Conceptual Design for Robustness

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Acknowledgements

This Master of Science thesis was the final for the master degree in Ergonomic Design and Production, specialization in Product Development. The thesis was conducted by Johanna Wallin at Volvo Aero Corporation in Trollhättan, Sweden, under the supervision of the Department of Human Work Science at Luleå University of Technology, Sweden.

I have had a group of four supervisors and I want to thank them all: Ola Isaksson for his support, guidance and his never ending thoughts and ideas through my work that has given me the challenges I was looking for, Tor Wendel for his guidance and inspirational views, Peter Forsberg for his support and for taking the initiative to this project, and Anders Håkansson for his support on a distance from Luleå.

During this work I have interviewed and discussed the topic with many people at Volvo Aero, I won’t mention you all by name, but thank you all for your time! Especially I would also like to thank Jesper Larsson and Erik Mattson, for a great cooperation in making changes to the conceptual process.

Finally, I want to thank Pär, friends and family for the never ending support in everything I do.
Abstract

The title of this thesis is a combination of the term Conceptual Design which implies construction of ideas into concepts, and Design for Robustness which focuses on improving the reliability of a product or a process.

The aim for this project was to implement a Robust Design Methodology (RDM) in the concept development process that takes into account the different perspectives at Volvo Aero Corporation which is a company that manufactures of aircraft components, rockets and gas turbine engines with high technology content. Volvo Aero has a quality management system that is called the Operational Management System (OMS).

A great part of this thesis work has been an external and internal literature study. To get information about the concept development process personal interviews were made as well as observations and a questionnaire has been given out to employees at Volvo Aero that have been part of a concept development process. The questionnaire gathered information allowing statistical analysis.

It was found that the prescribed way of working did not comply with actual best practice described in OMS, the estimation of risks was not spread throughout the process, the vision of the concept goal was poor, there was no overall methods that were used - except brainstorming, projects used different concept evaluation matrixes, lack of time was a big concern and projects tended to do the job first - document it later.

A new process design has been developed as a proposal for implementation in OMS which is clearer, simpler, and easier to over view, includes RDM and related to Volvo Aero’s product development philosophy.

A new tool has been developed, the Concept Start Sheet. The tool clarifies the task in the early stages of the concept development process and is based on Volvo Aeros product development philosophy. The basic aims for the start sheet are:

- Balance the project aim
- Visualize the task
- Implement the Volvo Aero Product Development Philosophy
- Clarify the directives from the steering committee
- Increase the communication in inside the project team
- Increase the communication outside the project team (to steering committee and marketing department).

“Robust Design Methodology means systematic effort to achieve insensitivity to noise factors. These efforts are applied from concept generation to the production of a product” (Gremyr 2005). Although the claim made in this report is that efforts can be applied before the concept generation, during the clarification of the task. The expression robust design is a craze that might not last for long, but the work with reducing variations will always be profitable.

Keywords: Robust design, Conceptual design, Engineering design, Design process
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1 Introduction

1.1 General Background

The starting point of this project was to study the concept choices, but in order to make good judgments and choose the best concept, the concepts themselves need to be as good as possible and to have good concepts the concept development process need to be good with good methods and tools as well as good prerequisites. Therefore this project has studied the whole concept development process instead of only the concept choices.

Conceptual Design is construction of ideas into concepts. It involves translating customer needs into technical requirements and interface design, generating solutions and concepts, analyzing concept, evaluating concepts and eventually selecting a concept for further optimization.

Robust Design Methodology (RDM) focuses on improving the reliability of a product or a process, which means making the system performance immune to variations. Variations are everywhere, wanted and unwanted, but the unwanted variations can lessen the quality of the provided products and/or services. The aim with a robust design is not to try and eliminate the variations but rather to make the product insensitive to them.

1.2 Problem Definition

Viewing the whole product development project time cycle, it is clear that changes to the product are more time consuming and expensive the later they are made in the process. But early on in the project, in the conceptual phase of the product, the freedom of changes is great and can be made at a low cost (figure 1).

![Diagram over freedom and cost of change during the project time](Johannesson 2004)

Therefore it is essential to have a workable process with appropriate methodology and practical routines to help to make the right decisions early on, to secure product quality and robustness.
INTRODUCTION

The thesis answers the following questions:

- What is Robust Design?
- How can Robust Design Methodology be implemented in the concept development process at the company?
- Can conceptual design methodology be used as methods to achieve robustness?
- How can the concept development process be made robust?
- What can the company gain with a Conceptual Design for Robustness methodology?

With company meaning Volvo Aero Corporation.

1.3 Aim

The aim for this project was to develop a Robust Design Methodology (RDM) for the concept development process and view the conceptual design methodology from a RDM perspective. The methodology need to account for the perspectives from all disciplines in the product development process at Volvo Aero. Further, the aim was to suggest implementation in design practices and in the quality management system (OMS) at Volvo Aero.

1.4 Company presentation

Volvo Aero is a world leading manufacturer of aircraft components, rockets and gas turbine engines with high technology content. The headquarters Volvo Aero Corporation are located in Trollhättan, Sweden, where the majority of the staff is located.

Volvo Aero is a subsidiary of AB Volvo and within the Volvo group the corporate values are the same, and Quality is one of them. It is a critical requirement with high quality in the aviation and aerospace industry and therefore Volvo has a quality-thinking in everything that is done. All the employees are committed to the continuous work with improvement of all processes. (The Volvo Aero global website)

1.5 Delimitations

The focus for this thesis has been on Robust Design Methodology and Conceptual Design such as concept generating, evaluations and selection. Detailed construction work, product layout and manufacturing adaptations have been excluded as well as the definition of concepts.

The focal point of the thesis work has been on Volvo Aero, finding method that suits this company and taking into account company conditions and culture. Other companies and organization has not been taken into consideration, therefore the suggestions that are made might not necessarily suit other organizations the same way.

---

1 Volvo corporate values: Quality, Safety and Environmental care
1.6 **Project Planning**

This thesis work had the duration of twenty weeks and in the beginning of the project a Gantt chart was made to ensure a fully planned master thesis. It shows the activities made during the work and the estimation of the duration of each activity. It also contains deadlines of the work. A few changes to the chart have been made during the project, but the entirety has remained the same. The Gantt chart can be found in appendix 1.

1.7 **Abbreviations**

<table>
<thead>
<tr>
<th>Concept</th>
<th>A technical solution that is sufficiently described for analysis and evaluation in condition to the product requirement specification</th>
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<td>CPM</td>
<td>Chief Project Manager</td>
</tr>
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<td>DfR</td>
<td>Design for Robustness</td>
</tr>
<tr>
<td>DOE</td>
<td>Design of Experiments</td>
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<tr>
<td>FMEA</td>
<td>Failure Mode and Effect Analysis</td>
</tr>
<tr>
<td>G1-G8</td>
<td>Gates in GDP</td>
</tr>
<tr>
<td>GDP</td>
<td>Global Development Process, the product development process within the Volvo Group</td>
</tr>
<tr>
<td>HoQ</td>
<td>House of Quality, a tool that is used to understand customer requirements.</td>
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<tr>
<td>Noise</td>
<td>Variations affecting the system performance</td>
</tr>
<tr>
<td>OMS</td>
<td>Operational Management System: A tool to secure quality.</td>
</tr>
<tr>
<td>PAP</td>
<td>Project Assurance Plan</td>
</tr>
<tr>
<td>PM</td>
<td>Project Manager, can otherwise be referred to as Project Leader</td>
</tr>
<tr>
<td>Producibility</td>
<td>Ease of manufacturing</td>
</tr>
<tr>
<td>QFD</td>
<td>Quality Function Deployment</td>
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<td>RDM</td>
<td>Robust Design Methodology</td>
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<td>S/N Ratio</td>
<td>Signal-to-Noise Ratio</td>
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<tr>
<td>TRIZ</td>
<td>Theory of Inventive Problem Solving</td>
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<td>VMEA</td>
<td>Variation Mode and Effect Analysis</td>
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</table>
2 Methodology

2.1 Research Strategy

There are many different systematic methods to use in the concept development process such as RDM and Conceptual Design Methodology. The research strategy for this thesis was to improve the concept development process at Volvo Aero Corporation and find methods that would help in the process and to suit the different projects and disciplines that are involved in the process. A suggestion of changes to the concept development process has also been made to suit the methodology. The research strategy was to learn about the product development process and get an understanding of the company, which was gained by interviews, questionnaires, observations and reading company documents.

2.2 Research Method

2.2.1 Literature Study

A great part of this thesis work has been an external literature study (literature, thesis’s and articles) on the topic conceptual design, product development, and robust design methodology. The literature study was also conducted internally with documents such as concept books, education materials, instructions etc.

2.2.2 Interviews

To get information about the concept development process personal interviews were made with open ended questions, where the interviewee freely could talk around the topic concept development and design for robustness. This was also a way to learn about the organization and projects, which is essential to be able to find appropriate methods and to find the problem areas and personal opinions on how the problems should be dealt with.

2.2.3 Questionnaire

A three-page, 18 questions questionnaire has been given out and also e-mailed out to 28 employees and consultants at Volvo Aero that have been part of a concept development process. It had both closed-ended questions, which could be answered by checking predetermined answers, and open-ended questions where the participant could answer in their own words. All answers were anonymous and voluntarily.

The questionnaire gathered information that could be statistically analyzed. The method was a complement and a confirmation tool to the information gathered in the interviews. The questionnaire is found in appendix 2.
2.2.4 Observations

Observations were made from participations at meetings and concept reviews sessions etc. This increased the understanding of how employees interact and how the tasks were carried out. The observations were unstructured since it is hard to know in before hand what to observe in particular, instead anything and everything was observed.

2.2.5 New Designs

A new process design has been developed ready to be implemented in OMS. It was evaluated by several Volvo Aero employees (process owners, chief engineers and design managers) so that it would suit the different projects and disciplines.

A new tool for clarifying the task has been developed, the Concept Start Sheet. This tool was evaluated by engineers and project managers at the company and one project was used to make an example.

2.2.6 Limitations of Methodology

The result may contain subjectivity; hence the same results might not be obtained in a similar study elsewhere. Interviews have been made with, and questionnaires have been handed out to, employees at Volvo Aero with the aim to reach all disciplines and projects. Although not many have refused, not everyone has been contacted which may have resulted in biased data.

Activities of interviews and observations have not been thoroughly documented to serve as references so that readers can follow the conducted research and be convinced about the findings. Rough notes were made during interviews and observations, but these can not be found in the thesis. However, the questionnaire answers are documented and can serve this purpose. The focus for this project has been on the findings rather than on the documentation of the activities during the work.
3 Current State Description

Volvo Aero has recently launched a Product Development Philosophy that “…embodies the ability to balance and optimize between fulfillment of Product Cost, Technical Requirements and Producibility” (figure 2).

3.1.1 The Product Development Process

The quality management system used at Volvo Aero Corporation, to help secure product quality in all activities, is the Operational Management System (OMS). It is an important tool for employees to understand what to do to reach the company goals.

The product development process is defined in what is called the Global Development Process (GDP) and is part of the OMS (figure 3 and 4). The GDP is a development logic based on what is used within Volvo Group. It is intended to be a common base for product development, flexible enough to adapt to different projects with different levels of work complexity. It describes the activities that need consideration from the idea of a new product through development, industrialization, commercialization and delivery. The product development process goes through six phases, which starts and ends with gates (G1-G8) (The Volvo Aero internal website).
It is the Steering Committee that approves gate criteria and gate openings based on material provided by the team. The Concept Study phase is the second part of the product development process. The focus for this project has been on The concept development process (figure 5), which can be found in the Concept Study phase (between G1 and G2 and between G2 and G3) as well as the Detailed Development phase (between G3 and G4). The process is iterative and the projects can loop the process. The only thing that differentiate the loops is that they each time pass trough different gates which has different criteria. For a bigger figure of the concept development process see appendix C. For gate criteria at G2 and G3 see appendix D.

The top level of large green squares in figure 5, are the first level in the concept development process; these contain underlying activities which in the figure are shown below as red squares. The lighter pink squares are the third level.

At Volvo Aero a concept is defined as a technical solution that is sufficiently described for analysis and evaluation in condition to the product requirement specification. The concept
development task is carried out in cross-functional teams and the work is documented in a concept book.

3.1.2 The Project Organization

The product development at Volvo Aero Corporation is organized in projects (Heavyweight Project Matrix Organization). Every project has a Chief Project Manager (CPM) who manages the project and reports to the Steering Committee (figure 6). The project gets resources from functional departments in a line organization. Different disciplines are represented in the projects depending on needs and resources and can vary throughout the project. The Steering Committee supports and supervises the project management and approves the Project Management Team including the CPM (Volvo Corporate GDP 2008).

The Project Management Team consists of the CPM and the Project Managers (PM). The PM is responsible for leading, planning, coordinating and communicating project activities within his/her specific area, such as design, definition, production and purchasing. The PMs report to the CPM. In the early stages of the project as the concept development, the design manager has a significant role. The design manager is often the one that conducts the concept evaluation. Some projects get requirements (with or without ranking) from the steering committee other projects get that from the customer only.

The different products at Volvo Aero are divided in hot and cold structures and each product has a Process Owner. Ownership means to establish the needed pre-requisites for project success and also to implement the results of the project. The process owner initiates the project and puts together a review group that has the function of reviewing the concept developments different stages and the gates that the project passes through (The Volvo Aero internal website).
4 Theoretical Framework

The theoretical framework for this thesis consists of The Design Process, Robust Design Methodology, Clarifying the Task, Concept Generating, Concept Analysis, Concept Evaluation and Design Rationale.

4.1 The Design Process

The design process determines the quality of the product and to improve the product, the improvement of the process is necessary. But even though the design goals and the scale of the project can vary, the design process can look the same. The process always has an input and an output (figure 7). But the design process can take different steps within the process. The main process can be divided into sub-processes and make loops for feedback (Dubberly 2004).

![Figure 7: The Design process (Dubberly 2004)]

Design process models describe the sequence of activities in the product development process in form of flowcharts and several different versions have been made. The purpose of establishing a systematic procedure for the design process is to ensure the generation of good designs (Sivaloganathan et al. 1995). And the purpose of a systematic procedure for the concept development process is to ensure the generation of good concepts.

Problem solving can be a sequential activity, where the problem must be defined before it can be solved. On the other hand, the solution can be inherent in the problem and by defining the problem; the solution is outlined if not defined. By trying to solve a problem, the problem is more understood. The design can therefore be an iterative problem-solving process and a progression from abstract to concrete (figure 8).

![Figure 8: Problem solving (Dubberly 2004)]
4.2 Robust Design Methodology

4.2.1 Thoughts on Robust Design

“Robust Design is to improve the quality of a product by minimizing the effects of the causes of variation without eliminating the causes”.
(Phadke 1989)

Andersson (1996) uses the term conceptual robustness and means a “conceptual solution that is robust to variations in specified input and to design variables’ deviations from nominal values”. Although the extent to what this can achieve depends on the level of abstraction of the concept and the variations that can be anticipated in the concept development process. But it is the first step that leads to product robustness. There is little to gain from trying to optimize a bad concept.

“Robust Design enables the engineer to efficiently gather the technological information required to produce high quality, low cost products”
(Taguchi et al. 2000)

“Robust Design Methodology means systematic effort to achieve insensitivity to noise factors. These efforts are applied from concept generation to the production of a product”.
(Gremyr 2005)

Hasenkamp (2006) has identified three basic principles that characterize RDM:

- **Awareness of variation**
  For a better understanding of RDM an awareness of variations are needed

- **Insensitivity to noise factors**
  The goal with RDM is to create insensitivity to noise factors rather than elimination of them.

- **Continuous applicability**
  RDM efforts are applicable in all stages of product design

4.2.2 P-Diagram

There are four factors in Design for Robustness methodology that require to be considered in the design process: signal, response, noise and control. These factors can be visualized in a P-diagram (figure 9). The signal factors are the input signals of the system and the response factors are the output signals. The noise factors are the different variations affecting the system performance. To compensate for each variation the designer must find methods of control.
According to Taguchi (1986) there are three categories of noise factors: Internal noise, external noise and unit-to-unit noise. Internal noise (can also be referred as deterioration noise) occurs during storage or use such as corrosion and ageing of the product. External noise is variable in the environmental conditions including temperature or variations of use that disturbs the functions of the product. Unit-to-unit noise (can also be referred to as variational noise) are differences between individual products that are manufactured to the same specifications.

The P-diagram can be used as a tool in concept development to identify and illustrate the inputs and outputs of the system and get an understanding of the parameters which contributes to the performance, the parameters of noise that can be controlled and those who cannot. This can help in the decision about the parameters that leads to a consistent behavior of the product and a robust design.

### 4.2.3 Nonlinearities for Robustness

Robustness can be accomplished by making use of the nonlinearities of the product characteristics. Box and Bisgaard (1998) illustrates this with a pendulum. The period (the response) of the pendulum depends on its length (the control factor), the period of the pendulum can be controlled by changing the length of it. The shorter the pendulum is the more sensitive it is to small variations of the length. So the pendulum can be made more robust, insensitive to small variations of the length; by making the length of the pendulum longer (Bergman 2007). If product characteristics are nonlinear like the example of the pendulum, robustness can be accomplished by making use of this fact.

### 4.2.4 The Signal-to-Noise Ratio

Taguchi uses The Signal-to-Noise Ration (S/N ration) is an index of robustness as shown in equation (1):

---

*Figure 9: P-diagram*
THEORETICAL FRAMEWORK

\[
\text{S/N ratio} = \frac{\text{power of the signal}}{\text{power of noise}} = \frac{(\text{sensitivity})^2}{(\text{variability})^2}
\]  

(1)

The appearance of the value can vary depending on the target value. If the target value is as high as possible or as close to zero as possible. But both Bergman (2007) and Hasenkamp (2006) question the use of an S/N ratio.

4.2.5 Design for Robustness at Volvo Aero

Volvo Aero uses the term Design for Robustness and has written their own definition of it: “Design for Robustness (DfR) means the ability to manage variations & uncertainties so that we are able to balance and fulfill customer requirements”. The company also has a DfR vision which is to: “consistently and efficiently design and produce a product that; Supports the customers’ expectations of functionality and quality, meets expectations for “producibility” and has minimal sensitivity to all sources of variations”.

4.2.6 Designing a Robust Process

To be able to produce a product repeatedly, a repeatable production that can handle variations is needed and therefore to produce a robust product a robust production is needed (Stimson 1996).

Taguchi et al (2000) suggest a six-step implementation process:

1. **Management Commitment**
   It is essential that the management fully understand the benefits of the process.

2. **Corporate Leader and the Corporate Team**
   It is important that the leader has a complete understanding of all of the elements involved and involve as many engineers as possible in a cross-functional team.

3. **Effective Communication**
   Robust Design offers a new vocabulary and it is up to the team to communicate the meaning of it.

4. **Education and Training**
   The importance of education and training can never be underestimated.

5. **The Integration Strategy**
   Create an environment where Robust Design can be part of everyone’s work activities.

6. **Bottom-Line Performance**
   “Prevent the fires by preventing the causes”.

4.3 Clarifying the Task

Clarifying the task consists of developing a general understanding of the problem and if necessary, breaking it down into sub-problems. A close contact between the costumer or project proposer and the design department is therefore essential if an optimum solution is expected. Otherwise necessary information is lost and the task is not clarified sufficiently. To
be able to design for robustness it is essential that the design team has clarified the task sufficiently so that the product in the end has an optimum solution and meets up with customer expectations (Pahl 2005).

The requirement list needs to be detailed and it should state whether the requirement is a demand or a need. Needs are requirements that need to be taken into consideration and a solution that doesn’t fulfill a demand is not acceptable. The requirement list can also be tabulated into quantitative and qualitative aspects, quantity involving numbers and magnitude, quality involving special requirement such as corrosion proof.

Andersson (2003) tabulates the requirements into Function, Behavior, Properties and Structure or in just Functional and Non-Functional. The requirements specification list can be used as a control mechanism, but also as a way to understand the problem and stimulate development.

In early stages of a project it is not always possible to make the statements in the requirement precise and must therefore be corrected later in the development process.

Hasenkamp (2006) claims that “The more people involved in a project, the greater is the need for a structured procedure in order to maintain capacities to act and to ensure that nothing important is overlooked”

### 4.3.1 Ishikawa Diagram

The Ishikawa diagram was first introduced by Kaoro Ishikawa 1943 (Bergman 2007) and it is a systematic tool to find potential noise factors to the product characteristics that effects the product performance (figure 10).

![Figure 10: The Ishikawa diagram (Hasenkamp 2006)](image-url)
4.3.2 Quality Function Deployment

The purpose of Quality Function Deployment (QFD) is to fulfill customer requirement. The method translates vague customer requirements into clearly formulated requirements that the company department can relate to (Pahl 2005). QFD is originated in 1972 at Mitsubishi’s Kobe shipyard site in Japan. (Sivaloganathan et al. 1995)

The House of Quality (HoQ) is a tool often used in QFD (figure 11) otherwise known as a QFD-chart. Customer requirements are described in relation to technical requirements in the center of the house, with symbols or weighting. Below the relationship matrix is the target value for the technical requirements. In the roof of the house is the correlation matrix where plusses and minuses describe the correlation between the technical requirements. For example low weight and steal material don’t correlate, which means a minus in the matrix. HoQ can also include competitive assessment in both customer and technical requirements, although the competitive assessment can be excluded from the house if it is not necessary or accessible (Bergman 2007).

The absolute score and the relative score is where the design team creates a hypothesis as to how the product performance contributes to customer satisfaction. Then they will understand where the product has got to measure up strongly in order to beat competition.

![Figure 11: House of Quality (Bergman 2007)](image)

The benefits of the HoQ are several:

- It gives a better understanding of customer needs.
- It gives a clear view of conflicting of mutual characteristics.
THEORETICAL FRAMEWORK

- It gives a clear view of what characteristics that has the greatest impact on customer satisfaction.
- It gives a clear view on competitive benchmarking
- It gives a good documentation on decision motivations.
- It completes the requirement list.
- It can increases innovation
- It can increase customer satisfaction

4.3.3 The Objective Tree

To identify the requirements and their ranking and also get a better understanding of the task, the requirements can be drawn up in a hierarchical objective tree (figure 12). Where the main objective is the target, what we want to achieve, i.e. the finished product. The branches are sub-objectives, or in this matter requirements and sub-requirements that are needed to achieve this. The objective tree will help to see the problem laid out clearly (Pahl 2005).

![Figure 12: The Objective Tree](image)

The tree can also help ranking the requirements. The highest level, the main objective (the product) is given the value of 1.00 and each level, or branch, below are given weight relative to each other, but with a total of 1.00. The weighting is calculated as a fraction of the
weighting of the above. If every branch has the same amount of levels a higher value than 1 can be used if dealing with decimals is considered difficult, for example 10 or 100.

The objective tree prevents the biased proposed by the “loudest talker” from being forced through, since the team can go through the weighting branch by branch, weighting them relative to each other.

4.4 Concept Generating

Often conceptual ideas are generated and documented informally. But the formal methods are either intuitive such as brainstorming and 635 or logical such as TRIZ. Intuitive methods work with the unconscious thought process of the human mind and the outcome is unpredictable. Logical methods are systematical decompose and analyze the problem (Shah et al. 2000). Some methods are group activities while others can be performed individually as well (figure 13) (Andersson, 2003). Not all methods will be analyzed in this thesis.

4.4.1 Brainstorming

The most common method for generating concepts is brainstorming, which is used by most companies and organizations (Johansson 2005). There are four simple rules with brainstorming:

1. Generate as many ideas as possible.
2. Generate as wild ideas as possible
3. Build on each others ideas
4. Do not evaluate the ideas

Although the method is common, research has shown that the brainstorming method often is used the wrong way. Johansson points out three reasons behind these problems:

1. Team member rely on the ability of others to generate good ideas
2. Team members avoided to present crazy ideas to avoid criticism
3. The teams are too big and only one person can talk at the time

It is important that the team members get the opportunity to brainstorm individually before the group activity start. This forces the team leader to have a clear problem definition and the team members will not forget their original ideas at the group activity. The group activity needs a high speed so that all ideas gets noted and discussed (Johansson 2005).

4.4.2 Method 635

Method 635 is a method that has been developed from brainstorming and like brainstorming this is a group activity. Method 635 involves 6 participants, who are asked to write down 3 general solutions, each solution is passed to the other 5 participants, who continues on the solution and develops further developments on the solution or new developments associated with the solution. This way the group participants use the different approaches to the problem as a springboard for new solutions.

The name of the method suggests that it should be 6 participants, although this is not necessary. Nor is it necessary that every participant produces exactly 3 solutions. The main thing is that every solution is passed to the other participants who tries to develop it further or develops something new with the association from the solution. Compared to brainstorming Method 635 has a more systematical approach (Pahl 2005).

4.4.3 TRIZ

TRIZ is a Russian acronym for Theory of Inventive Problem Solving or Theory of the Solution of Inventive problems (TSIP) and is a theory rather than a methodology, although it can be used to generate concepts (Altshuller, 1988). The idea is to identify technical contradictions that are hidden in a problem and eliminate them by transforming one formulation of the problem or solution to another (figure 14). Sometimes it might be necessary to look at the problem in a different way to be able to find the best solution. Every office and industry has as well as experiences a store of prejudice, which in some cases can help but in others stand in the way of more unconventional solutions. This will force the user to overcome preconceived ideas of what the problem consists of (TRIZ-journal).

![Figure 14: TRIZ (TRIZ-journal)](image-url)
When tackling an inventive problem knowledge is not the main concern but the ability to correctly reprocess the information and knowledge and by reprocess Altshuller means building a chain of consistent actions and direct these so that they lead to a solution of the problem (Altshuller, 1988).

### 4.4.4 The Morphological Matrix

It is often useful to divide problems into sub-problems or sub-functions and solve these individually. But when the solutions for the sub-problems are found they have to be combined in order to solve the general problem. A systematical way for this activity of combining solutions is to use a morphological matrix (figure 15) (Pahl 2005), where all the sub-functions that has to be performed are listed on the left-hand side of the paper and forms the rows in the matrix. For each of the sub-functions in a row, all possible solutions are listed. The different sub-solutions are then combined to perform the overall function. Some combinations will be incompatible and are then eliminated and the compatible solutions are listed as concepts (Sivaloganathan et al 1995).

![Figure 15: Morphological matrix (Pahl 2005)](image)

This activity lead to concept generating, an understanding of the whole problem and also to additional creative thought. But the main problem when combining functions and solutions is to decide which solutions are compatible and also narrowing down the number of solution concepts (Ulrich 2003).

### 4.5 Concept Analyzing

For conceptual robustness detailed and quantitative information is needed. Therefore concept analysis is necessary. Fulfillment of technical requirements, costs, risks and the ability for production needs to be evaluated and analyzed.
4.5.1 Cost Analysis

Takai (et al 2006) presents a method by Tanaka that allocated the product cost based on each parts degree of importance for product function in the following equation (2):

\[ VI = \frac{\text{Degree of importance}}{\text{Percentage of cost}} = \frac{\text{Importance of a part} / \text{Importance of the product}}{\text{Cost of a part} / \text{Cost of the product}} = \]

\[ = \frac{\text{Importance of a part}}{\text{Importance of the product}} \times \frac{\text{Cost of the product}}{\text{Cost of a part}} \]

\[ = \frac{\text{Target cost of a part}}{\text{Cost of a part}} \]

The purpose of the value index (VI) is to identify the parts that need a reduction of costs (VI < 1) or parts that need further development of the features (VI > 1).

Although Tanaka presented the methods for product parts, the same could be used to evaluate different concepts as well, where the value index equals the target cost of the product divided by the cost of the concept.

4.5.2 Probabilistic Design

Probabilistic design is a robust design methodology that analyzes the effects of random variability of the products performance. It is used to either identify the design that will have the smallest effect on random variability or finding the optimum combination of variables by studying the effect of control factors, the effect of noise factors or the S/N ratio. The method predicts the flow of variability or distribution instead of viewing each variable as a single value. There are different methods to be used for a probabilistic design, Design of Experiments (DOE) and The Monte Carlo method (Wikipedia).

Design of Experiments

Design of Experiments (DOE) is a method for systematic test and experiments which determines the relationship between factors affecting the process or the product. A series of structured experiments are designed with planned changes by varying the factors/input variables to the system (figure 16) (The Quality Portal and Bergman 2007).
The different factors/variables that could be tested are for example material, manufacturing method or design parameters such as length and width. The response signal can be measured either by product testing or by simulations.

The P-diagram can be used in DOE to identify the input variables and the response signal that is to be measured. The experimental plan says where to set each parameter for each run of the test and the response is measured. The benefits of DOE are:

- Fewer tests compared to “one change at a time”-testing
- Information of relationship between factors can be gathered
- The difference between random and significant influences on the system can be determined.
- The main contributing factor to the problem can be found

But DOE may be difficult to carry out in the concept development process for the following examples (Andersson 1996):

- there are no prototypes to perform the experiments on
- they are to difficult for practical reasons
- it is too difficult to change the levels of the factors in the experiment
- the domino effect may occur (if one factor is changed other factors or parameters might have to be changed as well)

**The Monte Carlo Method**

The Monte Carlo Method has similarities with the game Battleship: The player makes a random shot, then applies algorithms (i.e. a ship has a specified number of dots in a certain arrangement) and then based on the outcome of random sampling and the algorithm the player can then determine the location of the ship. The Monte Carlo Method uses the same basis, algorithms and random sampling but is most suited for computational calculations. (Wikipedia)
4.5.3 Tolerance Stacks

Tolerance Stacks can also be referred to as Tolerance Stack-ups and is a method of calculating the effects of accumulated variations that is allowed by the specified dimensions and tolerances. It helps engineers to understand the relationships between parts in an assembly by using the maximum and minimum values of the tolerances to calculate the maximum and minimum distance between two parts. It evaluates the values based on calculations combined with a method for establishing the likelihood on obtaining the maximum and minimum values, such as the Monte Carlo Method. This helps to define the product by completing the drawings and also helps in comparing different concepts (Wikipedia).

4.5.4 Failure Mode and Effect Analysis

Failure Mode and Effect Analysis (FMEA) or Failure Mode and Effect Critical Analysis (FMECA) are methods for identify potential failure modes (such as errors or defects in the design, process or product) and then analyzing the effects or risks of these failures with the aim to avoid them (Pahl 2005). The method addresses what can fail, how it can fail and what the effects are of the failure, it allocates the severity of the failure, the likelihood of occurrence, the likelihood of detection and the cost of failure. A cross functional team should be put together for the FMEA-activity and can be applied in the different stages of the product development.

4.6 Concept Evaluation

4.6.1 Concept Evaluation Matrixes

Concept evaluation and selection matrixes can be divided into selection charts, screening matrixes and scoring matrixes depending on the level of detail.

Selection chart

If a large number of solutions have been made a selection chart can be made to quickly narrow the number down. In the selection chart go/kill criterion are set up such as (Pahl 2005):

- Are compatible with the overall task
- Fulfills demands on requirements list
- Realizable in principle
- Are within reasonable cost

If the concept does not fulfill one of these criterions they are eliminated and there is no need to see if the concept fulfills the other criterions. However, a selection chart is only advisable when there are so many solutions/concepts that a full evaluation would be too time consuming or take to much effort. But for a more detailed evaluation of the concepts Pugh matrix or s concept scoring matrix should be used.
Screening matrix
The purpose of a screening matrix is to narrow the number of concepts down. A screening matrix can also be called a Pugh Matrix after Stuart Pugh who developed the methodology in the 1980s. (Ulrich 2003).

One concept can be chosen to be a reference concept, which all other concepts are rated against. The score “better than” (+), “same as” (0) or “worse than” (-) is placed in each cell in the matrix. It is advisable to rate all concept against one criteria before moving on to the next criteria. The all the ratings are then added, which results in a total rate and a rank order of the concepts.

Scoring matrix
An evaluation matrix can also include an importance weight and the ratings of the concepts have a numerical scale, the matrix is then called a concept scoring matrix. (figure 17). The scoring matrix can still use a reference matrix but this is not necessary. But it is essential that the design team agrees on the rating scale and what the concepts need to accomplish when getting a certain rate.

For a meaningful comparison and unbiased selection between the concepts, they need to be presented at the same level of detail. To reach high product quality the chosen criteria should be based on customer needs but also other technical requirements that the team has identified, such as manufacturing requirements, cost and risks. If the evaluation criteria are given an equal weighting the team needs be careful not to list many relatively unimportant criteria in the matrix.

It is advisable to verify that the results make sense and to discuss if there might be concepts that can be improved by combinations with other concepts. Finally the team needs to decide which concepts are to be selected for further refinement and analysis.

4.6.2 Cost vs. Functionality Evaluation

In the conceptual phase of the product development engineers often have to face tradeoffs between cost and performance. According to Takai (et al 2006) functionality and cost needs to
be evaluated separately to guarantee that the concepts with the highest score satisfies both the required functionality and the target cost. The value index from Tanakas method (4.5.1) can be put in a diagram with the total rate of each concepts (figure 18). The functionality can be measured by the fulfillment of technical or evaluation criteria. The problem is to determine where the feasible region starts on this axis. But the diagram gives a visual map over the different concepts in regard to cost and fulfillment of evaluation criteria which will help in the decision process.

![Figure 18: Fulfillment of evaluation criteria versus cost diagram (Takai 2006)](image)

### 4.7 Design Rationale

Rationale means “logic cause” or “principle”, but Design Rationale is (according to Andersson, 2009) “the reasoning and argumentation that underlies the activities that take place during the design process”. It is the answer to the why rather that what or how. Why have we designed a product a certain way? Why have we chosen a specific concept and not the other? Why do we manufacture the product the way we are? There are many why-questions that need to be answered in concept development and Design Rationale could therefore be a tool for design for robustness.
5 Analysis

This section in the thesis consists of an analysis of current situations as well as a robustness analysis of the concept development process with a P-diagram.

5.1 Analysis of current situations

The analysis of current situations has been based on analysis from interviews, observations and questionnaire as well as an analysis of the current used methods at the company. This section is ended with the problem areas that were found.

5.1.1 Analysis of Interviews and Observations

The focus point at the starting of the interviews was concept evaluation and robust design; although a good evaluation demands an adequate development process, which turned the interviews to other topics such as time, resources, directives, requirements, processes and methods as well.

Time and Resources

One thing that often came up during the interviews was the lack of time. Many also hinted about a lack of resources and skills. Employees could switch project with the aim to spread knowledge, but the reality was that they sometimes didn’t have time to hand over properly so the consequence was that things had to be redone unnecessarily. Other times team members could come in late in the project and then not have the chance to govern. In many cases the work was done first and the documentation later, because of lack of time to do them parallel or because documentation was not prioritized.

Directives and Requirements

There was often a lack of clear directives from the steering committee and requirements from customers. Requirements could change during the project, which may cause work to be redone. Requirements that couldn’t be fulfilled were reformulated into once that could be fulfilled. Some projects used a QFD or HoQ to formulate customer needs into technical requirements and others did not use any specific tool. But there was a need for harmony between requirements and the weighting, so that requirements in a certain area aren’t neglected because of quantity.

Processes and methods

OMS/GDP was not always followed and often projects made unnecessary loops in the process. Sometimes construction instructions were used instead of the GDP. GDP was considered to be too single-tracked and did not always relate to the customers view on the project process, for example could the view differ on what a concept is.

Due to different customers, the projects could not look at what other projects did or how they were doing it. The availability was locked and controlled only by those within the project and therefore a database of previous knowledge was requested.
The methods and tools were sometimes developed during the project. People requested methods and the tools that were easy and quick, nearly foolproof, although some education might be needed.

**Concept evaluation**
Old concepts were often more processed, and therefore more information was available about them compared to new concepts, which rather were estimations. The project must determine whether to renew/optimize old concepts or if to invest in something entirely new. Just because a concept had worked before does not necessarily mean it works in every situation. The conditions may have changed and the products needed a description on in what conditions the product can be used.

A project could consider choosing a certain concept just to get better at a specific type of production, although the risk was great. Sometimes a back-up concept was chosen when the risk was considered to be large with the concept first chosen. Sometimes combinations of concept solutions were made. But it could often be difficult to keep track of them and the concepts were given names such as 2A, 3C. Otherwise concepts could get bird-names for example to represent the different characteristics of the concepts.

There was a need for making clear in advance how the concept evaluations were to be carried out and to consider what information was essential when the concept choice was to be made. Sometimes there were parallel groups of specialists in particular fields who decided on specific parts. Sometimes the evaluation matrix was more accurate and detailed than the directives of the product itself. And sometimes the evaluation resulted in equal value between two concepts so that the project team made the decision based on feelings, and afterwards reviewed the evaluation again to change it in the chosen direction.

**Robust design**
There were several versions of what robust design means. Many had some idea of it, but did not really know how to attack it. Many had the thought of robust design in mind and tried to implement it in the work but did not have a specific method for it. Some believed robust design should be taken into account in every point in the concept evaluation matrix and others claimed it should have a separate point in the matrix.

### 5.1.2 Analysis of Questionnaire

The questionnaire was used as a complement to the interviews, with the objective that the outcome would confirm the information gathered in the interviews. The questionnaire turned to employees that had work with concept development to find what methods had been used, how the projects had worked, what they considered to be most important in the process and what the rationale were for the decisions that were made, if they followed the process described in OMS/GDP and also what the viewpoint were of Design for Robustness. The questionnaire can be found in appendix B and the answers can be found in appendix E.

**Summary of Questionnaire**
The questionnaire was given out to 28 employees at Volvo Aero (20 were handed out and 8 were emailed out) and 16 answered it (two by email). So the share of answers were higher when it was handed out compared to if it was emailed out.
The answers showed that the questionnaire participants had worked in several different projects and the most used method/tool was brainstorming, following by QFD and the Pugh matrix. But only 7 out of 17 thought that brainstorming was a good method and only 1 out of 7 thought that the Pugh matrix was good. Other methods that had been used was Volvo concept analyze method, Space concept process, Volvo Aero concept process, Function tree analysis, Risk analysis and Kepner Tregoe.

The requirements that the participant thought were the most important were Product cost and Technical requirements, followed by Producibility and Function. Most projects did follow the GDP in OMS, but few got sufficient amount of information from customer and steering committee for the concept generating task.

Some project decomposed all the requirements into sub-requirements and other only decomposed some of them. The requirements almost always changed during the concept development, but for some it was only small details. The ranking of the requirements were almost always justified. The matrix of choice was mostly easy or OK to work with and the design team mostly agreed on the outcome, otherwise there were team discussions or up to the manager to make the final decision.

The review group usually agreed with the proposed evaluation and selection by the design team, but not always. The decisions were mostly sufficiently motivated but sometimes not and usually the justification was documented in the concept book. There was a connection between these three questions, if the review group did not agree with the proposed evaluation; the decision was usually not sufficiently motivated and only some of the justification was documented.

The participants thought there might be needs for more methods or tools in the concept development and evaluation. Those who had not used many methods were more positive to new methods than those who had used several.

There was not a mutual agreement of what is implied with the expression: Design for robustness. Participants mentioned insensitivity to variations, handle deviations, large tolerances, fulfilling requirements, probabilistic design, using well known materials and as a way of thinking. Half of them did not work with design for robustness in the concept development process. And those who did mentioned probabilistic design or had robustness in mind in the evaluation of concepts.

### 5.1.3 Analysis of Current Methods

From interviews, observations, questionnaire and internal literature study (such as company educational materials and instructions) an analysis was made of the current methods used at Volvo Aero. This showed that there were no overall methods used to develop, evaluate or select concepts, except brainstorming. Otherwise the methods of choice differentiate project to project. In educational materials methods like QFD, TRIZ, Post it, Pugh matrix and Rationale were mentioned. But only brainstorming was an overall used method. A version of QFD was used in some projects and different matrixes like Pugh matrix was used by many but in varies ways, some unnecessarily complicated.
QFD at Volvo Aero

A link to a short explanation of the House of Quality was found in OMS. Although, the link was not found in the place in the process where it might be needed, but in a separate place for quality tools which could be hard to find. Furthermore the explanation was very simple and hard to follow if not used before. A version of HoQ was used by some projects at Volvo Aero, although they were not always aware of the name of the tool they were using and might therefore not recall the name if asked if they used it in an interview or in a questionnaire.

Concept Evaluation at Volvo Aero

Several projects used a go/no go-criteria for concept screening. If the concept could not meet one of the criterions it was discarded and only the concepts that could meet the criterion were left. The weighting scale in a concept evaluation matrix could differentiate in different projects, linear (1-5) and logarithmic (1, 3, 9) or plus and minus.

DOE at Volvo Aero

The Aerodynamic department at Volvo Aero has used DoE and Monte Carlo simulations for analyzing how manufacturing imperfections affect the aerodynamic behavior of the product. With simulations and CFD this could be done as early as in the concept development process.

5.1.4 Problem Areas

The problems found from the analysis have been divided into two areas, problems with the process and problems with methods/tools.

The Process

Several projects at Volvo Aero did not follow the process described in OMS, or followed it only partly. The concept development process in OMS was complicated and hard to overview. It explained what to do, rarely how to do it or who should do what and there were no links to tools or methods. The estimation of risks followed the concept evaluation, which could result in lack of understanding of the product risks and project taking either too big risks or playing it too safe during the process.

Since the only overall method used at Volvo Aero was brainstorming, it was up to the different projects to find methods of choice for concept generating, analyzing and evaluation. Finding these methods and tools could be a time consuming task itself and there was a need for easy and fast methods as well as routines. Nearly every project complained about lack of time and resources when needed. Lack of time was a problem which might not have a simple solution; rather it was a fact to work around.

The gate criterions were not clear and the projects could pass through gates without meeting all the gate criterions, they then got to rework on what was missing or not fulfilled. The project could pass through the gate even though the review group did not agree on the concept of choice. This made the gates amount to project update meetings or checkpoints rather than stage-gates.

Changes of requirements during the projects were more a rule than an exception, which means coping with these changes was a big issue in the concept development process and a concept was made robust if it could handle requirement changes.
In the concept development process the technical requirements were in focus and the design leader has therefore a significant role. At the same time the steering committee often gave unclear directives but pushed for low product cost. This indicated on a gap between the will of the steering committee and the project team. Producibility was often left as a problem to be dealt with later on in the process. This resulted in an unbalanced product development philosophy in the projects and a poor vision of the concept goal when the solutions were to get generated. Robustness is hard to accomplish in these circumstances.

The concept development process was lacking the following:

- Clearness
- Simplicity
- Design for Robustness
- A balanced product development philosophy
- Activities of combining solutions and concepts
- Activities of estimation of risks throughout the process
- Several documentation activities

Projects tended to do the job first and document it later, which could result in an inadequate documentation/design rationale. The individuals in the projects took the knowledge with them without giving the rest of the company the opportunity to benefit from it fully.

**The Methods and Tools**

Project managers have considered the Brainstorming method to be time-consuming because it generated too many ideas, with the consequences that it took time to sift out concepts that did not work. But the idea of brainstorming is quantitative generating and the thought of sifting needs to be put to the side during the activity.

Different projects used different concept evaluation matrixes with different requirements, weighting scales and complexity. Time was wasted on making these matrixes, using unnecessarily complicated matrixes and maybe even pursuing the wrong alternatives.

### 5.2 Robustness Analysis of the Concept Development Process

A robustness analysis of the concept development process has been made using a P-diagram and information gained in interviews and observations (figure 19). The analysis points out what factors that impact on the process robustness. The P-diagram includes signal, response, noise and control factors. The signal is the input to the process, the response is the output, the control factors are the means to achieve robustness and the noise factors are the variations that affect the process negatively.

Robustness requires control and to control a process data is required and data is supplied through measurements, therefore to reach a robust process it needs to be measurable in some way. The concept development process can be measured since it is passing a gate with a review group who is verifying the concept choices and the verifications can be measured.
The control factors acknowledged in the analysis were the following:

- Cross functional teams
- Clear project aim
- Clear gate criteria
- Easy and fast methods and tools
- Information and directives
- Routines
- Education
- Continuous documentation
- Recourses when needed

The lack of these control factors would give the response of the concept not getting approved by the review group and not getting through the gate. But some of these control factors already exists at Volvo Aero such as cross functional teams and education. The focus for this thesis has been on the following factors: finding easy and fast methods and tools, routines and clear the project aim.

### 5.3 Conclusions from analysis

Implementation of more robust design methodology at Volvo Aero would improve efficiency and decrease rework, leading to time savings. Although it is important to implement tools for robust design, it is inevitable that the robust design approach shall be fully understood by employees and that the tools are agreeable with the company approach. “Tools and methods can not by themselves guarantee more robust products, designers must think in terms of robustness to reach this goal” (Hasenkamp 2006). The end product should not be a product made by the individuals in the project that developed it, but a Volvo Aero product, independent on the individuals who participated in the project. Therefore there is a need for a
Volvo Aero way of doing it, and Volvo Aero methods. And if time and resources are spent early on in the project there is a lot that can be gained.

The process of developing new solutions is an iterative process. Although the further the concepts are developed and analyzed, different tools and more complicated matrixes could be used. The goal for every run is also different, the goal with an early concept screening is to reduce the number of concepts (in order to save time to focus on a few) and find combinations of solutions, but the goal with the final concept scoring is to choose one concept for further optimization. Therefore the process needs to be adjustable to the different loops, different projects and different project prerequisites to make sure that the best concept is chosen, since there is little to gain from trying to optimize a bad concept.

The gates in the product development process are not working sufficiently, since every project easily can pass through. According to Cooper (2008) the gates need teeth for effectiveness. Although since Volvo Aero often has delivery obligations to customers, projects can not be closed, even though it does not meet all the gate criterions. But this results in poor customs and gates with no teeth, even in those projects that do not have strict obligations to customers.

If a method is not at everyone’s liking it is not contributing to a robust design since it is then often not used properly. The robustness requires that the control factors are applied to the whole project team to be effective.

The projects chooses their own way of working; there is no “Volvo Aero”-way of doing things. But time and money could be saved if there was, since time is now spent on finding methods and tools for each project.

Company philosophies such as the Design for Robustness philosophy and the Product Development philosophy, not only need to be spread to every employee so that everyone are aware of them, but they need to be implemented in the working process. Otherwise they are just thoughtful beautiful words.

Volvo Aero’s product development philosophy could make the concept development process more balanced and therefore more robust, but then it needs to be implemented in all stages of the process. To implement the Volvo aero product development philosophy in the early stages of concept development would balance the project aim of the project.

The Design for robustness philosophy is not well known through out the company, since everyone has their own idea of the expression; it is in fact new and has not penetrated yet. A mutual understanding would give a clear idea of what the company is trying to achieve. For a robust design it is important that time is taken for documentation, this will lead to a greater design rationale, a more robust design process and therefore a more robust product.

Gremyr (2005) claimed that robust design methodology can be applied from the concept generating, though the claim made in this report is that the methodology can be applied before the concepts are to be generated, during the clarification of the task in order to clear the project aim. Hopefully this work has helped in the implementation process of design for robustness at Volvo Aero.
6 Suggestions

The suggestions that have been made in this project are divided into four areas in this section of the thesis: Process suggestions, Methodology and tool suggestions, Routine suggestions and finally Suggestions for future work.

6.1 Process Suggestions

To make the concept development process simpler, clearer and more overviewable a process suggestion has been made (figure 20). This can be compared to the old process that can be viewed in section 3.1.1, figure 4. For a bigger figure see appendix F.

![Figure 20: The new concept study process](image)

The first level in the process is in figure 20 represented with green squares. Each of these has a sub-process which in the same figure is represented with red squares. The blue circles show the outcome of each sub-process, which is the input for the next sub-process. In this process suggestion several changes has been made to the previous process:

- The first level (green squares) are reduced from seven to five; this makes the process easier to overview.
• **Evaluate Concepts** is an integration between **Evaluation** and **Concept selection** in the previous process, since the choice is the outcome of the evaluation.

• Activities of handling risks, such as **Estimation of risks** in the previous process has here instead been spread out through the whole process instead of being in one chunk. The risks also need to be implemented in the requirements in the beginning and in the evaluation in the end.

• More documentation activities are added, since there are many project that “do the job first and documents later” rather than documenting parallel the job.

• Idea seeking activities are divided into **individual idea seeking** and **group idea seeking** for best result. The previous process included a brainstorming activity, although brainstorming is not the only idea seeking method.

• The Product Development Philosophy (with Product Cost, Producibility and Technical Requirements) is implemented in **Analyze concepts**.

• Activities of combining solutions or concepts have been added in **Generate concepts** and **Evaluate concepts**.

• Robust Design Methodology, such as probabilistic design has been implemented throughout the process.

• Specific methodology and tools could be implemented on a deeper level in the process or linked to the activities.

There are several benefits with the new concept development process:

- The suggestion is easier to overview
- Design for robustness is implemented
- The product development philosophy is implemented
- It is simpler
- It is clearer

The concept development process is an iterative process, if more than one concept is selected and/or new concepts are found in the activity of combining concepts, the process should be looped, although it is not necessary to start at the very beginning since the task is already clarified. The process can then start over at the analysis of the concepts.

All activities are defined in imperative since the process activities are requests and it also clarifies the importance of the task.

### 6.1.1 Clarify the Task

Design problems are rarely entirely clear in the beginning of a project and therefore much effort has to be spent in understanding them thoroughly. This sub-process is divided into eight activities (**figure 21**). The first one, **Establish concept book**, has remained from the previous process. It starts the documentation process of the concept development process. This document will be filled with the coming documentation activities.

**Gather and order requirements and customer needs** can include activities like the objective tree and House of quality. To include Producibility in this first sub-process, manufacturing prerequisites need to be found. For a mutual understanding of the task a P-diagram can be used. It is also important to **establish evaluation criteria and go/no go criteria** this early in the
process as well as identifying functional risks. Project risks are identified in the previous phase, Pre-Study (before Gate 1).

A Concept Start Sheet can be made to implement the Volvo Aero product development philosophy, balance the project aim of the project and visualize the task. All this is then documented in the concept book.

6.1.2 Generate Concepts

In this sub-process the concepts are generated (figure 22) and it starts with individual and group idea seeking, since it is important to do both and if the individuals in the team has made their own brainstorming before coming to the group activity, it can be more efficient. But brainstorming is not the only method for idea seeking; TRIZ or method 635 can also be useful.

After idea seeking, possible combinations of solutions are made, to combine them to full concepts; here a morphological matrix could be used. These conceptual ideas need to pass through the go / no go criteria to evaluate if there is a point in continuing on the idea. The conceptual ideas need to be documented in the concept book.
6.1.3 Define Concepts

The generated conceptual ideas need to be defined (figure 23) with CAD-designs as detailed as necessary. Manufacturing, preliminary maintenance and development needs need to be defined and the risks identified for each concept. The defined concepts need to be documented in the concept book.

6.1.4 Analyze Concepts

For an implementation of Volvo Aero’s Product development philosophy the concepts need to be analyzed according to the three corners: Technical requirements, Producibility and Product cost (figure 24). This can be done parallel, since none is more important than the other, or one can deliberately be given higher importance.

The risks identified in the previous sub-process need to be fully analyzed with a FMEA/FMECA. And the concepts robustness needs to be analyzed if possible with probabilistic design and/or tolerance stacks. The analysis should be documented in the concept book.
6.1.5 Evaluate Concepts

The sub-process of evaluating the concepts starts with defining the rating scale of each criterion in the evaluation matrix followed by the evaluation itself (figure 25). After the evaluation it is important that combination of concepts are considered and new concept might be found. If this is the case a loop in the process is necessary for further definition and analysis of the new concept.

The process is ended with selection of concepts and documentation of the evaluation in the concept book.

6.2 Methodology and Tool Suggestions

The methods and tools that are suggested take in consideration that the time plan often is tight and might not even hold and the methodology could therefore be made optional. The methods and tools also need to be adaptable to different considerations in different types of projects. The methodology suggestions have been divided into four areas: Clarifying the Task, Concept Generating, Concept Analysis and Concept Evaluation. Methods of defining concepts have not been included, this is an area not included in the thesis. The tools or templates that have been made can be found in appendixes.

6.2.1 Clarifying the Task

The development of a P-diagram in the early stages of the concept development process will serve as a basis for awareness of variation, which is one of the corner stones in RDM. The P-diagram activity would include discussions on losses due to variation and the factors of making the product insensitive to the variations. The Ishikawa diagram might be used in the same purpose.

The objective tree is a systematical approach to find requirements and ranking them. The tree gives a general view over the project task and makes it easier to balance the requirement that is essential for optimization. The tree could be made very large and include the cornerstones...
of Volvo Aero’s Product Development Philosophy: Product Cost, Technical Requirements and Producibility as well as the corporate values: Environment, Security and Quality. These are general requirements and should then be at a high level. The first levels in the tree could even be standard in every project at Volvo Aero. The different projects could then decompose these into sub-requirements suited for the project and weight the requirement suited for the customer. The weighting of the requirements in the objective tree is a suitable activity to arrange with customer and/or steering committee. The objective tree can also clarify responsibilities, i.e. the design manager is responsible for the technical requirement branch of the tree and the production manager is responsible for the producibility branch. One of the branches in the objective tree could be Robustness. The objective tree could otherwise be made smaller and only have requirements suited for the specific project. The whole tree or parts of it could than be transferred directly to the evaluation matrix. If all the branches end on the same level, the value 10 or 100 can be used to as a sum instead of 1. An example of a suitable objective tree is found in appendix G.

Since the success of a manufacturing company depends on the ability satisfy customer needs, the House of Quality is a useful tool for this purpose, because it can determine what technical requirements that make the product satisfy customer needs and what requirements that is more important to fulfill than others if customer would decide. Because of its benefits it can be considered as a tool for Robust Design. HoQ elaborates with documenting product characteristics, although it does not address the function and behavior specification (Garg 1998). A HoQ template is found in appendix H.

The Concept Start Sheet
The Concept Start Sheet is a tool design to suit the concept development process at Volvo Aero. It is a document aimed to balance the project between the three corner stones of Volvo Aero’s product development philosophy: Product cost, Technical requirements and Producibility. The aim with the Concept Start Sheet is to frame the main project goal and the intent for design; furthermore the aim with the start sheet is to:

- Balance the project aim
- Visualize the task
- Implement the Volvo Aero Product Development Philosophy
- Clarify the directives to and from the steering committee
- Increase the communication in inside the project team
- Increase the communication outside the project team (to steering committee and marketing department).

The Concept Start Sheet is not a requirement specification. Only vital information that is necessary for concept development should be included in the Concept Start Sheet, in order to keep the focus on what is important for the project. Numbers, like maximum weight, is not important, what is important is the focus to minimize weight. The Concept Start Sheet should not be more than one page in order to keep the balance of the project goal, but if it is hard to include all important information, pictures can be kept separate.

If the project goal is clear for all parts in the project team the better concepts will be produced and therefore increase the robustness. A Concept Start Sheet template can be viewed in figure 26 (as well as appendix I). One project that was developing a Turbine exhaust case was used
to make an example of how the Concept Start Sheet could look like; this can be viewed in figure 27 (as well as appendix J).

The main question in this particular project was what manufacturing method would be used where on the product, how much should be casting and how much should be fabricated. And since fabrication is a more complicated method it raced the question if the company needed to invest in a new robot. The material for the product was set and the project had several lessons learned from previous projects with the different manufacturing methods. As in almost all projects at Volvo Aero the technical requirements of life and weight are most important.

6.2.2 Concept Generating

Thinking and generating solutions or concepts should be done both individually as well as in groups for best results. The method of choice for concept generating does not necessarily need to be brainstorming; there are many other methods that ought to be tried, since project managers have thought the brainstorming method to be too time-consuming and few has thought it to be a good method. One such method that could be tested is method 635 since this method has a more systematic approach, which may suit the project teams better and therefore contributing to a more robust design.

TRIZ is a good method for finding more unconventional solutions and could be used when the project team is having difficulties finding solutions.

The morphological matrix is useful when combining sub-solutions into concepts. Although it is important to try and reduce the number of sub-solutions in order to reduce the number of concepts.
Sifting of the ideas and concepts needs to be done after the generating. At this early stage a simple selection chart can be used with Go / No go criteria. The selection chart is a good tool to use to decrease the number of concepts when the concepts are at the idea stage, not that well defined and the criteria (such as go/no go criteria) are few. If a concept does not fulfill one of the criterions, it is eliminated and there is no point in seeing if they fulfill the next criteria. A template for a selection chart is found in appendix K.

### 6.2.3 Concept Analyzing

Probabilistic design is essential to achieve a high degree of robustness because it is a method that is measurable.

If DOE and/or Monte Carlo simulations can be completed early dimensions and tolerances can be set that leads to a robust product. Tolerance stacks also helps the engineer understand the relationship between parts and the maximum and minimum tolerances needed.

It is also important that the team understands the risks with each concept to be able to evaluate them correctly and make a good decision. Making a FMEA would serve this purpose.

### 6.2.4 Concept Evaluation

The most important things to consider, when choosing a matrix for concept screening or scoring, are that the matrix can:

- Find the concepts strengths and weaknesses
- Help find combinations of concepts to strengthen them and minimize the weaknesses
- Answer the question why a certain concept is to be selected

To do so there are different parts of the matrix that need to be addressed:

- Requirements
- Sub-requirements
- Weight
- Rating scale
- Reference concept

If the objective tree is used the work with the matrix will be decreased. The requirements from the tree could go straight in the requirement list of the matrix followed by the weighting. A matrix template could be used to simplify for the projects. Although it is important that it can be formable to suit the different projects. Blank spacing in the matrix is a good way to show that there is space for adding requirements suitable for the specific project.

Having robustness as a requirement in the matrix could help in the evaluation to determine if the concept is robust, although robustness could otherwise be part of many requirements. The project team should ask themselves the question: what happens if the requirements change, will the concepts be able to handle changes? Since in every project there is a high risk of
requirement changes during the project. Although making good choices makes the product more robust.

Choosing a rating scale, linear or logarithmic, is important since the outcome might differentiate with different scales. The choice should be depended on what characteristics are most important with the product. If it is important that the product does not have weak spots, a linear scale should be chosen. But if it is important that the product stands out and is especially great at something a logarithmic scale can be chosen.

If there is an earlier version of the product that now has been developed further, this product can be chosen as a reference concept. But a reference concept is not necessary if the team has a common understanding of the rating scale and agrees on what should be achieved for a higher/lower rating.

To achieve robustness the concept can not be vague in design or based on vague assumptions (Stimson 1996). And if different amount of work has been put into different concepts, the participants need to be aware that this might impact on the evaluation. Ideal is that all concepts are presented at the same level of detail.

When the product cost is an important requirement in the project, which it in most cases is, a function versus cost diagram should be used for a better understanding of the concepts.

The evaluation matrix makes the decision visualized which ensure that the decision making process is repeatable. Others have the ability to understand and evaluate the thought process of the project team and this would simplify the gate passage. Designer can defend the decisions that are made and later project teams can use the methods as foundation and save time. The evaluation matrix is a design rationale.

Even though the matrix gives us a value for each alternative on each criteria, the information is “dead” and lacks reasoning and justification of the preferences. For an evaluative rationale the matrix needs to be filled with comments and information on the decisions taken. It can then be used as a review on why some concepts were chosen and others were rejected. The concept evaluation matrix can then go straight into the concept book for documentation.

The most detailed matrix for a concept evaluation is the scoring matrix. This matrix needs concepts that are well defined and analyzed, it can be time consuming if more than a few concepts are to be evaluated and the criteria are many. A template for a concept scoring matrix can be found in appendix L.

If there are many concepts that pass the go/no go criteria, but too many for a thorough concept analysis a concept screening matrix, such as the Pugh matrix can be used to decrease the number of concepts down. A template for a screening matrix is found in appendix M.

### 6.3 Routine Suggestions

Method descriptions, preferably with examples, need to be easily accessible in the OMS and placed or linked where they are needed in the process. That way OMS would not only describe *what* to do, but also *how* and maybe even by *whom*. And the method descriptions need to answer the question *why* to use it.
6.3.1 Time

According to Johansson (2005) people are less creative under time pressure, although many think they are more creative. It is therefore essential to try and eliminate the time pressure at the creative phase of the conceptual process such as the concept generating activities. It is also important to separate the concept generating activity with the sifting and evaluation activity, since the human brain otherwise will compare ideas already in the concept generating activity which can be restraining in the creative process. It is also good to have time to think things through properly before evaluating the conceptual ideas.

Even though many project has a minimum amount of time and do not have time for methods such as Design of Experiments it could be routine to consider it, so that projects that might have the time don’t forget the method.

6.3.2 Documentation

Time needs to be spent documenting and writing reports which is crucial for Design Rationale. The documentation proves that you are doing what you say you are doing and if what you do is the same as what you say you do, you have a robust organization according to Stimson (1996). The documentation must be available when needed and easy accessible for employees that need them. Also, inappropriate documents need to be removed. Links to relevant reports or titles of them so they are easily found should be found in the OMS/GDP.

6.3.3 Gates

The gates need teeth according to Cooper (2008). Although at a company such as Volvo Aero the projects often have “orders” from customers which makes the projects not killable, the projects have to keep going even though the gate criteria might not be met. But if the projects that do not have these customer orders and are more like research projects, still have the routines of never being killed, the problem needs to be addressed. If a project team misses a target the root cause needs to be analysed to prevent its recurrence, the focus needs to be on improvement of the organization rather than blaming the team.

According to Cooper the gatekeepers’ requests boil down to three questions that are essential for the gatekeeper:

1. Have you done what you should have – are the data presented based on solid work?
2. What are the risks in moving forward?
3. What are you asking for?

6.4 Suggestions for Future Work

The OMS is not a completed tool and is under constant development. It needs to be complemented with links to tools and methods, that are well described and with examples. So that employees would follow it and use the benefit with it. Then it would work as it is supposed to; “as an important tool for employees to understand not just what we do, but how
we do it and how all the pieces and processes fit together” (The Volvo Aero internal website). And the development of the process needs to be continuous on all departments as well as development of the methodology.

The Design for Robustness philosophy needs to be spread and implemented at all stages in the product development process. If this is the philosophy behind product development it needs to be known, otherwise the philosophy is useless.

Volvo Aero’s Product Development philosophy also needs to be spread and implemented in all stages of the product development process, it is not only important in the conceptual phase.
7 Discussion

Since there are so many different methods that could be used in the concept development process, not all could be analyzed for this project. Finding out which method that works the best is a huge task for each sub-process itself, especially if the different project would be taken into consideration.

One project manager at Volvo Aero used a template similar of a HoQ. Knowing that this tool worked for some projects is a good reason for trying to spread the tool to other projects. The whole company could gain from opening up more and share discoveries with other projects. But since different projects have different costumers that are competitors, information about the products can not be share between projects. Although this does not mean that the methods could not be shared.

The intent of Concept Start Sheet should not be too controlling so that the innovation process will suffer with the tight boundaries. To tight boundaries might decrease the innovation, although the innovation could also increase within the boundaries.

Early on in this project an observation were made at a concept review meeting. Otherwise there were no projects that were in the concept development phase at the time of this thesis project since the projects at Volvo Aero continue for years. It would have been interesting to observe at an idea seeking activity or try other methods than the commonly used brainstorming. Brainstorming is a well known method and the word is often used for a wide range of idea seeking activities. The projects that say they are using the brainstorming method might not be using it the way it is meant to be. The fact that not even half of the employees using the brainstorming method thought is was a good method might be because of a “wrong” way of usage.

Time pressure in the project is a challenge that is hard to deal with and it gave consequences for this thesis project as well, lack of time was the expressed reason for some employees not to answer the questionnaire.

The expression robust design is a craze that might not last for long, but the work with reducing variations will always be profitable.

The continuous work with developing the process, methods and tools is important, but conservative employees can put sticks in the wheel, therefore a general “change is good”-attitude is needed for a smooth development.
References

**Literature**


REFERENCES


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• Volvo Global Development Instructions GDI 968-11

**Internet**


• The Quality Portal: [http://thequalityportal.com/q_know02.htm](http://thequalityportal.com/q_know02.htm) (2009-01-19)


The concept development process:

- Wikimedia commons:

- Wikipedia:
## Appendix A: Gantt chart

![Gantt chart image]

### Deadlines

| Deadlines                                      | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 1  | 2  | 3 |
|------------------------------------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 1. Purpose, aim version 1                     | X  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 2. Purpose, aim version 2                     |    | X  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 3. Rapport structure                          |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 4. Intervyredovisning                         |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 5. Redovisning av enkät                       |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 6. Redovisning av enkätresultat               |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 7. Redovisning av nulägesanalys               |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 8. Redovisning av rekommendationer            |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 9. Föreslå process                            |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 10. Redovisning av utvärdering                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 11. Redovisning av metodförslag               |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 12. Rapport del 1                             |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 13. Rapport del 2                             |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 14. Slutgiltig rapport                        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 15. Presentationstillståndsförslag 1          |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 16. Presentationstillståndsförslag 2          |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |

*I love deadlines. I especially love the swooshing sound they make as they go flying by*
Appendix B: Questionnaire

Questionnaire: Concept Development and Robust Design

This questionnaire turns to employees at Volvo Aero Corporation that has work with concept development. All answers are anonymous and voluntarily. If there is a question you don’t understand or can’t answer, you can skip it. The result will be analyzed in a thesis.

1. In what project/projects have you worked with concept development (concept generating or concept selection)?

__________________________________________________________

2. Which methods/tools have you used or are familiar with and what is your opinion on the method/tool:

<table>
<thead>
<tr>
<th>Method/Tool</th>
<th>Used</th>
<th>Familiar with</th>
<th>Opinion: (Good/Bad/OK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brainstorming</td>
<td>☐</td>
<td>☐</td>
<td>_____</td>
</tr>
<tr>
<td>P-diagram</td>
<td>☐</td>
<td>☐</td>
<td>_____</td>
</tr>
<tr>
<td>TRIZ</td>
<td>☐</td>
<td>☐</td>
<td>_____</td>
</tr>
<tr>
<td>QFD (House of Quality)</td>
<td>☐</td>
<td>☐</td>
<td>_____</td>
</tr>
<tr>
<td>Pugh matrix</td>
<td>☐</td>
<td>☐</td>
<td>_____</td>
</tr>
<tr>
<td>Design Rationale</td>
<td>☐</td>
<td>☐</td>
<td>_____</td>
</tr>
<tr>
<td>Other: __________________</td>
<td>☐</td>
<td>☐</td>
<td>_____</td>
</tr>
</tbody>
</table>

3. What requirements do you think are the most important to consider in concept evaluation? (Choose three)

☐ Material  ☐ Function  ☐ Risks
☐ Capability  ☐ Product cost  ☐ Producibility
☐ Production cost  ☐ Technical requirements  ☐ Strategy
☐ Other: ____________________________

4. In your opinion what are the most important questions for evaluating concepts?

__________________________________________________________

__________________________________________________________
Answer the following questions with the last project that you participated in concept development in mind.

5. Did the project follow the process description in OMS (GDP)?
   
   □ Yes □ No
   
   Comments:

   ____________________________________________________________

6. Did you get sufficient amount of information (from customer and/or steering committee) for the concept generating task?
   
   □ Yes □ No
   
   Comments:

   ____________________________________________________________

7. Did you decompose the requirements into “sub-requirements” before evaluation?
   
   □ Yes, all □ No, none □ Only some

8. Did the requirements change during the concept development?
   
   □ Yes □ No □ Only small details

9. Was the ranking of the requirement motivated/justified?
   
   □ Yes □ No □ Sometimes/a little

10. Did you think that the matrix of choice in the concept evaluation was easy to work with?
    
    □ Yes □ No □ OK
    
    Comment:

    ____________________________________________________________

11. Did the project team agree on the outcome?
    
    □ Yes, mostly □ No, rarely
12. If the project team did not agree, what method was used?

- ☐ Team discussions until you do agree
- ☐ Voting within the team
- ☐ Design manager or other manager made the final decision
- ☐ Other: ______________________________________________________________

13. Did the review group agree with the proposed evaluation and selection by the project team?

- ☐ Yes
- ☐ No

Comment: ______________________________________________________________

14. Do you think that the decisions were sufficiently motivated?

- ☐ Yes
- ☐ No
- ☐ Maybe

15. Was the justification of the decision documented in the concept book?

- ☐ Yes
- ☐ No
- ☐ Some

16. Do you think there are needs for more methods or tools in concept development and evaluation?

- ☐ Yes
- ☐ No
- ☐ Maybe

Comment: ______________________________________________________________

17. How would you describe Design for Robustness?

_____________________________________________________________________

_____________________________________________________________________

18. How do you work with Design for Robustness in the concept development process?

_____________________________________________________________________

_____________________________________________________________________

Thank you for your time!
Appendix C: The Concept development process
Appendix D: Gate criteria for G2 and G3

**Gate 2 criteria:**

- Concept or concepts on high level (system concept) created, evaluated, selected and documented in Concept book.
- Project and Product Requirements documented.
- Requirements Review performed and documented.
- Configuration Management updated.
- System Concept Review (SCR) performed and documented.
- First identification of Key Components.
- Potential development suppliers identified (TG1 in GSC).
- Updated Time plan for supplier choice and delivery time schedule per part.
- Financial calculation updated.
- Product Verification Report issued.
- Use of new technologies identified.
- Risk Management planned, Project and Product.
- Manufacturing activities initiated.
- Partner communication updated.
- Resources secured for the next phase and planned for the rest of the Project.
- Update Main Time plan and Detailed time plan updated for the next phase.
- Project Assurance Plan updated (PAP).
- Development plan updated.
- Project Plan updated.
- Project development metrics initiated.

**Main Objective:**

- Chose concept or concepts on high level.
Gate 3 criteria:

- Concept Review performed and documented.
- Configuration Management updated.
- Refined target description.
- Financial calculation updated.
- Potential LLI Key components suppliers identified (TG1 in GSC).
- Development suppliers chosen (TG3 in GSC).
- Updated Time plan for supplier choice and delivery time schedule per part (development parts and identified key components).
- Refined Product Requirements.
- Patent situation evaluated.
- Environmental analysis started.
- Verification, Validation and Qualification activities identified and documented.
- Manufacturing activities updated.
- Aftermarket plan initiated.
- Project risks evaluated including Supplier management (Risk Management).
- Product risks evaluated (Risk Management).
- Resources secured for the next phase and planned for the rest of the Project.
- Financial model for the project updated.
- Update Main Time plan and Detailed time plan updated for the next phase.
- Project Assurance Plan updated (PAP).
- Development plan updated.
- Project Plan updated.
- Lessons learned documents initiated.

Main Objective:

- Initiate detailed development of the chosen concepts and document project content.
Appendix E: Questionnaire results

1. In what project/projects have you worked with concept development?
GP7000, Vulcain, Vulcain 2, Vulcain 2+, Vulcain 2 FRP, Vulcain 2NE, Vulcain 2+NE Demo, Vulcain 2 LOX, FLPP, Vinci, TPX, GEnx FHF, GEnx TRF, PW1000G TEC, Trent XWB, TXWB ICC, Trent 900ICC, Trent 1000ICC, RS68 LH2 Turbin, RS83, NEWAK, FTD, RM12, Composer FOGU&AFC mfl

2. Which methods/tools have you used or are familiar with?

![Bar chart showing the results of the questionnaire]

- Brainstorm
- P-diagam
- TRIZ
- QFD
- Pugh matrix
- Design Rationale
- Other

Others: Volvo concept analys method, Space concept process, Volvo Aero concept process, Funktionsträdsanalys, Riskanalys, Kepner Tregoe

Comments:
- Brainstorming has its limits
3. What requirements do you think are the most important to consider in concept evaluation?

![Graph showing various factors and their importance in concept evaluation.]

Other: Weight, Time plan, aerodynamic

Comments:
- Depends on the product requirements and business case
- Depends on scope of project

4. In your opinion what are the most important question for evaluating concepts?
- Weighting of requirements.
- Functional & Technical requirements are mandatory. Remaining concepts to be evaluated against reliability, robustness (design, manufactory) product cost development time/cost performance.
- Questions to get the requirements.
- What are the requirements, functions, weight factors, demands and wishes?
- Need to define rating.
- What is the cost, the risk, the lead-time and the requirement fulfillment of the concept? What are the weight factors of the different requirements?
- Depends on type of program, technology development or product development. But the most times the cost is important in combination of fulfillment of technical requirements.
- New technology.
- Manufacturing costs – What generate costs?
- Will the concept meet the requirements?
- How do we find the best compromise based on different requirements, stress, stiffness, product cost and producibility.
- Understand all the functions of the product and how important these functions are relative to each other.
- That it is possible to make.
- What is the risk of failure.

5. Did the project follow the description in OMS (GDP)?

![Bar Chart]

**Comments:**
- Not to 100%
- Mixture of old space process and OMS
- Do not follow the OMS from the beginning, which makes it hard to start following it, but ends in the OMS.
- Very good and structured.
- I think so, probably with exceptions
- Yes in earlier projects, but No in resent

6. Did you get sufficient amount of information (from customer and/or steering committee) for the concept generating task?

![Bar Chart]

**Comments:**
- To be solved in the project
- Some requirements are contradictory from VAC compared to customer
- Iterative process
- All technical requirements were not set. The goal with the program was moving.
- You never do…
- Input from OEM tends to be limited and arrive too late. Quick evaluation tools are available for stress/stiffness calc. Etc. but not from all disciplines...
- Neither from customer nor steering committee, but you never do.

7. Did you decompose the requirements into “sub-requirements” before evaluation?

8. Did the requirements change during the concept development?

9. Was the ranking of the requirements justified?
10. Did you think that the matrix of choice in the concept evaluation was easy to work with?

Comments:
- (No) In a development project like XWB there are many different requirements with complex relationships

11. Did the project team agree on the outcome?

Comments:
- (Manager) or risk analysis.

12. If the project team did not agree, what method was used?
13. Did the review group agree with the proposed evaluation and selection by the project team?

**Comments:**
- No internal review was performed only with partners
- Have not presented to review teams yet.
- (Yes) Not fully
- Yes in most points

14. Do you think that the decisions were sufficiently motivated?

15. Was the justification of the decision documented in the concept book?

16. Do you think there are needs for more methods or tools in concept development and evaluation?

Comments:
- (Yes) The concept choice needs to be allowed more time/budget many choices are made too early, possible based on wrong assumptions. In later stages it is not possible to reframe and choose better.
- (Yes) Brainstorming type of activities / Risk management.
- No, but one tool that works well is needed.
- Yes, quick evaluation tools from all disciplines as in evaluation time
- Yes, a standardize evaluation matrix and a template for a concept book.
- No, but use the methods that exists.

17. How would you describe Design for Robustness?
- Good initiative
- Design for margin in fulfilling requirements related to load specification. Or design for tolerance to manufacturing variations; choose manufacturing processes which can give the desired tolerances.
- Choosing concepts with best potential and optimizing with probabilistic methods
- Robust function and robust manufacturing
- Design that is tolerant in function and does only depend on parameters that are under VAC control.
- It is a statistical approach to handle deviations tolerances etc early in the design process. Applications of methods with well described statistical outcome.
- Task in preliminary and detail design phase
- Design for large tolerances. A product that can handle deviations.
- A design less sensitive to variations
- (Don't want to comment on something I don't know much about.)
- A design that generate zero deviations and fulfills all functional demands.
- The design is made in a way that it will still stand up to its requirements even if the design is changed a little bit.
- Using well known material, processes, methods for design that will meet mfg set up processes
- As a way of thinking, there is no clear definition of the term. I think everyone has their own definition.
- Method development projects that should introduce probabilistic methods in order to make the product insensitive to variations.
18. How do you work with Design for Robustness in the concept development process?
- I don’t
- Evaluate different processes for manufacturing according to the capability of the process to produce the required tolerance range. Use probabilistic evaluation of analysis in order to optimise the basic parameters (such as thicknesses) of the concept.
- Known results from probabilistic analysis on design elements
- Not...
- Define FMECA in failure modes, drive relations and estimate probability to failure and use this info to prioritize activities in development
- Application of six sigma methods and tolerance analysis
- Not at all
- Look at manufacturing, good tolerances, possibility for adjustments, minimise mistakes, dummy proof, correct measurements
- A selection criteria in the matrix
- Don’t
- Working with a cross functional group where robust processes (at all stages) are evaluated and weighed in the evaluation matrix.
- We tested different types of welding, how the welding deformations would look like (from simulations) we check that the design works well in off-design
- Not at all currently in concept phase, only later (in the preliminary or detailed phase)
- Haven't worked with DFR so far
- Among other thing, we take manufacturing in consideration in the design process.
- Analyse different concepts sensitivity to variations in design parameters. Set up mathematical structure that relate design parameters and critical quality parameters
Compared answers:

How many methods have you used and are there needs for more methods?

Number of used methods

Number of answers

Yes, there are needs for more methods
Maybe there are needs for more methods
No, there are no needs for more methods
Appendix F: The new suggested concept development process

Define Concept
- Define concept design
- Generate ideas
- Select ideas by prioritizing

Generate Concepts
- Define concept requirements
- Define market requirements
- Define technical requirements
- Define regulatory requirements
- Define environmental requirements

Clarify Task
- Establish concept tool
- Define concept tool requirements
- Define concept tool characteristics
- Establish evaluation criteria
- Establish requirements
- Establish requirements
- Establish requirements

Document Concept
- Document concept in concept book
- Document concept in concept book
- Document concept in concept book
- Document concept in concept book
- Document concept in concept book

Balance Conceptual Requirements
- Balance conceptual requirements
Appendix G: Objective Tree

Volvo Aero Products

**First level**

- Product Cost
  - Technical Requirements
    - Productivity
      - Risks
        - Strategy
          - Material cost
          - Development cost
          - Production cost
          - Investments
          - Weight
          - Material
          - Life
          - Wear, tear, corrosion
          - Aero performance
          - Lead time
          - Ramp-up period
          - Capacity
          - Capability
          - MRB's
          - Suppliers
          - Robustness
          - Reliability
          - TRL-level
          - Security
          - Component tests
          - Quality on delivery
          - Sensitivity
          - Product platforms
          - Tooling
          - Manufacturing strategy
          - Widening supplier base
          - Work environment
          - Manufacturing additives
          - Transport

**Second level**

- Material cost
- Development cost
- Production cost
- Investments
- Weight
- Material
- Life
- Wear, tear, corrosion
- Aero performance
- Lead time
- Ramp-up period
- Capacity
- Capability
- MRB's
- Suppliers
- Robustness
- Reliability
- TRL-level
- Security
- Component tests
- Quality on delivery
- Sensitivity
- Product platforms
- Tooling
- Manufacturing strategy
- Widening supplier base
- Work environment
- Manufacturing additives
- Transport

**Third level**

Sum: 10

Sum: 100
Appendix H: House of Quality Template

Project: ____________________________

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<th>Functional requirements (How)</th>
<th>Customer competitive assessment</th>
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Appendix I: Concept Start Sheet Template

CONCEPT START SHEET

PROJECT:

Baseline design or interface picture

First Engine to Test:

PRODUCT COST
- Material
- Production cost
- The target cost of the project
- Risks
- Investments

PRODUCIBILITY
- Material: What material(s) can be considered for the concepts?
- Manufacturing methods/Capability: What manufacturing method(s) can be used? What method(s) should not be used?
- Manufacturing platforms: Standardize platforms/modularize
- Capacity: What capacity is there when it comes to: Competence, machinery, lead time and space (size and volume)?

TECHNICAL REQUIREMENTS
- Function description: What has to be achieved rather than how it can be achieved? Sub-functions? Interactions between sub-functions?
- Steering technical requirements: Life, Weight, Performance

Datum: ____________________________        Sign: ____________________________
Appendix J: Concept Start Sheet Example

CONCEPT START SHEET

PROJECT: Turbine Exhaust Case

Baseline design or interface picture

First Engine to Test:

PRODUCT COST
- Investments: New robot?

PRODUCIBILITY
- Material: INCO 718.
- Manufacturing methods/Capability:
  - Minimize size and difficulty of casting
  - Maximum advantage from automated fabrication.

Lessons learned:
- Casting process gives non-uniform thickness
- Sheet shaped parts is not cost effective
- Welding positioned in low stress areas
- Strut trailing edge impacts on weld penetration
- Many weldings impact on shrinkage and heat treatment deformations
- Many tack-welding parts is difficult.

TECHNICAL REQUIREMENTS
- Function:
  - Provide rear engine mounts
  - Provide rear hoisting points on engine
  - Provide oil supply, scavenge, scupper drain tube
  - Have provision to seal airflow from going between LPT and TEC.

- Steering technical requirements:
  - Life
  - Weight
  - Centerline shift
  - Structural stiffness
  - Mount lug strength
  - Containment capability

Datum: ________________________ Sign: ________________________
### Appendix K: Concept Selection Chart with Go / No go criteria

**Project name:**

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<th>Decision:</th>
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<tr>
<td>(-) no</td>
<td>(−) Eliminate solution</td>
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<tr>
<td>(?) Lack of information</td>
<td>(?) Collect information</td>
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**Remark**

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# Appendix L: Concept Scoring Matrix

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Rank 1 2 2 3

Continue? Yes No Back-up
# Appendix M: Concept Screening Matrix

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