findings it is important to notice that statistical significance in a scientific meaning has not been used. The ranking and division of themes into categories based on relevance is merely a way to make them manageable. Not all of the themes could be taken into account or the analysis would have ended up to disparate and non-understandable. Given the fact that all the themes were elicited during the analysis, the relevance of themes that was mentioned more times was considered higher. Of course it can always be debated whether or not a researcher can keep a completely open mind for what he finds in his research. A person's perception is always biased by earlier experience. What is important regarding those concerns is that the researcher is aware of the bias, to always reflect on what is found. To tackle this problem the respondent validation has been useful to give at least some confirmation of the relevance of the findings.

When performing this kind of study it is of interest to ask oneself how large part of the actual problem has been identified and addressed? Through the constraints that are put on the research when the task is defined a risk that important knowledge is missed occurs. Both through what literature is studied and through what questions that are asked. If a pre-understanding of what the issue is exists, it is easy to be to narrow-minded when planning the work. A means for counteracting this has been to consult knowledgeable persons at both Chalmers and Volvo Aero Corporation. Still, it is hard to say that the results from this study are the only truths. Other angels to address the problem might lead to other answers that are just as valid. Considering this, the researchers intention has been to affect the progress at Volvo Aero Corporation in a positive way.

An interesting aspect of performing research is the “corruption” of the interviewees by their inclusion in the study. This is especially relevant when the subject of interest concern peoples knowledge or perception of something. By asking questions the researcher inevitably change the interviewees understanding. In the case of this study this can be seen as a positive effect. In this way the interviews serve two purposes; to gain knowledge about the situation at Volvo Aero Corporation and to increase the awareness of the studied subject among the interviewees.

7 Conclusions and recommendations

This thesis has explored the use of Design for Robustness (DfR) at Volvo Aero Corporation (VAC). DfR means systematic efforts to achieve insensitivity to noise factors, is founded on an awareness of variation and can be applied in all stages of product design. (Arvidsson & Gremyr, 2009) The focus has been to investigate how the Centre of Excellence Design for Robustness (CoE DfR) – a unit at VAC that is responsible for implementation and development of DfR at VAC – can gain a better impact from the work they do. A systematic interview study, comprising nineteen qualitative interviews, was conducted with the aim of answering four research questions. Those questions were derived from the study of literature on DfR and through consultations with members from CoE DfR.

The search for an answer to the first research question – How do the engineers at Volvo Aero Corporation perceive Design for Robustness? – has led to two major findings:

- ♦ The knowledge about DfR is at an overall basic level and unconsolidated
- ♦ The knowledge of CoE DfR is poor at VAC

With the overall basic-level knowledge about DfR there is a good starting point for addressing the cornerstone of Robust Design: Awareness. Awareness of variation, awareness of methods and awareness of procedures. This awareness should be increased and especially set to a common level (Hasenkamp, 2009). To be able to increase the use of RDM's at VAC those issues need to be addressed first to create a foundation for the future efforts. One big problem is that robustness isn't clearly defined, especially not in relation to producibility. Many instances at VAC claim to be working to increase producibility, some people equals robustness with producibility whilst some consider robustness to incorporate more etcetera. To gain a proper impact, CoE DfR needs to clarify those issues. This statement is also supported by a lot of the findings on research question three – What can Volvo Aero Corporation do to increase the use of Robust Design Methodologies? – and this leads to the following recommendations for VAC:

Recommendation 1

- Initiate an organizational study at VAC to identify who does what when it comes to robustness and producibility
- Relate this to CoE DfR

Recommendation 2

- Initiate a study that investigate what methods, tools and practices VAC should use to work with DfR
- Develop a basic educational material

Recommendation 3

- Perform a massive, basic, educational effort throughout the development organization to create a common ground of understanding about DfR.

With the need of DfR, and the acceptance of DfR at VAC, clearly established through the answers to research question two – What is the need for Design for Robustness within Volvo Aero Corporation? – the anticipation is for this kind of efforts to be successful.

Findings on research question three has also led to the identification of the following three areas that can lead to an increased use of DfR and an increased impact of the efforts:

- The introduction of system support for DfR
- Increased knowledge about the production processes in the development work
- Increased cooperation between departments

To view those areas at the same time is of interest since they can support each other. A system support for DfR can both depict how process knowledge should be used and improved and how the departments should cooperate in a process context such as the Global Development Process (GDP – the generic stage gate process at VAC). Supported by the generic product development process from Ulrich & Eppinger (2008), this can be suitable in many of the phases of product development, such as: concept development, system-level design, detail design and testing & refinement. At the same time it is important to remember the suggestion from some interviewees to have practical guidelines for working with DfR. Incorporating ways to achieve robustness in the existing design practices can be a way to do this. System support for DfR is something that CoE DfR works with today in a good way. The development of design practices and process descriptions for working with DfR is ongoing and it is important to continue that work and support it with extra efforts. What is needed for this support is ultimately more resources in the shape manpower – the employees at CoE DfR need more hours available for this kind of work.

By improving the usability of the KPS – the VAC system for managing production data – a support for increasing the knowledge about the capabilities of the production processes in the development work can be created. Together with education on how to use the information from the KPS this can be a good way to confirm the robustness of the designs before they are left to down-stream activities. The information in the KPS is used by members of CoE DfR as a support for evaluating designs, but the information is hard to collect and transform in a way that makes it efficient for use in the design process. With this knowledge from CoE DfR as a starting point the KPS could be improved.

One implication of the need for increased cooperation between departments that was found was that CoE DfR could act as a facilitator of this cooperation. With CoE DfR involved from the start of the project they could act as robustness-mentors that support the development in all phases and bring special competence on the subject of

DfR to the project. A role of a robustness-mentor could include – but is not necessarily excluded to – continuous education in the projects, creator of a project robustness plan and be the connection point between departments working for producibility. Based on this, the following recommendations can be made:

Recommendation 4

- Initiate a study that survey the available operational systems, such as the GDP and the OMS, to identify where DfR can be incorporated
- Develop process descriptions for working with DfR based on the results from this study

Recommendation 5

- Evaluate existing design practices and update them to account for robustness

Recommendation 6

- Initiate a study on how the KPS system can be improved to better support the design work at VAC
- Implement improvements on the KPS system
- Educate engineers at VAC on how to use the KPS system for design purposes

Recommendation 7

- Perform a study to analyze different ways to introduce a robustness-mentor in the project organizations and what its work description should look like
- Introduce a robustness-mentor that guide the joint effort of all the departments to achieve robustness

One of the issues that this thesis was set out to investigate was the possibility and relevance of a way to measure robustness. The idea was that "what gets measured gets done" and to look into this the forth research question – How can robustness be measured and how can it help Volvo Aero Corporation? – was formulated. This proved to be a difficult question to answer with certainty. Even though many interviewees had some idea of how to measure robustness, no overall consensus could be established. There was also a confirmation of the usefulness of a robustness measurement, if it could be established. Interviewees indicated that with quantification of robustness it would be easier to compare design solutions, and to argue for the correctness of a decision. Without a real consensus about how to measure robustness in a way that can be used in the design work, it is hard to give any recommendations on how to do it – they would lack the proper support – but the ideas that were found could be used as a starting point for further investigations on the subject. The most tangible finding from the study concerning a robustness measure was that it could be used to confirm that the robustness in VAC's products is increased by the efforts of working with DfR, and this is something that could be implemented at VAC today. As a result from the study the following recommendation can be made regarding the development and use of a robustness measurement:

Recommendation 8

- Investigate possible robustness indicators
- Set up a database on those indicators and start recording from all projects
- Study older projects with respect of the identified robustness indicators to enhance the database

Robustness indicators that have been found as possible alternatives from the empirical study include number of deviations, reliability measured in probability of failure, number of tool changes and number of fixture changes. Those all need to be confirmed as suitable in a more thorough analysis.

7.1 Priority of recommendations

To further direct the efforts of VAC to improve their work with DfR, based on the recommendations in this report, the recommendations have been prioritized. Two reasons for priority have been used: Urgency and dependency. To do this the relations between them were mapped (figure 5). With this mapping the dependencies could be assessed.

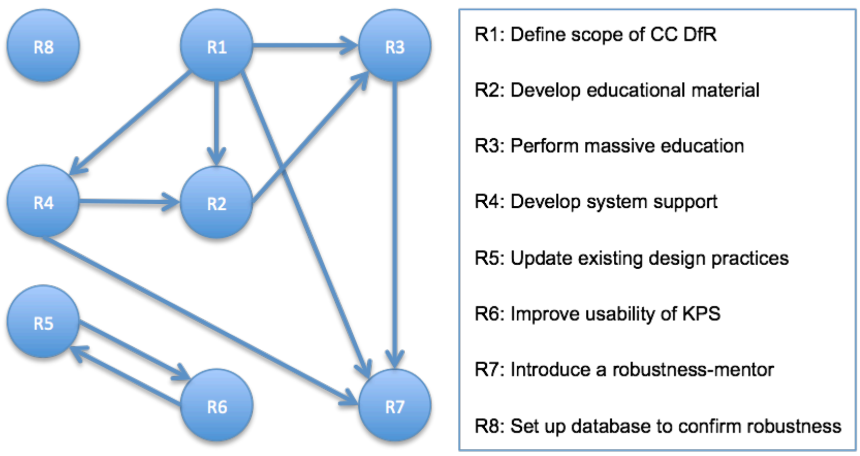

Figure 5 Dependencies between recommendations

From the mapping in figure 5 it can be concluded that some of the recommendations must be performed in sequence and that others can be done in parallel. This is illustrated in figure 6. With the updating of existing design practices and the improvement of KPS being mutually dependent they need to be addressed simultaneously, with one providing input to the other and vice versa.

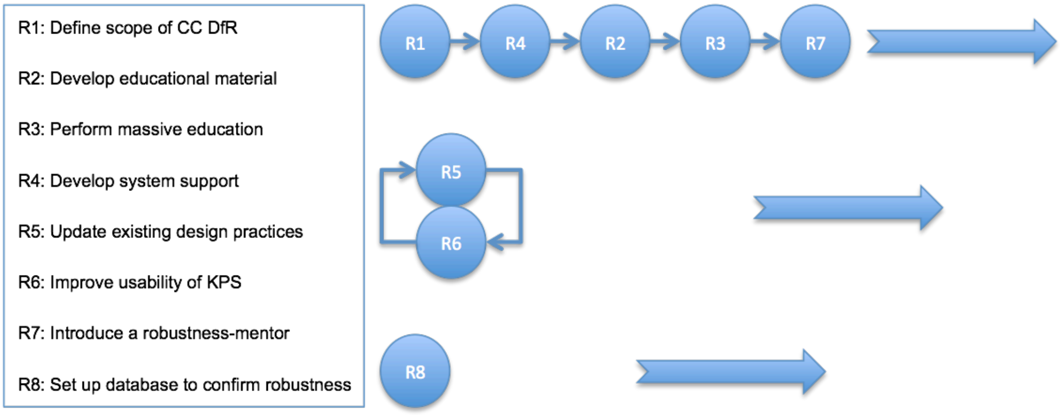

Figure 6 Order of execution for recommendations

To speed-up the process, the order in figure 6 should not be seen as forcing with one recommendation fully completed before the next one. Instead, they should, in most cases, be iterated and continued even when the next step is commenced. What is important is that the preceding recommendations at least can serve as input to the following.

When assessing the urgency of the recommendations, from the description of them, it can especially be concluded that the introduction of a robustness-mentor is more urgent than figure 6 suggests. With the time for completion that the preceding recommendations can be expected to consume, VAC need to start implementing a robustness-mentor sooner than figure 6 suggest. The introduction of a robustness-mentor in the projects will then be supported by the continued work with recommendations 1-4, and its position will be strengthened as the work proceed.

7.2 Timeframe for implementing the recommendations

Since recommendations 1-3 – definition of CoE DfR, development of educational material and education – all concern the foundation for the future efforts of working with DfR, the activities connected to them should be initiated as soon as possible. As they follow on each other, the definition of scope and the development of education material should be started immediately. As can be seen in section 7.1, the recommendation to incorporate DfR in the operational systems should precede Recommendation two. This work should be started to function as input to Recommendation two and will then be a part of the educational effort. Thus the education can be started. The aim of CoE DfR should be to have reached out to everybody within six months. The reason for this is to really have a fresh start for projects that are about to start soon. Even if all projects at VAC will benefit from the creation of a common understanding the greatest impact can be achieved if the understanding is at a proper level already from the beginning. To account for this the work with creating system support for DfR will have to be started soon and carried out simultaneously with recommendations 2 and 3.

The improvement of the KPS system and the initiation of a robustness-mentor is of the nature that they can be initiated as soon as the resources for this kind of work are secured, but they are quite complex and results could possibly be expected after one to two years. This kind of work will then have to be performed continuously by CoE DfR to secure the evolvement of DfR.

If the resources could be found a Robustness-mentor, according to Recommendation 7, should be established already in the start-up of the next big commercial project. With this person in place, the possibility of achieving good cooperation to develop a robust product would most likely increase. Even with the implications from section 7.1 about Recommendation 7 needing input from the work with recommendations 1 – 4, the opportunity to put a robustness-mentor in place should be taken as soon as possible.

The set-up of a database over robustness indicators, according to Recommendation 8, is a long-term commitment that should be initiated directly. The usefulness of this database could show within a year or two. However, the true value of it will probably not be reached for five to ten years.

A visualization of the time frame can be found in figure 7.

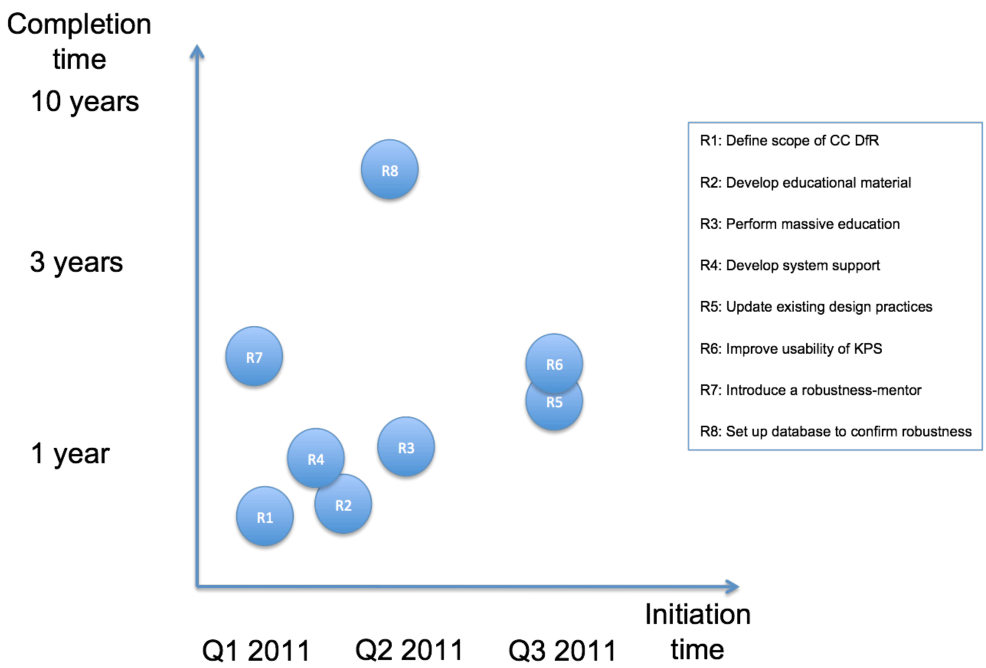

Figure 7 Time Frame for recommendations based on urgency and dependency

8 Further research

The findings that lead to recommendations 1-3 – all related to education on Design for Robustness and the Centre of Excellences work – has only been connected to the increase of a basic understanding at VAC. After that effort a more diversified educational effort will have to be done. How that effort should look cannot be elicited from the work that falls within the scope of this thesis. A starting point for future research in this area would though include identifying who needs to know what, how to “sell” an education to different levels of the organization and how the education should be executed.

To understand how a system support for Design for Robustness should look (according to Recommendation 4), more research needs to be directed towards the use of VAC specific systems such as their Global Development Process and Operational Management System. This needs to be done to identify where the practices and methods of Design for Robustness could be incorporated.

If the KPS system at VAC – a system used to store production data – should be improved, as Recommendation 6 suggest, further research needs to be performed. This research could investigate e.g. possible uses of production data in design work and/or integration of KPS with existing PLM (Product Life-cycle Management) system.

What is meant with a robustness-mentor – as mentioned in Recommendation 7 – in this thesis can seem a bit unclear. And it is! This is something that will have to be thoroughly investigated through further research consisting of e.g. benchmarking. To investigate how other companies work with these issues can be a great source of knowledge and other Volvo Group Companies or partners to VAC might be suitable benchmarking objects.

In the work conducted in the context of this thesis no clear answer to research question four – How can robustness be measured and how can it help Volvo Aero Corporation? – has been found. It has however been established that VAC would benefit from a robustness measurement if it can be identified and this is an area where more research needs to be done. Regarding the identification of robustness indicators and set-up of a database to confirm robustness (Recommendation 8), benchmarking can be a suitable way to initiate a study to establish proper knowledge. Suggestions for benchmarking objects are first of all other Volvo companies where efforts to achieve robustness might have come further but also other companies that have been successful in their robustness work.

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Appendix A – Interview template

1 Introduction

Introduction of my self and the study.

Explanation of why I have to record and that it's only me that will have full access to the recordings; all results will be randomized and neutralized.

1.1 What is your background?

Education, work experience etc.

1.2 What is your role at VAC?

2 The engineers at VAC's perception of Design for Robustness

2.1 What does design for robustness mean to you?

2.2 Where does your knowledge about DfR come from?

2.3 Do you utilize DfR in your way of working?

How/when/why (not)?

Do you use any special tools for DfR?

2.4 Do you need any resources to apply DfR?

2.5 What do you know about KC DfR and the work they do?

3 The need for DfR within VAC

3.1 What is your perception of VACs intentions with DfR?

3.2 How do you think VAC benefits from DfR?

3.3 Can you see other ways to benefit from DfR?

4 How to increase the use of RDMs at VAC

4.1 How do you want to work in order to better utilize DfR?

4.2 What kind of feedback do you get from working with DfR?

5 How robustness can be measured and how this can help VAC

5.1 How do you realize the effects of DfR?

5.2 How can you see how "robust" a design is?

5.3 Can this be done in another way than it is today?

6 Finalization

Say thank you!

Ask if there is anything that's unclear.

Ask if there is anyone he/she recommends to interview.

Promise to send over the transcript to the interviewee for verification.

Offer to send the results of the interviews.

Ask if they are interested in attending my final presentation.

Appendix B – Findings on RQ1 from the empirical study

In this appendix the identified themes found on RQ1 – How do the engineers at VAC perceive Design for Robustness? – are presented along with references to in which interviews the themes could be found. The first list in this appendix constitute the themes found in all interviews and after that follows an adjusted list where the contributions from KC DfR has been removed to avoid bias on the result.

DfR should be used in all phases of PD with the aim of producibility

2, 3, 4, 5, 11, 12, 13, 15, 16 (9)

DfR is about insensitivity to noise and variation awareness

1, 5, 9, 12, 17, 18, 19 (7)

DfR methods should be applied early

1, 2, 3, 4, 12, 13 (6)

Knowledge about KC DfR is based on contact with individuals

3, 8, 12, 17, 19, 20 (6)

DfR is about basing design decisions on facts (e.g. capability)

1, 3, 6, 20 (4)

DfR has two sides: Reliability & Safety and producibility

1, 8, 20 (3)

DfR is about a mind-set for design

1, 10, 18 (3)

At VAC it's not entirely clear what the scope of KC DfR is

4, 16, 19 (3)

There has been no DfR education at VAC (There has been some)

4, 20 (12) (3)

DfR is about geometry assurance and fixturing

7, 9, 18 (3)

DfR isn't used very much at VAC

7, 19 (2)

The responsibility for robustness should not be owned by one department

10, 20 (2)

DfR is about requirements fulfilment

13, 15 (2)

DfR is related to DfSS

16, 20 (2)

DfR is related to Six Sigma

18, 20 (2)

DfR can be viewed in many ways that are easy to mix-up

4 (1)

Thinks designers at VAC has the necessary knowledge to work with DfR

7 (1)

Adjusted list of themes with the contributions from KC DfR removed

DfR should be used in all phases of PD with the aim of producibility

3, 11, 12, 13, 15, 16 (6)

Knowledge about KC DfR is based on contact with individuals

3, 8, 12, 17, 19, 20 (6)

DfR is about insensitivity to noise and variation awareness

9, 12, 17, 18, 19 (5)

DfR methods should be applied early

3, 12, 13 (3)

DfR is about basing design decisions on facts (e.g. capability)

3, 6, 20 (3)

DfR is about geometry assurance and fixturing

7, 9, 18 (3)

DfR has two sides: Reliability & Safety and producibility

8, 20 (2)

DfR is about a mind-set for design

10, 18 (2)

At VAC it's not entirely clear what the scope of KC DfR is

16, 19 (2)

There has been no DfR education at VAC (There has been some)

20 (12) (2)

DfR isn't used very much at VAC

7, 19 (2)

The responsibility for robustness should not be owned by one department

10, 20 (2)

DfR is about requirements fulfilment

13, 15 (2)

DfR is related to DfSS

16, 20 (2)

DfR is related to Six Sigma

18, 20 (2)

Thinks designers at VAC has the necessary knowledge to work with DfR

7 (1)

DfR can be viewed in many ways that are easy to mix-up

(0)

Appendix C – Findings on RQ2 from the empirical study

In this appendix the identified themes found on RQ2 – What is the need for DfR within VAC? – are presented along with references to in which interviews the themes could be found.

DfR can improve producibility

1, 2, 3, 4, 6, 7, 8, 9, 11, 12, 13, 15, 16, 17, 19, 20 (16)

VAC needs to improve their PD process due to the change to a design organization

3, 4, 6, 7, 9, 10, 11, 12, 13, 15, 17, 18, 19, 20 (14)

There's good experience from working with DfR

9, 10, 11, 13, 15, 16, 17, 18, 19, 20 (10)

To reduce cost in PD

2, 6, 7, 10, 12, 13, 17, 18, 19 (9)

VAC needs to handle new, demanding production processes

1, 2, 5, 9, 10, 12, 15 (7)

Design decisions needs to be based on facts

3, 8, 10, 13, 19, 20 (6)

DfR is demanded by customers

1, 4, 5, 17 (4)

VAC must be able to meet increased volumes in production

5, 12, 15 (3)

A centre of excellence is a good way of introducing and developing new methods

11, 12 (2)

VAC needs to measure reliability

8 (1)

Appendix D – Findings on RQ3 from the empirical study

In this appendix the identified themes found on RQ3 – What can VAC do to increase the use of RDMs? – are presented along with references to in which interviews the themes could be found.

Knowledge about the production processes

1, 3, 4, 6, 7, 8, 9, 12, 13, 15, 17, 19 (12)

A system support for controlling that DfR is used

2, 3, 4, 5, 6, 10, 11, 15, 16, 19 (10)

Awareness of KC DfR at VAC

2, 5, 7, 9, 10, 11, 15, 16, 17, 19 (10)

Cooperation between departments

1, 4, 7, 8, 9, 10, 12, 17, 19, 20 (10)

Defined methods to work with DfR

2, 3, 4, 5, 6, 11, 13, 15, 17, 18 (10)

Defined place in the projects for KC DfR

1, 2, 4, 8, 9, 10, 15, 16, 17, 19 (10)

Awareness of DfR methods

1, 2, 3, 4, 9, 10, 13, 15, 16 (9)

Defined scope of KC DfR

2, 4, 5, 7, 9, 13, 16, 18, 20 (9)

Early involvement

1, 2, 3, 5, 7, 9, 12, 17, 20 (9)

Educate the personnel

3, 4, 9, 11, 15, 16, 17, 18, 19 (9)

Improved usability of KPS

1, 2, 4, 13, 17, 19 (6)

Better on lessons learned

1, 9, 15, 20 (4)

Help suppliers to work pro-actively

3, 9, 13, 17 (4)

Increased knowledge about suppliers capabilities

1, 4, 6, 10 (4)

Provide more resources to KC DfR

11, 15, 17, 20 (4)

Market KC DfR

9, 10, 17 (3)

Measure robustness

11, 12, 20 (3)

Variation awareness

1, 3, 19 (3)

Define who is the customer of KC DfR

3, 9, 18 (3)

Follow-up on results from working with DfR

2, 19 (2)

Early involvement with a defined place in the projects

3, 4 (2)

Management support

9, 18 (2)

Show on success with DfR

2, 11 (2)

Think long term

16, 18 (2)

Define and set the requirements more clearly

17 (1)

Defined methods to work with DfR on a practical level

13 (1)

Reach a critical mass that wants DfR

11 (1)

Appendix E – Findings on RQ4 from the empirical study

In this appendix the identified themes found on RQ4 – How can robustness be measured and how can it help VAC? – are presented along with references to in which interviews the themes could be found.

Setting up a data base for confirming robustness (deviations, reliability, # tool changes, # fixture changes etc.)

1, 2, 4, 5, 7, 11, 17 (7)

Measuring number of deviations

1, 2, 4, 13, 17, 20 (6)

Tolerance analysis connected to capability.

2, 3, 6, 10, 17, 20 (6)

Measure and predict reliability

1, 7, 8, 20 (4)

Connect robustness indicators to cost

4, 12, 13, 17 (4)

A robustness measurement can support concept selection

7, 11 (2)

An assessment of the producibility would be good in the early phases

7, 12 (2)

Base evaluations of requirements fullfillment on statistics (mean value with variation)

4, 6 (2)

Hard to measure robustness from a functional POV since VAC don't release faulty articles to customers

4, 8 (2)

Hard to point out results from pro-active work

1, 4 (2)

It's seen as a missing link in the work with DfR

8, 13 (2)

Not absolute numbers but rather relations

1, 5 (2)

S/N

2, 16 (2)

Assess consequenses of robustness indicators

4 (1)

Balancing geometric robustness, reliability and life-length to get an overall measurement.

5 (1)

If possible the measurment should be numerical to reduce subjectiveness

3 (1)

If robustness is measured it's made more factual

3 (1)

Measure activities connected to robustness (education, usage of methods etc.)

5 (1)

System analysis is needed to asses robustness

3 (1)

Target system analysis.

1 (1)

Try to identify "good-enough" values

11 (1)

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