Organizational Development

CAE driven development in the early phases of product development

Master of Science Thesis in the Management and Economics of Innovation Programme

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Glossary

CAD - Computer aided design

CAE - Computer aided engineering

CAE driven development - A development which is centered around and supported by CAE

Category one CAE - Evaluates performance of attributes such as NVH, crash and safety and durability

Category two CAE - Covers methods and activities that can be used for supporting and developing design areas

Design grammar - used for examining the topology layout

Design of Experiments (DoE) - Can be used to evaluate how the performance changes of the design depending on variation of parameters, hence information can be gather around the behavior of the design and alternative solutions.

Early phases - In this research the early phases of the product development process stand for the strategy phase and the beginning of the concept phase (this is based on VCC's product development process)

First optimization approach - a combination of DoE, parametric studies, sensitivity analysis and response surfaces

Parametric studies - working with parametric models that can be modified and evaluated easily

Response surface - Helps in finding the optimal parameters determined by the relationship between performance and design variables

Second optimization approach - Topology optimization

Sensitivity analysis - A sensitivity analysis can be made to investigate which parameters that affects and contribute to a product the most and how the design behaves in regard to different changes

Set-based design - Allows postponing the decision of a single design though variation of parameters and building knowledge around alternative solution in a set design space

Symbolic CAE - enables investigation of the physical layout through very basic layout concepts

Topology optimization - A method to look for an optimal material layout, it is used to find the optimal material distribution within a given design space

Verification - Verification in this thesis stands for verification of CAD design made through CAE (most often on a complete vehicle level)

Abstract

The automotive industry is exposed to extensive competition and automotive manufacturers are continuously looking to improve their product development process to make it faster, less costly, and to deliver vehicles with higher quality. During the last decade, CAE driven development has been putting the automotive industry through a paradigm shift (Schelkle, 2006). Higher emphasis on the design of the structure of the vehicle is stressed (Yan et al., 2011), since the structure influence the vehicle performance, and is produced first in the development process. CAE driven development in the early phases of product development is a solution to produce better vehicles, while making the product development process less costly and faster, and at the same time improving the quality while gaining knowledge about alternative solutions. However, the literature available, discussing CAE driven development from an organizational perspective, is often unavailable, outdated and articles with best practices is usually not captured as applicable knowledge for future use (Stampouli & Pappas, 2014). Therefore, there is a need for updated knowledge within this area, where focus will be on the organizational part of a CAE driven development.

By performing a literature study, case studies at Volvo Car Corporation (VCC) as well as on five other companies in the manufacturing industry, this thesis investigates what key factors and methods (CAE) an automotive manufacturer needs to consider to enable a CAE driven development approach. Furthermore, based on these findings a process and workflow is suggested, which can be used by automotive manufactures as inspiration when implementing CAE driven development in the early phases of product development. 17 interviews were held at VCC, where the early phases of the product development was outlined, current issues discussed, and key factors and methods that are necessary to enable a CAE driven development in the early phases of product development identified. The data from the five other companies examined, was used as input, and to triangulate the issues and solutions proposed by the theoretical framework and by VCC, when analyzing what the important key factors and methods to enable a CAE driven development approach. Also, aspect of change management is included in this thesis. This is to give the reader an understanding of the holistic approach an automotive manufacturer must take when implementing a CAE driven development approach in the early phases of product development.

A process and a workflow, including five methods and 17 key factors, are presented in the analysis of this thesis (see Figure 22). This figure illustrates in what order the methods should be used and divide the key factors into two categories: *key factors that enables an organizational change towards a CAE driven development* and *key factors that enables an automotive manufacturer to work CAE driven*. While the key factors in the first category are necessary in order to work with a structured CAE driven product development, the key factors in the second category are not a precondition when working CAE driven. These key factors are important but the width of usage of these key factors are up to the automotive manufacturer. Lastly the research ends by suggesting what to focus on in the short- and long-term perspective as well as possible benefits of having a CAE driven development approach.

***Key words**: CAE Driven Development, CAE, Up-front CAE, Organizational Development, Product Development Process, Automotive Manufacturing, Knowledge Building*

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This thesis is the last assignment at the master's program Management and Economics of Innovation at Chalmers University of Technology for us. It is also the ending project for our five-year study at the Industrial Engineering and Management program, and we are happy to have had this research as our concluding work. Many people have made this research possible and we would like to take the opportunity to express our gratitude toward them.

We would like to express a special thank Per Björklund, our supervisor at Volvo Car Cooperation, for giving us the opportunity to conduct this research and the necessary support to finalize it. The advice and guiding have been indispensable. We would also like to thank Harald Hasselblad and Andreas Carlsson for the useful inputs and knowledge. To conclude, we would also like to express our thanks to all the interviewees as Volvo Car Cooperation for showing their interest in our research and for sharing their knowledge and ideas.

We would also like to show our appreciation to all the representatives from the case companies for wanting to be involved in this research. We would like to thank the representatives from CEVT, GKN Aerospace, Scania, Combitech and Opel for their time, support and necessary data they contributed with to enable the finalization of this research.

Lastly, but not least, we would like to express our thanks to our supervisor Associate Professor Lars Trygg at Chalmers for the support and guiding necessary for completing this research.

Contents

1. Introduction

This chapter presents the background, problem analysis and purpose of this research project. This leads up to two research questions that this thesis project aims to answer, and lastly the limitations to the thesis are mentioned followed by an overview of the structure of the report.

1.1 Background

To be competitive in the automotive industry, regarding the time it takes to create a new product and for the product itself to be competitive, there is a need to introduce a larger focus on the design of the structure of the vehicle (Yan et al., 2011). The structure of the car is developed first in the vehicle product development process. Yan et al. (2011) continues to argue that the reason for introducing a larger focus on the design of the structure of the car, is that the structure greatly influences the performance of the vehicle. However, as Yan et al. (2011) is stating, most of the car manufacturers today are underperforming in this aspect. Because of this, the later stages of the product development are characterized by modifications and iterative work. A solution to this is to introduce Computer-Aided Engineering (CAE) driven development in the first phases of the product development (Yan et al., 2011). By introducing a CAE driven development already from the start of the product development process, the time to market and costs can be reduced while the performance of the car can be increased (Yan et al., 2011). What have just been described, is the main focus of this master thesis; to understand what key factors and methods are necessary to enable a CAE driven development, and how the process and workflow can be changed so that an automotive manufacturer resembling Volvo Car Corporation (VCC) can introduce a CAE driven development in the early phases of the product development process.

CAE driven development has been putting the automotive industry through a paradigm shift the last decade, which can be visualized in Figure 1 (Schelkle, 2006). Moreover, another large challenge for industry companies is to link different engineering activities, for example product design and product analysis (De Martino, 1998). The need to integrate CAE, which is used for analysis, with Computer-Aided Design (CAD), which is used for design, origins primarily from the need to reduce lead times (Maier et al., 2009). The automotive industry is characterized by the pressure to shorten lead times in the product development process, both because there is a need for a greater variation of vehicles but also because companies want to develop and produce more efficiently (Duddeck, 2007). Moreover, to focus on collaboration between, and integration of, CAE and CAD in the early phases of the product development process forms a basis for creating effective and efficient designs (Maier et al., 2007). This thesis will investigate what is needed for introducing a CAE driven development in the early phases of VCC product development but there will also be some focus on the integration of the two disciplines (CAE and CAD). This is because, according to VCC, the integration between the two disciplines is essential in order to reach a high performing CAE driven development. The early phases of the product development process at

VCC are called the strategic phase and the concept phase. However, in this research, only the beginning of the concept phase is reckoned as the early phase. Hence, here on, the phrase *early phases* in this thesis refers to the strategy phase and the beginning of the concept phase.

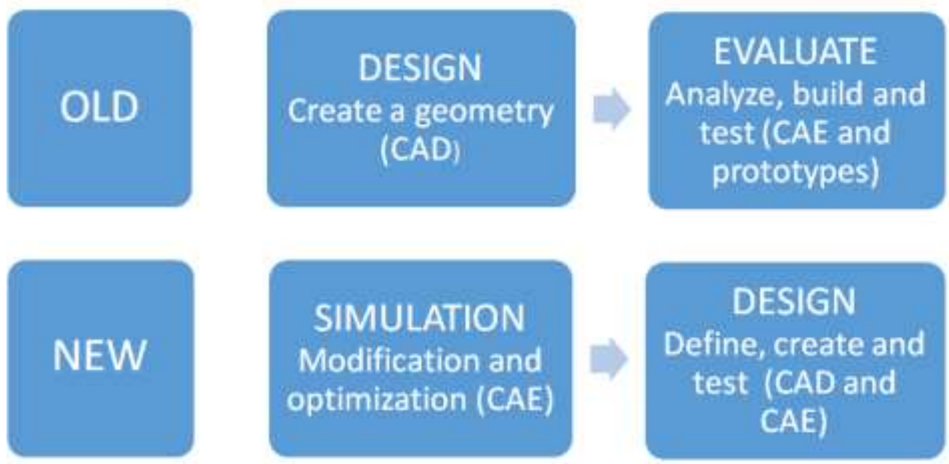

Figure 1. A visualization of the paradigm shift taking place in the automotive industry, depicting the old and the new focus of the product development process, the figure is based on Schelkle's (2006) figure.

Furthermore, future environmental legislations will put more pressure on the automotive industry to produce cars with low levels of pollutants and CO2 emissions, since it will be costly to go above the required emission levels. In 2020, the transition from the New European Driving Cycle (NEDC) to the Worldwide harmonized Light vehicles Test Procedure (WLTP), methods for testing how much pollutants a vehicle emits, is planned to be in place in several regions of the world, including Europe, India and Japan. This new testing procedure will require higher demands on the automotive manufacturers, and will put higher emphasis on the weight of the vehicle (Mock et al., 2014). According to VCC, optimizing and balancing the design of components through CAE early in the product development process has shown not only to decrease lead time but also weight, cost and late changes as well as enabling to evaluate alternative solutions which is in accordance to what Yan et al. (2011) as well as Autosim Consortium (2007) mention in their articles.

The background for this thesis is based on, among other things, lessons learned from the development of the SPA platform. SPA stands for Scalable Product Architecture, which is a platform that several VCC models are based upon (e.g. Volvo XC90, S90, V90). Weber (2009) describes a platform as a shared set of components common to a number of different vehicle models. Platforms are used to develop cars faster and at lower cost, since some components and systems are reused in more than one model. There are two main lessons learned from the development of SPA that are of importance to this thesis. The first one is to use optimization (via CAE) as soon as possible in the product development process to reach greatest efficiency. The second one is that CAE-CAD integrated engineering is requested early in the product development process - to create scalable CAD templates - but also late in the process for verification. Another aspect that highlights the aim of this research is that the literature available that discusses up-front CAE and CAE driven development, to create an environment where CAE processes supports development in the early phases, is often unavailable (many articles written about CAE driven development is found in conference material), outdated and the articles with best practices are usually not captured as applicable knowledge for future use (Stampouli & Pappas, 2014). This thesis will hence add to the available literature.

1.2 Problem Analysis

To understand the underlying issue for this thesis the following needs to be understood about CAE: CAE can be divided into two main categories (Rydberg et al., 2012). The first category evaluates and verifies the performance of attributes such as NVH (noise, vibration and harshness), crash and safety, as well as durability. The attributes are usually depending on complete vehicle testing and simulation. The second category covers methods and activities that can be used for supporting and developing design areas. For a vehicle, a design area can for example be chassis, interior as well as body and closure (Rydberg et al., 2012). Basically, VCC has well developed standards and processes when it comes to the first category of CAE, especially in the later phases of product development process (see Figure 2, the green triangles represent CAE verification). However, the second category of CAE is the main focus of this thesis, as it is this type of CAE methods that are not well defined in the early phases at VCC and it is necessary to have to enable a CAE driven development approach. Today the use of this type of CAE is mostly dependent on the employee's own network and visions for the product.

By having a CAE driven product development in the early phases of the product development process, evaluation can be completed *before* a detailed concept is set in CAD. A CAE driven development would, according to VCC's own studies, enable the possibility of lowering weight and cost, and shorten lead times as there would not need to be as many verification loops in the later phase of product development (CAE category one). Also, since a deeper understanding of the structure is obtained early in the product development, the knowledge about flaws in the design can be discovered earlier, leading to better quality of the product. This is also stated by several authors within the subject (Donders et al., 2008; Autosim Consortium, 2007; Yan et al., 2011; Schelkle, 2006). The balance between different attributes would be improved and the solution performance increased. More importantly, what representatives at VCC have underlined the most is the possibility of building knowledge and evaluating alternative solutions faster, which means that more solutions can be analyzed. This, to create knowledge about systems and how they behave. This knowledge should then be used as an input to the CAD modeling. The reason for why it is important to build knowledge is, firstly, to enable investigation of different alternatives and learn about which solution is most optimal, and secondly, by building knowledge, problems that occur later in the process can be minimized as they can be detected and fixed early on. In addition, if a problem occurs later in the product development process, it is easy to go back and look at the collected data and fix the problem without the need of time consuming tests.

Below is a slide from a presentation made by the Optimization Culture Arena (OCA) at VCC, promoting the essence of this thesis. As Figure 2 shows, there is a large optimization (and other CAE methods) potential and design freedom in the early phases, and as described previously, this is not utilized today at VCC because there are nowell defined tools, methods, processes and workflow for CAE category two (see the red box in Figure 2). By creating an environment where CAE driven development is possible, knowledge about how solutions behave, created through different CAE methods, can be used as an input to CAD templates (illustrated in the bottom of the figure). Figure 2 also illustrates the problem with today's workflow, where detailed definitions of CAE activities, in form of verification loops, first appears in the concept phase (illustrated by the three green triangles: *Con*, *V0* and *V1*) where the potential for optimization (and other CAE methods) becomes smaller and the freedom for design changes are limited. The green triangles stand for CAE verification (CAE category one). However, VCC have a very well developed work here and the verifications are of very high quality. Moreover, a consequence of the current workflow is that the design is set before an evaluation has been made in these verification loops. Hence, the possibility for optimizations that can influence the design is limited. In addition, the figure below shows that concept templates and the beginning of engineering templates are made before the verification gates. However, there are smaller verification loops verifying these templates as well, but the input from CAE is limited at this stage, as well as the resources for optimization.

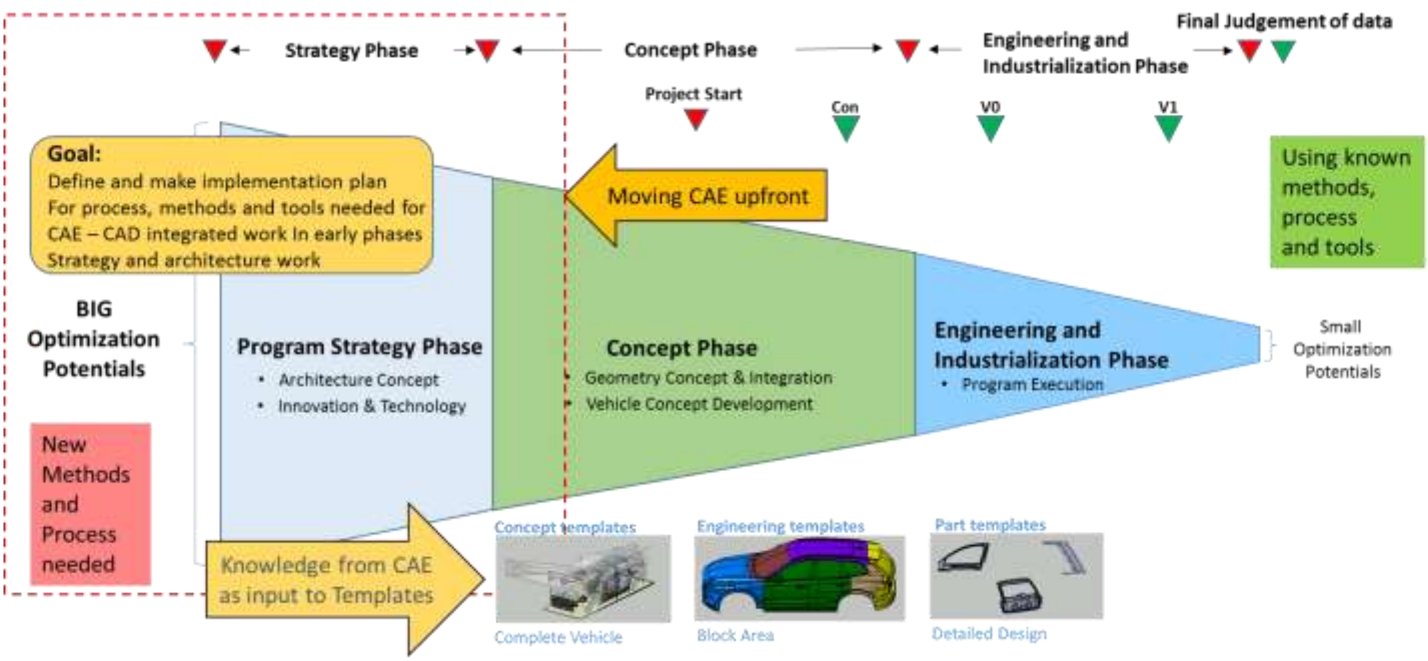

Figure 2. The phases of the product development process at VCC. Today, modifications and iterative work characterize the late phases at VCC, however CAE and discipline integration between CAE and CAD is requested in the early phases by introducing key factors, methods, tools as well as a process and workflow that supports a CAE driven development. This figure is copied from VCC's internal document.

1.3 Purpose

This master thesis focuses on the product development process at VCC, and more specifically, on the early phases of it. The purpose is to identify key factors and methods that will enable a CAE driven product development process, as well as a suggestion for a process and workflow for how to work CAE driven in the early phases of the product development process.

First, necessary key factors and methods (that enables a CAE driven development in the early phases of automotive manufacturers' product development) will be investigated and identified through literature and case studies. Second, a proposal for a process and workflow that supports a CAE driven development will be examined. The proposal will be based on VCC current way of working, together with VCC's wanted way of working, case studies and literature. The proposal can be used when VCC, or a resembling automotive manufacturer, moves towards a CAE driven development approach. The hope from VCC, is also that this research will find and support the possible benefits (if there are any) of a CAE driven development approach, e.g. building new knowledge around alternative solutions, reduced lead time, cost and weight when developing new products, while increasing the quality of the product (see Figure 3).

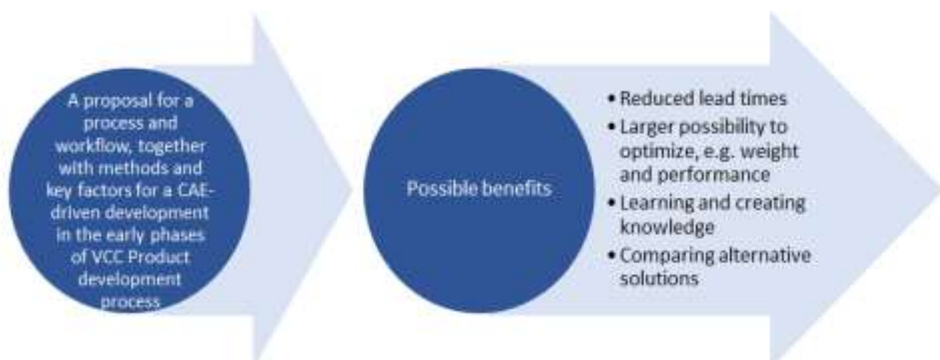

Figure 3. An illustration of the hoped outcome of this research in regard to the possible benefits of having a CAE driven development approach final (according to VCC).

1.4 Research Questions

To accomplish this master thesis project, two research question have been formulated. The second question is dependent on the first question, since a process and a workflow will involve the found key factors and methods.

- What key factors and methods does an automotive manufacturer need to consider to enable a CAE driven product development approach in the early phases of product development?
- How can an automotive manufacturer structure its process and change the workflow so that a CAE driven product development approach can be incorporated in the early phases of the product development process?

1.5 Delimitations

Firstly, it will be assumed that VCC's decision to investigate CAE driven product development in the early phases of the product development process is based on prior investigation made by VCC. Thus, this master thesis project will not investigate whether this decision is right or wrong, but instead investigate how VCC best can utilize their organization to use CAE driven product development.

Secondly, the focus will be on the departments in the product development process that are active in the early phases of VCC's product development process and especially the departments working with CAE and CAD. The departments in focus are Complete Vehicle Development, Technology and Implementation, Vehicle Hardware, as well as Vehicle Software and Electronics. In addition, the Design unit (responsible for the styling of the car) will also be part of the study, however the main focus will be on the other four departments as they are part of the Product and Quality unit at VCC.

Thirdly, as stated in the problem analysis there is a need for suggestions about key factors, methods, tools that would enable a CAE driven development together with a proposal for a process and workflow (see the red box in Figure 2). However, this thesis will be delimited from an investigation of CAE tools because of the limited time frame. However, when conducting case studies for this thesis, information about different software tools that are proposed to support CAE driven product development will not be neglected.

1.6 Structure of the Thesis

This master thesis constitutes of seven main chapters. In the first chapter, the introduction, the background to the problem has briefly been explained, followed by the purpose of this thesis, which have then been narrowed down to two research questions. Furthermore, some delimitations have been presented, that tightens the scope of this thesis.

The second main chapter is the methodology, where the underlying method is described. Furthermore, the interview techniques used are discussed as well as the sampling methods. Also, the basis for the empirical research is described, followed by a discussion about the quality of the research.

The literature review is the third main chapter of this thesis. It focuses on three main areas: *product development* (with a focus on the early phases of product development within the automotive industry), *CAE driven development*, and *organizational change* (focusing on process-change). However, the focus will be on the first two areas since these areas are used to answers the two research questions. Although the third area, organizational change, is not directly related to the research questions, it is included because, to introduce a CAE driven development approach an organizational change is required.

Chapter four and five contains the case studies. In chapter four, the case study at VCC is presented. This case study is more detailed than the case studies at the other industry companies presented in chapter five. The reason for this is that the research questions focuses at VCC's product development process, in addition this research is made based on the request from VCC.

In chapter six, the analysis of the literature and empirical findings is described. The chapter is divided in five parts. The first part covers an analysis of whether VCC should consider a change or not, the three following parts includes an analysis of the key factors, methods, and the process and workflow. The last part present an analysis that highlights some important factors that VCC needs to consider when introducing a CAE driven development approach.

In the last chapter, a conclusion is presented. In the conclusion, the researchers' findings will be narrowed down to recommendations for VCC. The recommendation will constitute of short term recommendations and long term recommendations as well as a conclusion about the possible benefits of a CAE driven development approach.

2. Methodology

When conducting a research, the design of the method is an important factor, if not the most important factor, in order to be able to answer the research questions. This chapter describes the methodology that was used for this thesis. The research methodology and design is presented below. This is followed by a description of the data was gathered and a section about the quality of the research, which includes research validation, reflections and ethics.

2.1 Research Methodology and Design

The relationship between theory and research is usually represented by three common approaches, deductive, inductive and abductive (Patel & Davidson, 2003). Briefly, using a deductive approach means that the researcher deduces a hypothesis by studying the literature within the domain of interest. This hypothesis is then tested against observations (empirical studies) to confirm the hypothesis (Bryman & Bell, 2015). With an inductive approach, the choice of theory is instead an outcome of the empirical findings, and the conclusion is drawn from a combination of theory and empirical findings. An abductive approach is a combination of the two former approaches mentioned. However, Dubois and Gadde (2002) introduces a combination of the three different ways of reasoning, which they call *systematic combining* (see Figure 4). This approach could be seen as a development of an abductive approach, but with a systematic combining approach the researcher is allowed to evolve the theoretical framework, the empirical findings and the case analysis simultaneously (Dubois & Gadde, 2002). By conducting the research in this way, researchers can exchange information from the different parts in order to increase their understanding. As stated by Dubois and Gadde (2002), “This stems from the fact that theory cannot be understood without empirical observations and vice versa”.

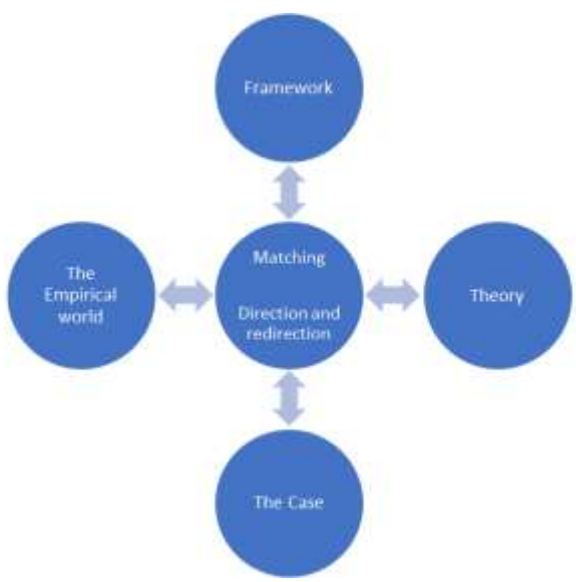

Figure 4. A visualization inspired by the article of Dubois & Gadde (2002), depicting systematic combining.

The systematic combining approach highlights the fact that a researcher rarely follows a linear process. Furthermore, the approach also opens a possibility to handle the interrelatedness between the different parts of a research.

This approach has been used in this study since it made it possible to have an exploratory mindset when collecting data. Since the subject of the research from the beginning was formulated from a technical standpoint rather than an organizational standpoint, and because the literature around this subject is of a more technical nature, this iterative approach enabled a concurrent development of all parts of the research. An example of the usage of a systematic combining approach in this study is that the interview guides were inspired by the initial theory found. This affected the empirical finding which then affected the theoretical framework.

2.1.1 A Qualitative Research Study

There are two research methods that are most commonly mentioned in the literature, qualitative and quantitative research (Easterby-Smith et al., 2015). A quantitative study has the benefits that historical data can be used, which decreases the amount of data collection. Also, using a quantitative method enables large statistical analysis, which can be used for fast interpretations of the data. Thus, quantitative methods can be economical and fast. However, on the downside, quantitative methods tend to be inflexible and are not good for understanding a process, or what part the human factor have on different actions. Qualitative research methods on the other hand, emphasizes words instead of numerical collection and analysis of data (Bryman & Bell, 2015). The benefits of qualitative research methods are the ability to understand the meaning of what people communicate, to be able to adjust to new issues as they emerge and to look at change processes from a wider time perspective. Also, qualitative research methods are useful in the evolution of new theories (Bryman & Bell, 2015). However, as with quantitative research methods there are drawbacks. For example, qualitative research methods can be both time and resource demanding. Moreover, the interpretation of data and the analysis of the empirical finding can be difficult, and can depend on the tacit knowledge from researchers. Also, there is a risk with qualitative studies regarding the credibility form policy makers, since they are based on subjective opinions (Easterby-Smith et al., 2015).

In this research study, a qualitative research method was used since it is suitable when analyzing a subjective phenomenon that is difficult to quantify. Furthermore, since the data collected in this research study was supposed to be interpreted by the researchers, and since questions and new ideas emerged during the study, a qualitative research method was most appropriate. As qualitative research, many times are unique, the created theories can sometimes not be transferred beyond the certain context (Easterby-Smith et al., 2015). However, this research has, to a certain extent, a generic result as it can be applicable to other companies with complex product development processes wishing to investigate a CAE driven development approach. Also, the result implicates on certain key factors and methods to use together with a CAE driven development approach which is usable for other companies within the industry, or for other researchers within the area. However, the analysis and results of the second research question is less transferable as it is associated with VCC's current development process and organization, but it could be used by companies with a resembling development process.

2.1.2 Case Study Design

The choice of research design is important when conducting a research. Most commonly mentioned in the literature are five different design methods: *grounded theory, ethnography, phenomenological research, case studies and narrative research* (Creswell, 2014). With the support, and the initial research request from VCC, and by conducting case studies at other industry companies, the aim of this study has been to find what key factors and methods that VCC, or a resembling automotive manufacturer, needs to consider when implementing a CAE driven product development approach, and also to suggest a process and a workflow that allows this type of product development to be incorporated in the early phases of product development. Hence, a case study design approach has been applied to this research. As Bryman and Bell (2015) states, a case study design approach is popular in business and management theory. Easterby-Smith et al. (2015) states that case studies can vary in the form of the number of companies that are used as input to the analysis. Easterby-Smith et al. (2015) put forward the design approach developed by Kathy Eisenhardt, who advice to use case study designs that are flexible, and where a *within case* and *across case* analysis can be used in one research study. Bryman & Bell (2015) also mentions this. They argue that the original form of case studies is based on a single organization, person, location or event, but that the approach has evolved to allow multiple-case study design. As mentioned earlier, this study will be of a qualitative nature why a case study is an appropriate design. However, it is important to understand that a case study can also be of a quantitative nature, even though this is not as common (Bryman & Bell, 2015). When conducting a case study research, while using qualitative data, the approach tends to be inductive (Bryman & Bell, 2015). However, while using a systematic combining approach this adds another dimension which removes the hinder that the research must flow in a certain direction. Thus, the systematic combining approach, together with a case study design, made it possible to explore and learn during the process, which both improved the theoretical findings, but also the quality of the case study.

2.2 Data Collection

As stated in chapter 2.1 this thesis is going to be of a qualitative character with a case study approach. Hence, the data collection methods have been decided based on this. To meet the objectives of this thesis both primary (interview) and secondary (literature) data sources have been used.

2.2.1 Literature Study

The literature study should be made on a wide range of information and appropriate information sources in regard to the objective of the research (Easterby-Smith et al., 2015). Hence, because published articles and books have been carefully reviewed before publication (Easterby-Smith et al., 2015) this has been the main source of information for the literature study. Other sources that have been used are conference material and white papers. However, all information sources have been evaluated according to Easterby-Smith et al. (2015) “four criteria for evaluating an information source”, to enable an approach that is source critical, namely: purpose (the purpose behind the creation of the source), authorship (who has the responsibility for the source), credibility and accuracy (is the information credible and accurate?), and timeliness (when was the information created and updated?).

The review process of the literature has followed Easterby-Smith et al.’s (2015) approach which consists of three stages.

1. Establishment of the topic, scope and aim of the literature. This, was decided based on the research topic given by VCC together with the identified research questions. This step helps identifying keywords and search terms for the literature study. As the research proceeded and more knowledge was built around the subject, the topic, scope and aim of the literature was altered. This is also stated by Easterby-Smith et al. (2015) that argues, that it might be necessary to change the research topic and questions throughout the research process.
2. Searching for literature, organization of relevant literature and finally reading and evaluating the literature. This was conducted all through the research in parallel with other data collection methods.
3. Literature review writing.

This review process lead to a theoretical framework that consists of three main areas, namely: product development (with a focus on the early phases of product development within the automotive industry), CAE driven development, and organizational change (focusing on process-change). As stated in chapter 1.6, the two former are the areas which this thesis will focus on. Apart from these three main areas, a set-based design approach has been reviewed as well as the integration between CAE- and CAD engineers within an organization. Moreover, to understand the current situation at VCC internal documents have been reviewed.

2.2.2 Interviews

One of the most common data collection methods when conducting a qualitative research is interviews in different forms. The aim of having an interview is to collect information about how someone perceives a situation. Having a qualitative approach is suited when aiming to collect information about a person's feelings, experience and thoughts connected to a specific situation (Dalen, 2008). Interviews were made at VCC and at a selection of companies (the case studies).

At VCC, interviews were made for two reasons. Firstly, to understand the current way of working, and secondly, to understand the different opinions about how to work CAE driven at VCC together with what key factors and methods the interviewees consider to be important to enable a CAE driven product development in the early phases.

The first interviews at VCC were made in an exploratory manner to understand the product development process at VCC. An exploratory interview approach is used by e.g. Greenleaf et al. (2006) as well as by Johnsen and Ford (2000) to gain understanding of a subject through an exploratory approach. This is also the approach used in the initial phase of this research. This, to understand the product development process at VCC (with a focus on the early phases), through a discussion with employees involved in different activities. The reason behind this approach is that the early phases at VCC is not well described, and therefore the exploratory approach enabled an interview process that lead to an understanding of the early phases that was required for this thesis. These interviews were a combination between semi-structured and unstructured. Semi-structured interviews have a list of certain questions that can be used in a flexible manner, while unstructured interviews have questions in order to stimulate a conversation instead of guiding towards a response (Easterby-Smith et al., 2015). A combination was used because the aim was to stimulate a conversation but at the same time guide it towards responses that could be used to make a comparison to other interviews. During the interviews the interviewee was asked about the tasks he/she performed in the early phases and how he/she would describe the overall process in the early phases. Based on these two questions a further discussion was created with the aim to map the early phases. Because the early phases are not well described at VCC there was also a lack of one common picture about how the work is performed. This was problematic. However, the contradictions and questions which arose during an interview were written down and then discussed during other interviews. With this exploratory approach, an overall understanding of the product development process of the early phases, and the perceived issues connected to a CAE driven development in this phase, was concluded.

In addition to these exploratory interviews, semi-structured interviews were conducted. These were conducted to understand how the interviewees work with CAE today and how they believe a CAE driven development at VCC could look like. The employees that had a deeper understanding of CAE were also asked about what key factors and methods they consider to be important to enable a CAE driven development at VCC. During each interview, a simple interview guide was used (see appendix I). However, as each representative had a different role, and a different perception of the early phases, questions were added during the interviews to get a deeper understanding of the issues that the representative experienced, and to give room for the representative to elaborate their answers based on their expertise.

Regarding the interviews at the other companies (here on called *case companies*), interviews were made to understand how different companies work with CAE in the early phases today, and what key factors and methods the different representatives considered to be important to enable a CAE driven product development. A semi-structured approach was used in order to enable flexibility (to adjust to the different companies and representatives' background) but at the same time make sure that all aspects were covered by all interviewees. This enabled a comparative analysis between the companies. The same approach, as the approach used during the semi-structured at VCC, was used at the case companies. A simple interview guide that was modified during the interview can be found in Appendix II.

Both for the interviews at VCC and for the interviews at the case companies, regarding key factors and methods that would enable a CAE driven development approach, the interviewees were asked what they considered to be most important. Hence, no leading proposals were used. This, not to guide the interviewees in a certain direction. Because of this the answers varied. For the case companies, important key factors and methods were investigated during the interviews. However, as a complement to this, after the interviews, each interviewee was asked to answer what key factors and what methods they considered to be most important for a CAE driven product development. This was done by sending a separate email to each interviewee. Moreover, since the data from the interviews was gathered with this approach, there is no grading in whether a key factor or method is more important than the other in the analysis. Instead, key factors and methods will be presented in alphabetical order. The number of YES (see Table 17) does not correspond to the importance of the key factor or method. This can be seen as a weakness. However, since the data was gathered with an exploratory approach, the researchers had more information and knowledge about CAE driven development in the later phases of this research project. Hence, the interview questions could be better adapted to the specific situation later on.

2.2.3 Sampling of Interviews

When conducting a qualitative study the aim is often to select a purposeful sample and at the same time reduce the risk that the sample choice will influence the results - a so called non-probabilistic approach (Easterby-Smith et al., 2015). To make sure that a non-probabilistic approach was kept when making the sampling of interviewees non-probabilistic sampling strategies were used.

Initially purposive sampling was used, a technique described by Lewis (2007), to find the first interview objects. Hence, interview objects were selected primarily with the support from VCC, since they already have a wide network inside the company. Based on these first interview objects new interview object was found. This technique is mention by Bryman & Bell (2015) and is called snowballing technique. This is a recommended strategy when own access is difficult or limited, which it was, as at the researchers' network and knowledge was restricted. However, to make sure that a wide range of employees (with different roles, from different departments and with different opinions) were interviewed, variation sampling was used. Variation sampling aims to select interview objects from a wide range. In total 17 interview objects have been sampled and interviewed from different departments and a variation of roles (CAE engineers, CAD engineers, transformation leaders and different managerial positions), see Table 1.

Table 1. Interviews conducted with employees at VCC.

Title	Date of interview
Manager Knowledge based engineering	2017-03-06
Organization Development leader	2017-03-10
Manager Endurance attribute	2017-02-21
Manager CAE durability - Body & Trim	2017-02-27
PD transformation	2017-02-18 & 2017-04-14
CAE PD transformation	2017-04-14
Senior CAE analyst - Part of concept team	2017-02-20 & 2017-04-18
Senior Manager - Vehicle Concept Development	2017-02-20
Senior Director - Architecture Concept Management	Mail contact
Vehicle Engineering Program Manager	Continuously
Senior Analysis Manager	Continuously
System responsible - Wheel Suspension system	2017-05-02
Director - Strategy & Concept	2017-05-03
Senior Expert Studio engineer	2017-05-03
Director - Innovation and Technology	Mail contact
Weight Management and Optimization	Continuously
CAE engineer	2017-03-07

For sampling of case companies an ad-hoc approach was used. This means that the companies were chosen based on availability and ease of access. This is usually used when speed and low cost is a priority (Easterby-Smith et al., 2015). To find company representatives, the network of the OCA (Optimization Culture Arena at VCC) was used for the interviews at GKN Aerospace, CEVT and Scania. Representatives at Opel and Combitech were found through the researchers' own investigation. Because of the limited time frame only one or two representatives at each company were interviewed. This has of course an impact on the result as the answers are based on the interviewees' opinion and experience. Moreover, all names of the representatives have been changed to fictive names. This is to keep the representatives anonymous. For details see Table 2.

Table 2. Interviews with representatives from the case companies. All names are fictive.

Name	**Case company**	**Title**	**Date of interview**
Albert West	CEVT	Director CAE	2017-03-08
Phil Johanson	GKN Aerospace	Technology lead for multidisciplinary design	2017-03-09
Magnus Tapper Karl Jakobsson	Scania	Technical Manager Senior Technical Advisor	2017-03-24
Tobias Svensson	Combitech	Manager CAE and Analysis	2017-03-29
Hans Bartling Herman Becker	Opel	Manager CAE for strategy and operation Director Vehicle CAE for strategy and operation	2017-03-22 & 2017-04-04

2.3 The Quality of the Research

In this subchapter, a research validation is conducted which is followed by the researchers' own reflections on the study. Next, the quality of the research is evaluated and a description of the ethical considerations made in this research is made.

2.3.1 Research Validation

According to Easterby-Smith et al. (2015) an important aspect of validity is to be transparent when performing research methods, both during data collection and analysis. This has been done by being clear about what methods that has been used and by detailed documentation. Documentation has been done through transcription of interviews and saving relevant articles in an organized manner. Moreover, it is important to critically review the collected data (Eliasson, 2010). In order to do so respondent validation and triangulation has been used. By performing triangulation, the reliability of the data is increased by using multiple sources. Respondent validation has been used by giving the interviewees a chance to read through the answers and the key-takeaways after an interview. This has been done in order to make sure that the interview is understood correctly and to give the interviewee an opportunity to give comments (Guion, 2002).

2.3.2 Reflections on the Conducted Research

The data collection was made through a literature study and interviews. Moreover, the result of the study is based on the collected data and, hence, the range of the collected data in comparison to the "real world" affects the representativeness and quality of the result. To start with, the literature study was difficult to conduct as the amount and range of literature about CAE driven development is limited, especially from an organizational perspective, and many times outdated which is also stated by Stampouli & Pappas (2014). Moreover, the sampling of interview objects (at VCC and at the case companies), as well as the companies chosen for the case study, was limited because of the time frame and the researchers' network. Hence, the result is affected by the limitations to both the literature and the interview sampling. However, the aim was always to keep as much of a holistic approach as possible throughout the whole process.

The researchers' knowledge about the technical parts of the research subject was limited when the research started. Because of this, the result might have been affected. To minimize this risk, consultations and discussions have been held with employees at VCC and with interview objects when conducted interviews or gathered literature have been outside the scope of the researchers' technical knowledge.

Furthermore, Easterby-Smith et al. (2015) argues that qualitative research carries the risk of subjectivity as it often aims to explain a research within a certain setting (internal generalizability). As the result of this thesis is based on interviews about personal opinions, subjectivity is a risk. However, some of this subjectivity is lowered as the interviews have been compared to literature.

2.3.3 Research Quality

Easterby-Smith et al. (2015) presents a checklist of eight criteria that can be used for determining the quality of a qualitative research. The eight criteria are the following: worthy topic, rigour, sincerity, credibility, resonance, contribution, ethics, and meaningful coherence. Table 3 is based on the checklist questions corresponding to each criterion presented by Easterby-Smith et al. (2015).

Table 3. Eight criteria for determine the quality of a qualitative research.

Criteria	Motivation
Worthy topic	The research topic is relevant for VCC as there has been a defined need among some employees that a CAE driven development is necessary to stay competitive. In addition, the topic is relevant and timely as there is a paradigm shift in the automotive industry at the moment and the topic is discussed among industry competitors. Furthermore, as there have been difficulties in finding literature it is considered that the research topic is worthy as it can contribute to the literature supply.
Rigour	Considering the time frame and the limitations in the researchers' base knowledge, appropriate data and methods have been used.
Sincerity	The study has been made with reflexivity in mind and with the aim to give the reader the necessary information to evaluate the study.
Credibility	Triangulation have been used during the research, comparing different sources with each other (both literature and interviews).
Resonance	As qualitative research many times are unique, the created theories can sometimes not be transferred beyond the certain context (Easterby-Smith et al., 2015). However, this research has, to a certain extent, a generic result as it can be applicable to other companies with complex product development processes wishing to investigate a CAE driven development approach.
Contribution	This research contributes with a practical and concept impact to the research topic.
Ethics	See chapter 2.3.4.
Meaningful coherence	The research fulfills its aim by answering to the research questions in an appropriate manner. The research design and methods have supported the aim of the research. The literature and interviews are meaningfully connected to each other.

2.3.4 Ethics

When conducting a research there are ethical issues that needs to be taken into consideration. Several different research ethics are mentioned by Easterby-Smith et al. (2015). For example, interviewees cannot be harmed by agreeing to take part in the research. Hence, how and what type of questions asked during the interviews was evaluated with this in mind. In addition, it needs to be taken into consideration how and to whom the information gathered is used and presented. Because of this, interviewees were asked if they wanted their answers to be anonymous. Making statements anonymous helps in regard to another ethical issue, namely invasion of privacy (Bryman & Bell, 2015). In order to make the interviewee comfortable it is important to inform that they can chose not to answer a question and chose not to participate in the interview at all, this was communicated to the interviewees in this research. Bryman and Bell (2015) also discusses the importance of *lack of information consent* and the issue of *deception*. This has been taken into consideration during the interviews at VCC, but even more when interviewing representatives from the other case companies, by notifying the interviewees about the aim of the research, what the information will be used for and how it will be analyzed.

3. Literature Review

This chapter present the literature framework. It covers the product development process in the automotive industry, CAE driven development, set-based design, CAE and CAD integrated engineering, and lastly literature about changing a process and workflow.

3.1 Product Development Process in the Automotive Industry

Below is an explanation of what a process, workflow and product development process is. This is followed by a brief presentation of the product development in the automotive industry, and finally how choices made in the early phases impact the rest of the development.

3.1.1 Definition of a Process and Workflow

A process consists of sequential procedures which are interdependent. Each step of a process consumes resources to turn input into output. The output of one step, is the input for the next step, until the end goal is met (Business Dictionary, 2017). A business process consists of five parts - its customers, activities (the activities create value for the customers), humans or machines operating the activities, and finally a business process usually involves different organizational units (Lin et al., 2002). A workflow on the other hand are steps (interactions, tasks) that result in a work process where value is created or added to the activities of the organization. It involves two or more people (Business Dictionary, 2017). A workflow can be modeled in two ways, by basing the workflow on communication or on activities (Georgakopoulos et al., 1995).

3.1.2 Definition of a Product Development Process

According to Lapperroère and Reinhart (2014) developing a product means that a product with different or new characteristics is created. The aim is to create new or added value to customers. There are four parameters that influence the product development process - the project itself (e.g. type, size, constraints and complexity), the employees (e.g. team size and know-how), the organization (e.g. type, size, design capacity and structure) and the product (e.g. type and complexity). An important aspect of the product development process is that there is a need of specified requirements in order to steer the development. In many ways the product development process can be seen as a process of decision making (Laperrière & Reinhart, 2014). Moreover, there are three main forces that drive product development, namely: intense international competition, fragmented and demanding markets, and diverse and rapidly changing technologies (Wheelwright & Clark, 1992).

3.1.3 Product Development in the Automotive Industry

To start with, developing a car is a complex procedure. Many different experts, skills and roles are necessary (Rydberg et al., 2012). Clark and Fujimoto (1991) used two dimensions to rank a product: internal and external complexity, i.e. the technical specifications are as important as the design and the user interface. The automobile is high ranked on both axes. This complexity makes the integration of systems and components (i.e. the coordination of the whole vehicle) demanding and challenging. Furthermore, different projects have different magnitude which makes it hard to generalize all projects. The effort and the time a vehicle development project takes is determined by the required design level (Weber, 2009). A project can have the scope of a complete redesign of the car, all the way to just a minor yearly update.

A generic product development process in the automotive industry is presented below (see Figure 5) with focus on the activities and workflow in the early phases. It is made by Schelke (2006) and it shows that there is a pre-development phase which leads to a concept development before the design is set. It also presents the sequential way of working with iterations between CAD and CAE. Packaging of the vehicle and CAD design are the main driving forces in this traditional product development process. Packaging is decided already in the pre-development. Figure 5 also shows that traditionally, one solutions is evaluated and verified during the concept development.

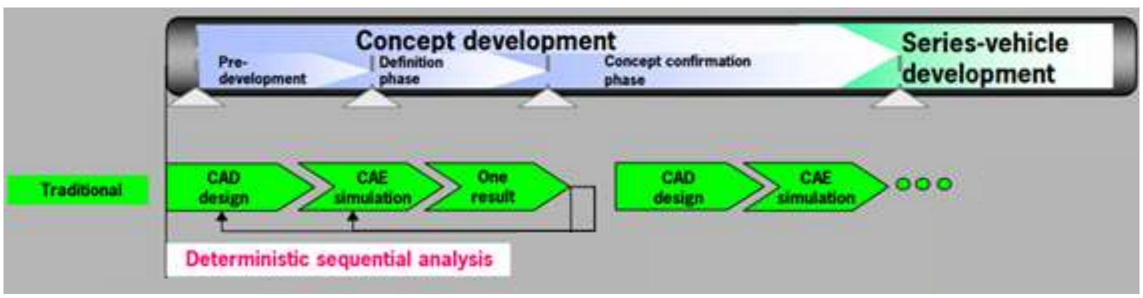

Figure 5. A generic product development process of the traditional way of working in the automotive industry [Source: Schelkle, AutoSIM, 2006].

3.1.4 Product Development in the Early Phases and the Impact of Choices

Decisions that are made in the early phases of product development greatly impact the development performance. Wrong assumptions will have a negative effect upon the process. This, because adjustments in late stages are of high cost and consumes much time (Verganti, 1997). By performing the activities as best as possible early on may have a direct impact on the success of a novel product. Resources and efforts need to be put on the activities that exist prior to the more formal development, the so called front-end (Kim and Wilemon, 2002). Khurana and Rosenthal (1998) argues that the largest benefits are reached when the work done in the front-end is improved, that is, activities concerning for example formulation of product strategy, project planning, product definition, opportunity identification. The front-end of the product development process is often called the Fuzzy Front End and is usually characterized by unaccountability and difficulties in assigning responsibilities (Koen et al., 2001). Companies that experience the greatest success are the companies that have a holistic approach in the front-end activities. Business strategy, product- specific decisions and strategy should be covered (Khurana & Rosenthal, 1998).

3.2 CAE Driven Development in the Early Phases of Product Development

This chapter starts by explaining the reasons behind having a CAE driven development approach in the early phases. This is followed by a description of CAE methods and an example of how a CAE driven process can look like. Next, an explanation is made of "The Circle of CAE" and of how knowledge can be built and how problems can be solved through a CAE driven development approach. Finally, structural optimization is explained.

CAE, as written in the introduction, stands for Computer-Aided Engineering and can be used in all types of engineering branches (Bordegoni & Rizzi, 2011). The engineer has greatest possibility to impact on the cost and the vehicle characteristics early in the product development process according to Schelkle and Elsenhans (2001) and Autosim Consortium (2007). Figure 6 shows just that. The possibility to make changes to the design is greatest in the early phases and becomes limited further in the product development process (Schelkle, 2006). Autosim Consortium (2007) also emphasizes that changes in the early phases can be made at a lower cost than later. Hence, even though the information about manufacturing costs and vehicle features are unreliable and incomplete in the early phases it is advisable to use CAE before deciding on a design (Schelkle and Elsenhans, 2001). Using CAE early helps in identifying risks and minimizing them, in addition the structural performance can be established before making detailed CAD designs, in contrast to the more traditional process flow, where a design draft is made in CAD and then the draft is verified regarding to its structural performance in CAE (Schelkle and Elsenhans, 2001), see Figure 5. Because of the trend to be faster to the market in the automotive industry, CAE driven development is common to use to meet these market trends as it shortens the product development process (Donders et al., 2008).

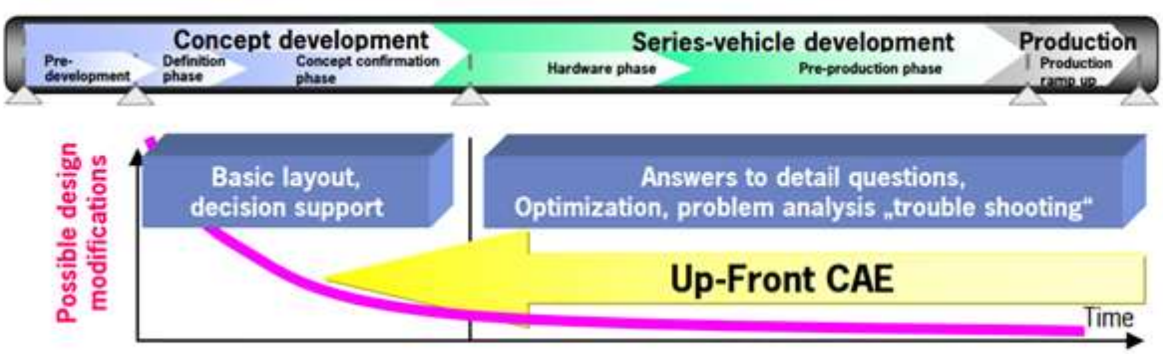

Figure 6. The figure shows that the impact to make changes to a design is greatest in the early phases of product development, hence, CAE is needed up-front to enable modifications. In the early phases, basic layouts are investigated and decision support is made. Later, detailed work is conducted [Source: Schelkle, AutoSIM, 2006].

The purpose of having a CAE driven development in the early phases is to support the decisions about material and architecture by quantitatively examining the structural performance, make feasibility- and what-if studies, estimating weight by increasing accuracy and evaluate alternative solutions (Bordegoni & Rizzi, 2011). The outcome presented by the digital simulations made in CAE can then be used to adapt the design. As described before, the design becomes more fixed with every step in the product development process which decreases the opportunity to change the design according to the virtual simulations in CAE, which is one of the reasons behind having a CAE driven development early on (Donders et al., 2008). Moreover, the reason why it is crucial to focus on the early phases in the product development process is because the actions taken here have the greatest impact on the design work later in the process (Yamamoto et al., 2007). Furthermore, in the very early phases of product development the focus of engineers should be on evaluating different options and to have a holistic approach. In general, few engineers work in this early phase, compared to later in the development process (Donders et al., 2008). In this early phase, decisions are taken that can only be changed with tremendous effort and high cost later in the process (Wehrle, 2015). Autosim Consortium (2007) argues that working CAE driven in the early phases enables engineers to perform more analysis faster which speeds up the time until a concept definition is set in the product development process.

3.2.1 A CAE Driven Process and Methods

The CAE driven product development is putting the automotive industry through a paradigm shift (Schelkle, 2006). The picture below shows the impact it has on the product development process in regard to a generic automotive product development process, the figure is focusing on activities in the early phases. See Figure 8.

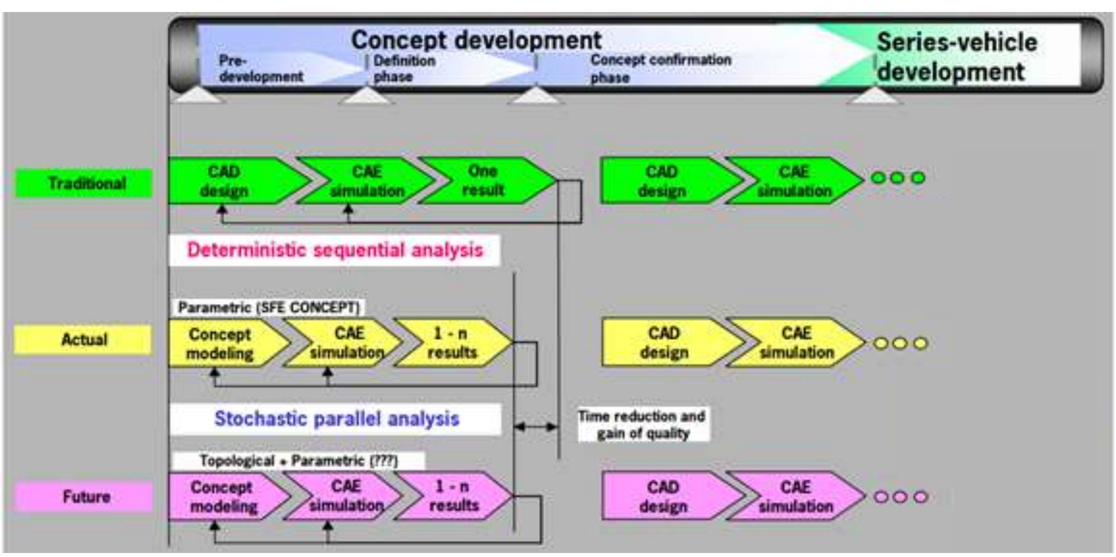

Figure 7. This figure shows the traditional product development process in the automotive industry with a focus on the activities made in the early phases. It shows how a CAE driven development will change the process and workflow, and how it will lead to time reduction and gain of quality [Source: Schelkle, AutoSIM, 2006].

Figure 8 shows that the traditional sequential process of CAD design followed by CAE is being exchange. Instead, a process is introduced where CAE methods together with CAD creates concept models which are then used as input for the CAD design. The figure also shows that a CAE driven development in the early phases enables evaluation of many different solutions (represented by the “1-n results”), reduction of the development time and an improved quality of the product. The activities in the pre-development and definition phase is made in fast iterative loops. (Schelkle, 2006). Moser and Schweiger (2007) and Schelkle (2006) presents what they call a “Conceptual Design Process” which incorporates the CAE methods that can be used in the early phases of the product development process. The process presented in their article is shown in Figure 9.

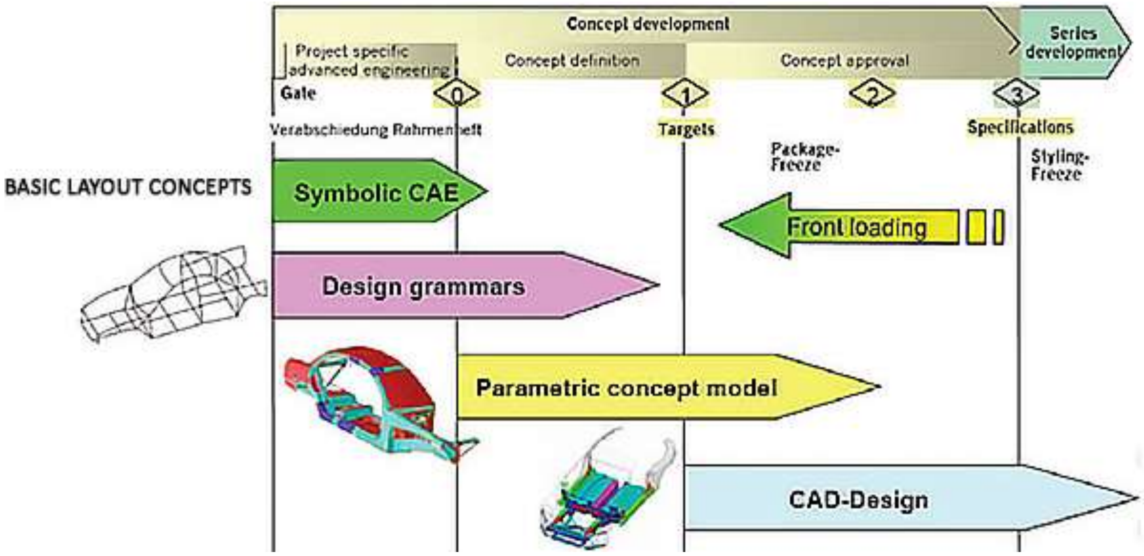

Figure 8. The figure shows what type of CAE methods that can be used and when in the early phases of the product development process [taken from Moser and Schweiger, NAFEMS, 2007, but with some modifications].

Three methods are presented in this process: Symbolic CAE, Design Grammars and Parametric Concept Model. After this the traditional CAD design is started which later will turn into CAE verification and redesign in CAE-CAD verification loops (Moser and Schweiger, 2007). Symbolic CAE enable investigation of the physical layout through basic layout concepts. By Design Grammar the topology layout can be examined. Parametric Concept Models enables early geometry findings by generating a parametric CAE model which can be modified and evaluated. The parametric geometries are based on e.g. the design space, information about packaging and styling, moreover, the parametric model can be based on CAD information, however it does not have to (Schelkle, 2006). Having flexible models is essential in order to enable solution evaluation and dynamic changes if e.g. requirements change. Moreover, parametric models encourage design work through CAE (Autosim Consortium, 2007). Lastly, what is not shown in the picture, optimization of the concept can be made through e.g. Design of Experiments (DoE) and response surface methodology (Schelkle, 2006), more about this in the next paragraph. Moser’s and Schweiger’s (2007) figure also show that the packaging is frozen after the parametric studies have been made and that the design of the styling is frozen first when CAD engineers have started working on the concept designs.

Moreover, DoE can be used to evaluate how the performance changes of the design depending on variation of parameters, hence information can be gather around the behavior of the design and alternative solutions. The result from a DoE can be presented using different graphs (Flager et al., 2009). Furthermore, when doing a parametric concept model, parametric studies can be made. By conducting a parametric study the performance of the product can be improved, this is done by sequentially changing design variables. A sensitivity analysis can be made to investigate which of the parameters that affects and contribute to the product the most (Kojima, 2000). Kojima (2000) continues by arguing that DoE can be used to decide the scope of the parameters that should be examined and the combination of them (in the parametric studies and the sensitivity analysis). Together with these methods (DoE, parametric studies and sensitivity analysis) response surface methods can be used. They find the optimal parameters (based on a sequence of DoE with e.g. parametric studies and sensitivity analysis) determined by the relationship between performance and design variables. This approach, using a combination of DoE, parametric studies, sensitivity analysis and/or response surfaces is considered to be one type of optimization approach. A second optimization approach is using different types of topology optimization (Kojima, 2000). Flager et al. (2009) states that DoE is a good way to start investigating the design space in addition it can be used as the basis for other methods such as structural optimization (more information about structural optimization can be found in chapter 3.2.4). An iterative process can be created between the two optimization approaches. For example, while conducting a parametric study a structural optimization study can be done in parallel where information is exchange (the output from the parametric study becomes the input to the structural optimization study, next the output of the structural optimization study is used as an input to the parametric study and so forth) (Autosim Consortium, 2007).

Pisipati et al. (2016) further argues that the requirements used as input to CAE is often too complex since the requirements often are based on detailed CAD templates. In the early phases of product development there is of great value to use less complex requirements to weigh different design solutions against each other (Pisipati et al., 2016).

3.2.2 The Circle of the CAE Driven Development

This circle consists of four phases and is described by Hilmann (2014), the author works as Supervisor Vehicle Architecture at Ford. Below is an illustration (see Figure 10) of how a CAE driven development could work. The figure shows that the work is circular and consist of four phases – preprocessing, processing, post processing and decision. The input to this circle is a problem or question, where a question could an identified gap.

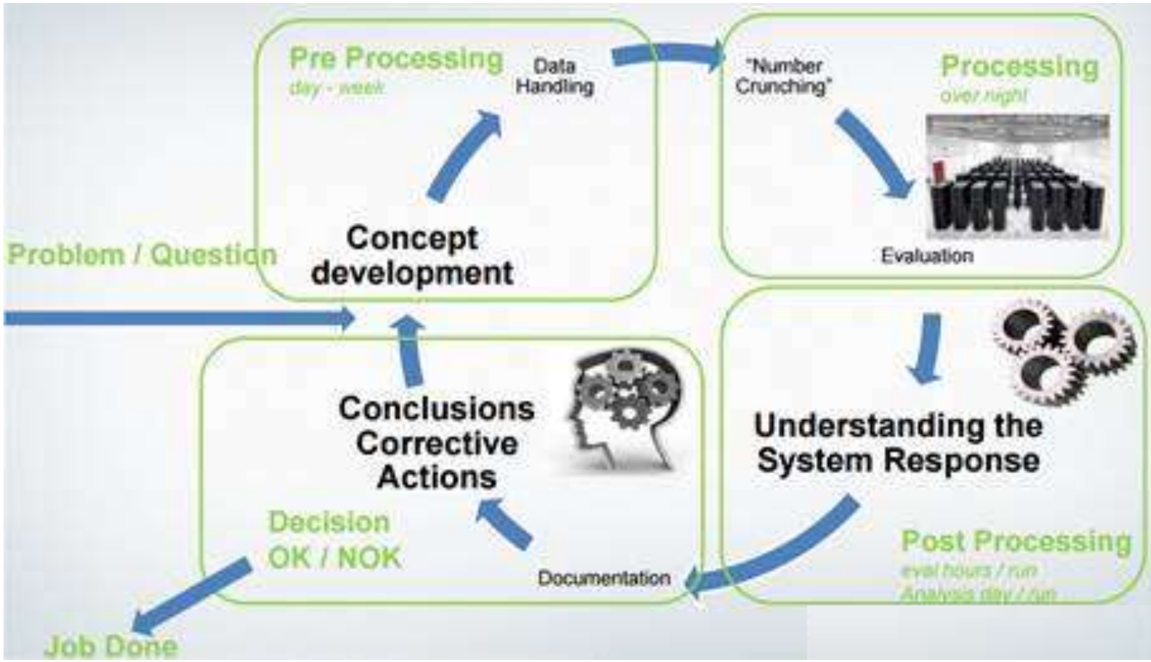

Figure 9. The circle of CAE driven development and its different phases [Hilmann, Ford Motor Company, 2014].

The preprocessing phase consists of:

- Developing ideas and solutions. This requires a cross functional work, creativity and high experience. This work is done manually.
- Concept development in CAD and CAE (critical experience here is 3D development). This work is done manually and creativity is encouraged.
- Information exchange to get manufacturing and packaging feasibility. Share models to global database including assumptions for material. This is a standardized and automated routine as it is vital for achieving success.
- Handling data – making backups, storing and registering. This is a standardized and automated routine as it is vital for achieving success.

When the preprocessing is concluded, the next phase start which is processing the data. After processing the data, the phase of post processing starts which consists of:

- Evaluation, which is made on e.g. mass, pulses etc. This is a standardized routine which is automated to avoid mistakes.
- Analyses, which demands great experience. The validity of the result is judged here, a root cause analysis is also made. If more time is spent on the analysis the conclusion will get better. The analysis is made manually and creativity is encouraged.
- Documentation of findings and changes is necessary. This is a standardized and automated proceeding.
- Combining the analysis with the desired outcome for the product. This work is done manually, encourages creativity and requires experience.

By standardizing and automating the activities *documentation* and *evaluation*, more time can be provided for analysis and conclusion which are the key activities. After the post processing conclusions and corrective actions are made.

- Ok or not ok? If ok the job is done, if not ok the circle start over again.

3.2.3 Building Knowledge and Solving Problems with a CAE Driven Development Approach

Autosim Consortium (2007) states that having a CAE driven approach increases the ability of building knowledge around the product significantly through the ability of assessing alternative solutions. Improving the knowledge about the product in the early phases of product development helps to reduce costs and time to market while increasing the quality. It also makes it easy to evaluate different solution through verification and validation. Consequently, risk assessment can be conducted more easily, through the design robustness, which needs a balance between the environment complexity and environment uncertainty. As the environment is uncertain in the early phases, a complex model will be fragile and not robust. Hence, a simple model is recommended in the early phases, and the more certain the environment grows the more complex the model can become (Autosim Consortium, 2007). Moreover, because of the uncertainties there is also no need for high accuracy (Bordegoni & Rizzi, 2011). In addition, even though simple models may only have an overall resemblance to the final CAD models, more knowledge and insights can be created in a shorter time period than if the model would have been complex (Autosim Consortium, 2007). Moreover, creating more detailed models in CAD is time consuming. Hence, using simple models do not only save time because they enable faster analysis, but resources are saved when simpler models can be created instead. In addition, some CAE methods do not require a CAD model as an input which means that resources can be saved. However, all vital performance need to be investigated to minimize the risk of re-design later in the development (Bordegoni & Rizzi, 2011). In addition, introducing a CAE driven development solves engineering problems early in the design phase which saves both time and money (Donders et al., 2008).

> "[...] the cost of fixing a problem that designers should have corrected in the planning and concept phase increases 10 times if the company discovers it in the testing phase, 100 times if it finds the problem in the production phase, and 1000 times if the customer discovers it." (Autosim Consortium, 2007, p.3)

Autosim Consortium (2007) also writes that problems should be handled as early as possible. When applying a CAE driven process, knowledge about the product is built in the early phases, in addition, knowledge created around previous products can be brought in (Autosim Consortium, 2007). The transfer of this knowledge and experience is, according to Thomke and Fujimoto (2000), the most important precondition for effective front-loading problem solving, since it lowers the number of problems that needs to be solved in the early phases of product development. Furthermore, Autosim Consortium (2007) also states that, because of the usage of a knowledge base, problems can be solved more easily and faster in the early phases of product development. However, to enable reuse of knowledge and a build-up of a knowledge base, data must be stored and made available easily. By applying a CAE driven development, faster iterations can be performed in the early phases and more problems can be solved than when having a traditional approach. Furthermore, the more experiments and simulations that are performed, the more problems can be solved (Autosim Consortium, 2007), generating a high-quality product in less time and to a lower cost, see Figure 7. Moreover, if a product is late by six months to the market, even though within the budget, it will generate a revenue that is 33 percent less than average. With this in mind, building knowledge in the early phases, and making sure it is stored, is crucial as it can help reducing the development time in the early phases and reduce the amount of redesign later in the product development (Autosim Consortium, 2007).

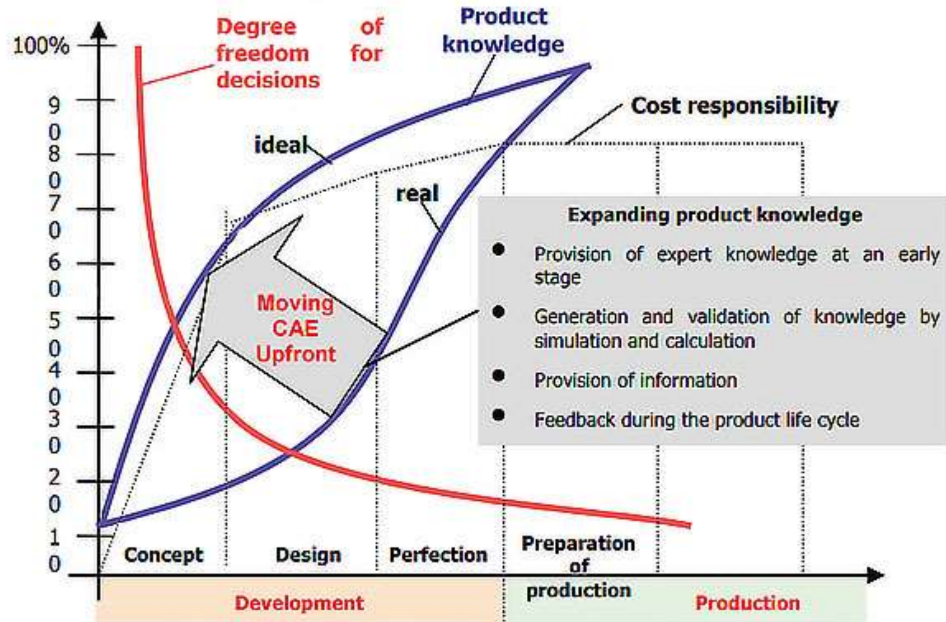

Figure 10. Benefits of introducing a CAE driven process in the early phases of product development. [SOURCE: Autosim Consortium, 2007].

3.2.4 Structural Optimization with a Focus on Early Topology Optimization

Structural optimization can be made by CAE and is the procedure where one finds the optimal, the best, way to structure materials in order to sustain loads in the best way. However, for this to make sense limitations or constraints and requirements needs to be set. Therefore, when constructing a component there are certain variables (weight, stiffness, material, cost etc.) that are set as constraints in order to find the optimal, i.e. the best, solution depending on these constraints. Furthermore, structural optimization can be divided into the classes (Christensen et al., 2009; Yildiz, 2012; Hilmann, 2009; Bordegoni & Rizzi, 2011):

- Topology optimization: A method to look for an optimal material layout of a system or component. The method is used to find the optimal material distribution within a given design space.
- Shape optimization: With a fixed topology, shape optimization aim to find the optimal shape, or contour, of a structural system.
- Sizing optimization: To find the optimal cross-sections of elements in a structural design, sizing optimization is used. As with shape optimization, the topology is fixed.

As a result, time, material and cost savings can be made (Yildiz, 2012). Moreover, Schramm and Arold (2006) writes that by focusing on topology optimization *early* in the design process, lead time and costs has shown to decrease as this way of working is less expensive. If topology optimization is used early, the concept will be relatively compliant with the requirements of performance and hence less iterations will be needed later on in the product development process. Topology optimization also drives innovation and encourages the development of unique concepts. An important aspect of topology optimization is that many of the tools also consider manufacturability (Schramm & Arold, 2006). Yamamoto et al., (2007) also describes the positive aspects of topology optimization in the initial phase of a design process by highlighting that performance and weight of the product is improved.

3.3 Set-based Design and Building Knowledge

The objective of set-based design is to delay the decision of a single design by defining and narrowing the design space. By doing so, final decisions about the design can be avoided in the early product development process (Hannapel & Vlahopoulos, 2014). Traditionally, point-based design is used. Point-based design means that a point solution is developed within the design space, then, this design is modified through an iterative process until it meets the requirements. However, this iteration process is often time consuming. In addition, there is no guarantee that the design will be an optimal solution. Creating a point-based design early in the product development process does not give any information about how the product is affected by variations of parameters (Inoue et al., 2010). However, by practicing set-based design, parameters affecting the product are not set before making the design. Instead parameters are intentionally varied in the early product development process to learn what is feasible and what is not. The design is then made with the knowledge about the performance of these parameters and how they interact. By creating knowledge and then designing (instead of designing and then testing like in point-based design) reusable knowledge is created. An issue for many companies used to be that time was spent on testing and gathering information about a product while developing it, however not enough time was spent on breaking down the information and creating knowledge about available options. However, by using a set-based design, knowledge can be visualized. The impact of the variations of key parameters is clearly visible by creating graphs. Consequently, the parameters that e.g. leads to lowest cost, can be chosen together with other key attributes knowing that the design will be feasible. Hence, set-based design enables the investigation of the limits connected to a design by making a visual representation and then, by using the knowledge built around the visualization, a design within those limits can be created. In addition, using a set-based design decrease the time it takes to create a solution compared to when using a point-based design (Oostrewal, 2010).

To build knowledge with set-based design does not only require variation of parameters, but also includes learning cycles where what is known is defined and what needs to be known is pointed out. By using graphs for visualization, teams can easily and immediately share information between each other. This means that knowledge can be reused, and new knowledge can be added to the visualization. The graphs clearly show where a design will fail and what trade-offs that can be made, hence it is a good way to gather and share knowledge (Oostrewal, 2010).

3.4 CAE and CAD Integrated Engineering

When there is no integration between CAD and CAE, the two disciplines work separately - the designer designs a model in CAD which is then transferred for analysis in CAE (Deng et al., 2002). This creates an iterative loop of analysis and redesign. By integrating the two disciplines (CAE and CAD) and then also performing a CAE driven approach the product development process is not only done faster, there is also an opportunity to minimize cost and weight and to maximize performance (Park & Dang, 2010). The process time is reduced because fewer iterations between analysis and redesign are needed and because each iteration takes less time (Maier et al., 2009).

When integrating CAE and CAD, these two disciplines need to work closely together which put emphasis on the collaboration and communication between the engineers. All people concerned must work toward one goal. This means that communication and task coordination (especially of shared tasks) is important (Maier et al., 2009). Maier (2009) further argues that one issue that is the basis for integration, yet a limitation to it, is that CAD engineers and CAE engineers focus on different aspects of the product development. CAD engineers focus on one component or a group of components, and the geometrical structure of it, while CAE engineers focus on the function of larger parts of the product, or the function of the final product. Therefore, to produce a product that is satisfying in both geometrical structure and function, CAE- and CAD engineers need to understand each other's way of working and communication between them is vital (Maier et al., 2009). Bordegoni and Rizzi (2011) argues that knowledge sharing is a key for companies to utilize the knowledge within a company (and to learn from other companies). Information sharing can often happen without the influence of human being whereas knowledge sharing requires the interaction of human beings. Tacit knowledge (e.g. rule of thumb, individual perception) is harder to transfer as the physical distance increases, thus a close collaboration and focus teams is important to utilize the knowledge within the company (Bordegoni & Rizzi, 2011). Also, human interaction and face-to-face meeting affect morale, loyalty and performance in a positive way. However, according to Kathoefer and Leker (2012) one of the aspects that hinder knowledge transfer is the Not Invented Here Syndrome (NIHS). NIHS is the behavior when a project group considers that they have a monopoly on the knowledge within that specific group. This leads to rejection of ideas from outside the group (Katz & Allen, 1982; Agrawal et al., 2010). Agrawal et al. (2010) argues that cross-functional cooperation minimizes the risk of NIHS. In addition, information transfer is important as well as having the right people that understand the whole problem and how to solve it need to be brought together (McAfee et al., 2012). Ragatz et al. (1997) states that building a relationship between the parties and communication to lower the NIHS. Furthermore, Kates and Galbraith (2007) discusses the importance of teams rather to complement a network. Since teams are more formal than network, the participation is required. Network depends on the willingness of the employees to use their network. Also, teams share the responsibility of the outcome which is not the case in a network. However, an innovating organization must be able to encourage and utilize divergent perspectives in the organization in order to create innovations and solutions that will result in workable ideas.

3.5 Changing a Process and a Workflow

In this subchapter literature about changes in processes, workflow and work tasks are described. This is followed by literature about change management and business process reengineering.

3.5.1 Process and Workflow Change

In general, it is hard to handle change. However, there are situations where change of e.g. workflow is essential to the company because of new legislations or for the company to stay competitive (van der Aalst & Jablonski, 2000). To design a new workflow, it is important to involve representatives from all involved parts to assure that all important aspects have been taken into consideration (Hudgins & Macklin, 2000). Sometimes, it is not only the workflow that needs to be changed but also the work tasks. Updating or changing work tasks comes with a risk, the risk that employees will not adapt the new task or method. A way to reduce this risk is by making sure that the new tasks and methods are taught properly to the employees, and to make sure to put aside time that is intended to be used for trying the new task or method (Jensen & Friche, 2007).

A difficulty with changing processes is to reach an agreement with all involved stakeholders and to make them participate actively. The satisfaction of employees influence the success of a change in the long-term perspective (Cima et al., 2011). An important part when implementing process changes is therefore change management, in addition it has a direct relationship to project success (Grover et al., 1995). Kotter (1995) discusses the importance of creating an understanding and acceptance among the employees that will be affected by the change. For example, employees should be given the opportunity to give propositions about the change and participate in creating the new way of working as they have knowledge that the management may not about their specific tasks. Moreover, it is important to establish the changes by introducing standards and routines to make changes a natural part of the organization and its long-term way of working. However, it is also important that positive results from the change are communicated early in the change process, regardless of size. Positive results increase the devotion of employees and creates a culture where individual performance is important (Kotter, 1995). If there are sources to motivation employees perform better which increases the organization's total efficiency (Bruzelius & Skärvad, 2011). Furthermore, Lakos and Phipps (2004) argues that the outcome of an organizational change is very much dependent on cultural transformation lead by the management. If changes, or other initiatives, are made without reflecting upon how the culture of the organization needs to be changed, unexpected and possibly even negative consequences often occur.

Moreover, Kotter (1995) argues that change should occur stepwise to maximize the chance of succeeding, which he has summarized in the following eight steps:

- Create a sense of urgency for change
- Create a strong and influential group that can take the lead of the change
- Create a vision for the change
- Communicate the vision
- Get others to act according to the vision
- Plan to create short term wins
- Consolidate the improvements and produce more changes
- Institutionalize new way of working

This eight step process provides guidance during the change by addressing important aspects that need attention to succeed. The first four steps create a process flow, as one step leads to the next. The last four steps, on the other hand, highlight areas that need attention and care (Anderson and Anderson, 2010). Anderson and Anderson (2010) also argues that a change process needs to be structured but it needs to be able to adjust to the constantly transforming nature of change.

3.5.2 Business Process Reengineering

Business Process Reengineering (BPR) is used when wanting to achieve radical redesign and processes (Motwani et al., 1998). The reason behind redesigning processes in an organization are among other things to reduce cost, managing new challenges in the business, increasing the operational efficiency and product quality (Cima et al., 2011). When carrying out a BRP there are two basic tasks that are made - mapping the current processes and modeling the new processes. When mapping the existing processes activities and their related elements are modeled (Lin et al., 2002). Kettinger (1997) describes a framework that can be used for BPR. It consists of six steps: envision, initiate, diagnose, redesign, reconstruct and evaluate, these steps are described below:

- Envision: In this step, the BPR-project needs to get support from top management. The BPR is also reviewed based on the strategy of the organization and IT opportunities.
- Initiate: In this step, a BPR-team is put together, performance goals are set, and stakeholders and employees are notified about the project. A business case is created through benchmarking, external customer needs and a cost benefit analysis.
- Diagnose: In this step, the current process is documented. Activities, communication, roles, resources, IT and cost mapped.

- Redesign: In this stage, the new process is designed and developed. To come up with different ideas brainstorming or other creativity techniques can be used. Important though, is that the new process needs to follow the strategic objectives of the organization and it need to fit the IT architecture and human resources.
- Reconstruct: In this step change management is of great importance in order to achieve a smooth implementation in regard to process responsibilities and roles.
- Evaluate: In this step, the new process is monitored and evaluated to make sure that its goals are met.

Moreover, each of these steps consist of several different activities, see Figure 11.

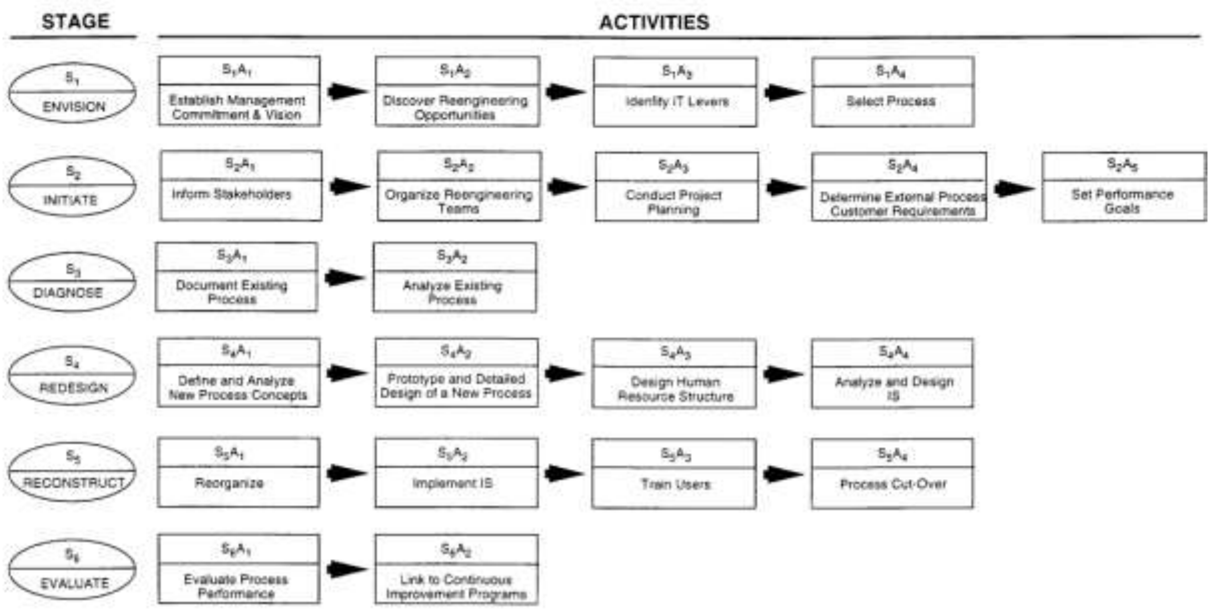

Figure 11. Kettinger's framework for performing BPR including six stages and 21 activities [Source: Kettinger, MIS quarterly, 2007].

3.5.3 Changing to a CAE Driven Product Development Process

Changing to a CAE driven product development process is a paradigm shift in the automotive industry (Moser and Schweiger, 2007). Current methods and tools must be exchanged and the process time eliminated in order to make room for CAE methods like Symbolic CAE, topology based parametric models, Batch-Meshing etc. These methods must be understood and accepted by the users. It is important to make sure that they are used consistently by e.g. the concept team, this can be realized through continuous training (Schelkle, 2006). Also, it is important that executive management set a strategy and expectation of what the organization wants to accomplish (CIMdata 2016). A problem is that simulation and optimization is not always trusted within an organization and not embedded in the current engineering processes (CIMdata 2016), Thus, an organization need to show good simulation and optimization result in order to create trust and confidence in these disciplines (CIMdata 2016). Moser and Schweiger (2007) argues the importance of involving the people that will be affected by the change as early in the change process as possible. It is also important to have good communication with suppliers when changing to a CAE driven development as the virtual development will become much more complicated, organizations that are involved need to be on the same page. Moreover, education is a necessity. Especially for CAE engineers. This because they will need an overall perspective, much like a system engineer today. In addition, a vital factor is standardization of processes, but it is still important to encourage creativity (Moser & Schweiger, 2007). Autosim Consortium (2007) also states that confidence has to be built around the CAE models. If there is no confidence in the model, it cannot bring significant benefit or value as the result will not be thought of as correct and reliable. To create confidence around the CAE models, four factors are recommended to take into consideration according to a study made by Autosim Consortium (2007): educated staff, the validity between the digital model and the physics of the problem, accurate material data, and the complexity of the model as well as that the mesh density should be adjusted to the problem in investigation and the resources at hand.

An effective way to implement a CAE driven development is to use a simulation data management tool, both Moser and Schweiger (2007) and Schelkle (2006) states this. A simulation data management tool creates the infrastructure for capturing and managing CAE data, processes and methods. The results can easily be made available for usage.

4 Current Way of Working at VCC

This chapter describes the current way of working at VCC in the early phases of product development based on the 17 interviews made at VCC. This is done by presenting essential processes and workflows in the early phases at VCC, examples of CAE driven projects that have taken place at VCC, and lastly key factors and methods that would enable a CAE driven development at VCC according to interviewed employees will be presented. Furthermore, during the interviews issues with the current process and workflow connected to CAE were identified, which are also described in this chapter.

4.1 The Early Phases at VCC

At VCC there is a number of different projects going on at the same time. These projects have different characteristics and are in different stages of the product development process. Each project has a so called "Program Team" who is responsible for the project. There are three main areas that are of concern for the Program Team when developing a new product - business, customers and technology (see Figure 12). When searching for new technologies, or developing existing ones, the solution must be balanced between the three areas.

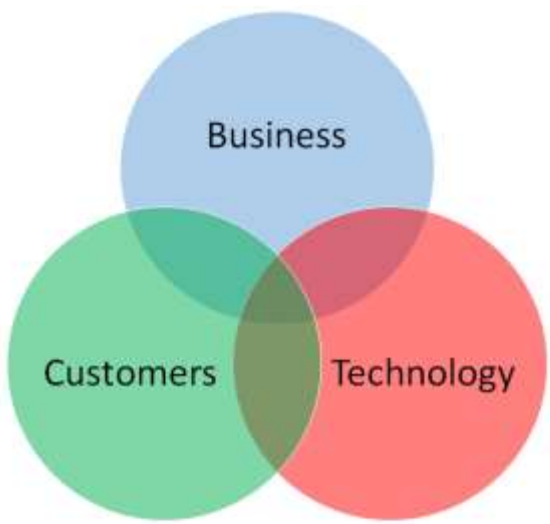

Figure 12. The three areas that the Program Team must balance when developing a product.

The Product and Quality department at VCC is the department in focus as it is involved in the product development process. There are four main sub-departments engaged in the product development process that are of interest for this thesis, Complete Vehicle Development (responsible for CAE verification of the complete vehicle in regard to different attributes, i.e. CAE category one), Technology and Implementation (responsible for geometry integration, i.e. packaging, and attribute integration of the complete vehicle), Vehicle Hardware (responsible for the development of different areas of the vehicle e.g. body and closure, chassis, interior, exterior etc.) as well as Vehicle Software and Electronics, see Figure 13. In addition to these main departments, the Design department (responsible for the styling of the car) has also been involved in this research as the styling engineers have a great impact on the design in the early phases. The organizational chart below shows that it is not only the Complete Vehicle Development department that have CAE resources. Technology and Implementation, Vehicle Hardware, and Vehicle Software and Electronics have local CAE resources (these activities are here on called *local CAE*) which aims to optimize during the development, however all verification is made by Complete Vehicle Development. Furthermore, in 2014 VCC started an initiative called Optimization Culture Arena (OCA). The vision of OCA is to create a network of cross technical knowledge and together develop one shared optimization competence within the company, but also to create a network with other companies to gain and share knowledge. Moreover, OCA have several missions. Among other things, some of the goals are to promote and support a culture that drives optimization, implement more CAE driven product development, and integration of the CAE and CAD disciplines.

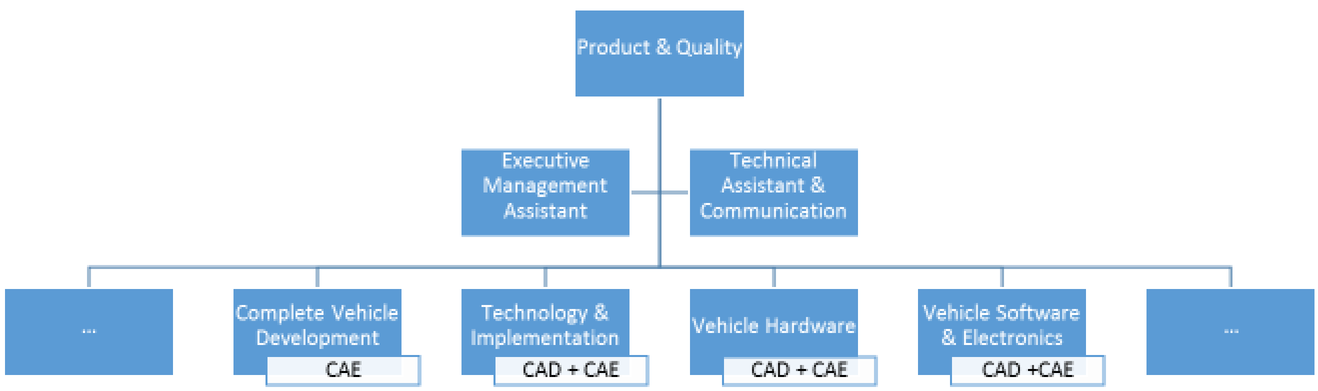

Figure 13. A visualization of the organizational departments involved in this research.

The product development process at VCC consists of a strategy phase, a concept phase, an engineering phase and an industrialization phase. During this process, a strategy is decided and different ideas tested, concept templates are updated/created, engineering templates (which are more detailed) are produced and lastly part templates (which are on a component level) are made.

- In the first phase, the strategy phase, of the product development process a program strategy is developed. In this phase, input from the yearly strategy- and technology development process, what VCC call the Annual Process, influence choices and proceedings.
- In the concept phase the product-, business- and marketing concept is developed and made compatible to the system level.
- In the engineering phase a full solution is defined and verified through iteration between the CAD engineers (the department of Technology and Implementation, Vehicle Hardware

as well as Vehicle Software and Electronics) and CAE engineers (the department of Complete Vehicle Development).

- The industrialization phase ends the product development process.

These are however not independent and isolated. In theory, there is a clear border where one phase shifts to the next phase. However, in the early phases, these borders are not as clear and the phases overlap. Moreover, the early phases, the strategic phase and the beginning of the concept phase, are not as well documented as the later phases. A reason for this is that the work in the early phases varies depending on what product is developed. However, generally the strategies for a new vehicle are decided in the early phases. For example, decisions such as if the vehicle shall be electrified, back wheel driven, or a small city car are decided in this phase. Based on these strategies an architecture of the car is proposed. Moreover, the Annual Process is a yearly process, where VCC identify gaps to understand where the company is leading and where the company needs to improve. The early phases together with the Annual Process will be described more in subchapters below.

During the interviews two issues were brought up that affects the whole product development process. First, the collaboration between CAE- and CAD engineers is hampering the effectiveness in the product development process, which was confirmed by all interviewees. Most CAE engineers and CAD engineers work in separate departments. This hinders a close collaboration. CAD engineers work on their design for a long period of time before it is sent for verification, this limits the room for changes and fast verification loops. Today, a verification can take up to six weeks, hence the CAD engineers have often already made changes in the CAD design when the verification result is complete. However, the benefits with today's workflow is that CAE engineers can build knowledge together (when grouped together with other CAE engineers). Another issue, brought up by the members of OCA and a Manager of Endurance attribute at Body and Closure, regarding the organization is that decisions about suppliers are made high up in the VCC organization. An issue which has been brought up by interviewees at VCC is that the suppliers are usually chosen depending on price instead of factors like e.g. if they can support optimized solutions from a CAE driven approach.

4.1.1 Annual Process

Each year at VCC there is an Annual Process. It is a process where strategies are updated and aligned, and it consists of three phases which will be described in this subchapter. The input to the Annual Process is for example long-term general business environment objectives, as well as benchmarks and future trends. By analyzing and trying to understand the results from the input to this phase a Product Attribute Profile (PAP) is created. The PAP visualizes complete vehicle requirements. This means that a table is made where all attributes are covered such as safety, design, noise and vibration, fuel consumption (including weight), environment and durability etc. It is also stated how VCC wants to perform in regard to each attribute, i.e. if a certain attribute should be leading, competitive or among competitors. Using the PAP, gaps are identified by examining current technical solutions and comparing them to the performance statement of each attribute. The gap analysis can for example show that to reach the project targets, methods needs to be changed, external suppliers needs to be investigated and that better alignment between internal departments is essential. Also, in the first phase of the annual process, design proportions, sketches and complete vehicle specifications are made. Topics that can be covered in this first phase can for example be platform architecture, scalability and fuel consumption (including weight). Decisions that are made here are aspects that affects the whole concept of the car. Lastly, producibility restrictions are examined.

The aim of the second phase of the Annual Process is to understand how to close the identified gaps, either by new technical solutions or by developing existing solutions. In the second phase some CAE is conducted. In the early phases mostly rough calculations of different ideas are made giving a go or a no-go result. Basically, old models and designs are used and modifications are made to these. Decisions are made whether to continue investigating in these modifications or not through CAE calculations (CAE category one). In order to have someone calculate on the new ideas usually the employee's own network is used. There have been projects were CAE category two have been used as an input to CAD models in the Annual Process, however this has only happened occasionally and it has steamed from employee initiative and individual actions. Hence, there are no defined processes or methods for how, or what type of CAE, should be used in the early phases. Moreover, these activities are represented by the four green lines in Figure 14. The category two CAE activities that have taken place in the Annual Process are the following:

- Subsystem MDO (multidisciplinary optimization)
- Load case sensitivity studies
- Concept studies
- Refinement optimization

These studies have then been used as an input to CAD. This is a start towards reaching CAE driven development process. However, the lack of defined processes, workflow, methods and tools makes it difficult to standardize the work. Furthermore, where the early phases end there is a gap where limited CAE is done. This gap was first brought up as an issue by an employee at the department of Body and Closure. The members from the OCA argues that, because CAD templates are created during this gap where there is limited CAE, the design is locked to the CAD engineers work. The wish is to have concept templates that are based on the input from CAE. One of the employees of OCA (a Senior Analyst Manager) further argues that a consequence of this is that parametrization of models today is made in CAD and not CAE which makes it difficult to use different CAE methods for optimizing the solution. Moreover, another issue brought up by a Senior Director for Architecture Concept Management and a Senior Analyst Manager regarding the current workflow, is that areas with problems or issues are often investigated without having built knowledge about how e.g. the system behaves, hence there is no clear picture of what to look for in order to make improvements. One solution is investigated in-depth before consequences have been understood.

This process is time consuming. A consequence to this is that investigation is made on a detailed level too soon and unsystematically.

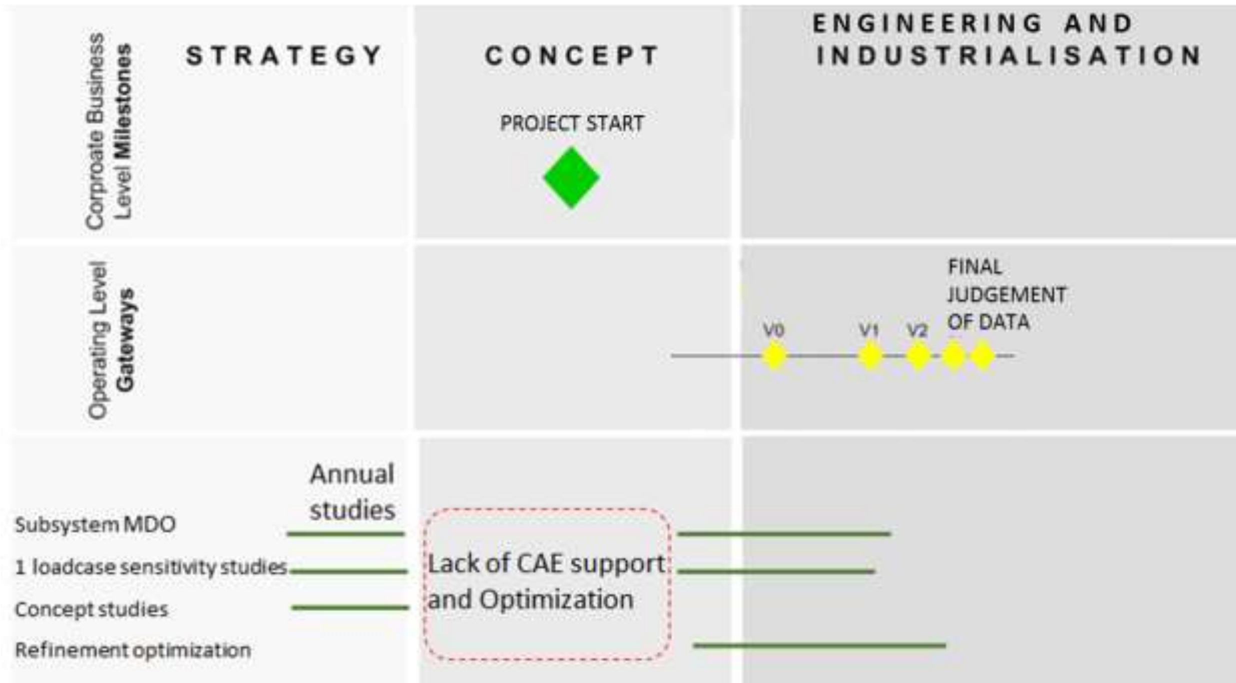

Figure 14. An illustration of the product development process at VCC. The green lines represent CAE activities, corresponding to the four different activities to the left in the figure. The Yellow diamonds V0, V1 and V2 are the defined CAE verification loops. This figure is taken from VCC's internal documents.

In the third phase of the Annual Process, the focus lays on alignment between new solutions and the current strategy. By reviewing if the solutions developed in phase two fit with the current strategy, the need for adjusting the strategy is identified. If the solutions do not fit the strategy, the strategy can be rebalanced or the solutions need to be discarded, reengineered or saved for the future.

4.1.3 The Needs/Means Process

Once a year, as a sub-part of the Annual Process, attribute teams and product systems structures (PSS) meet to discuss needs and means (Needs/Means). PSS:s are subsystems with departments responsible for that subsystem (e.g. PSS 270 which are responsible for the systems rear floor and front structure, where PSS270 is a subsystem to Painted Body and Closure). Attribute departments deliver input for the Needs/Means process, where the feasibility and priority of these are discussed and decided about. The needs are often based on external factors such as benchmarks, trends and legislations.

Needs/Means follow the PAP created in the Annual Process. However, Needs/Means is on a lower level than the annual process. Decisions about what gaps should be filled is not about steering the company in a certain direction, rather steering, and improving, a certain PSS. Table 4 is an example of how a PAP can look like.

Table 4. A simplified example of how a PAP could look like.

Attributes	Leading	Competitive	Among
Safety	X		
Design	X		
Noise and Vibration		X	
Weight			X
Environment		X	
etc.			

When the needs have been identified, all departments investigate their means. Analysis are made on how these needs can be met. The Needs/Means process define what projects, so called future projects, a department should invest in. In these future projects, CAE calculations are common, both during evaluation of the projects and when the project is ongoing. CAE calculations on ideas are common and if the department has a local CAE workforce other methods are applied as well if someone proposes it. The cooperation between local CAE engineers and CAD engineers makes it possible to make concept studies together in a cross-discipline team. The integrated team work together to deliver different concept alternatives. Hence, as this description implies, there no defined processes or methods for how to work with CAE other than calculations of a more verifying nature, however there are employee initiatives that are of a more CAE driven character.

4.1.4 The Strategy Phase of the Product Development Process

The Annual Process is used as input to the strategy phase in the product development process. In the strategy phase, the insights and knowledge from the Annual Process are taken and applied to a specific project. Project specific strategies regarding e.g. electrification, autonomous drive and fuel consumption are decided here. Moreover, when the first concept templates are produced in CAD there need to be clear requirements, hence requirements are updated and decided upon in the strategy phase. These requirements are usually already on a detailed level which has been brought up as an issue as the requirements are too complex to work with in the early phases. Moreover, project and product planning must be done in the strategy phase so that when the concept work starts, the process runs as smoothly as possible.

In the early phases of the product development process, a cross-functional team is appointed to work together until the concept work starts. The team is put together so that it reflects a holistic view of VCC and the departments involved in the product development process. The group has a pyramid structure where representatives from the architectural team is in the upper part. The architectural representatives are followed by representatives from each unit (such as Complete Vehicle Development, Technology and Implementation, Vehicle Hardware, as well as Vehicle Software and Electronics). Next, each unit has representatives from each department within the units. Approximately once a week these department representatives meet with their specialist to know what to communicate to the cross-functional team. It is also the department representatives, together with their specialist, that are involved the Annual Process. However, in the meantime there is also strategic work in the styling team. The styling-team designs the looks of the car. However, this approach (the cross-functional team) is new at VCC and the interviewees agrees that there is still a large issue with the NIHS. This can be noted in the early phases as different departments and disciplines have different ideas regarding how to improve the product. A wish is to create a mindset that implies that there is one joint product that requires a collaborative work

As stated before, new ideas are investigated in the early phases, these are made into rough CAD designs. These are then sent to CAE engineers for go or no-go calculations. Hence, the development is geometry driven. CAD drawings are made and these are tested in CAE to check if requirements are fulfilled or not. An issue which was brought up during interviews with OCA and with a Senior Director for Architecture Concept Management is that the CAE activities today have been developed to replace physical testing, mostly through the verification loops. These verifications demand detailed models and large computer resources. However, in the early phases, simple models are better to work with. This leads to a problem as there is a lack of simplified models today at VCC. In addition, all the interviewees requested the ability to compare different solutions with each other using simple models and CAE methods that can support this type of activity. Moreover, a Senior Analyst Manager at Complete Vehicle Development and an Advanced Engineer leader at Body and Closure states that there are a sufficient number of CAD models (concept-, engineering and part templates), but there is a lack of CAE models, which makes it difficult to work CAE driven in the early phases. Furthermore, the desired degree of a CAE driven development varies depending on the interviewee in question at VCC. Some would like to see a completely CAE driven development process with only CAE models that from time to time would be sent to CAD and Complete Vehicle Development for construction input and CAE verification. Others are skeptical to a pure CAE driven development and considers that CAE only should be used to support the development and creating knowledge around alternative solutions. The interviewees agree that there is a need of being able to evaluate alternative solutions in the early phases, as well as a possibility to create knowledge around their behavior. This is not done to a satisfying extent today according to all the interviewees at VCC. Moreover, another issue brought up by a Senior Analyst Manager at Complete Vehicle Development and a Senior Expert Studio engineer at Styling (i.e. design engineer) is that styling and packaging of the vehicle is set in the early phases. Hence, today this is one of the most driving forces to how the templates are designed. An issue with this is that the design is decided by packaging and styling before CAE can make a greater impact.

As mentioned earlier, there are some optimization and other CAE projects at VCC today, mostly made by the local CAE engineers at the different departments within Technology and Implementation and Vehicle Hardware. This, because employees are starting to realize the importance of a CAE driven development approach (two examples of such projects are described in chapter 4.2). However, there are no defined processes, workflow, methods or tools for how to work CAE driven. Also, as stated in several interviews, resource allocation is important when trying to achieve a development process with more CAE and optimization activities in the early phases. This is a problem today since there is not enough resources dedicated for CAE and optimization activities in the early phases at VCC. To find resources for CAE and optimization activities is often dependent on employees that identify problems, who then need to rely on their network within VCC in order to find resources. The interviewees argue that the resource allocation must come from management, and that defined processes must exist so that these activities are performed. Furthermore, a Senior Expert Studio engineer, working in the early phases, stated that there are CAE resources in the concept team today, but there are just not enough CAE resources in order to be able to do optimization early, and to evaluate as many concept as the team wished.

4.2 Examples of Local CAE Driven Projects at VCC

As discussed in the Annual Process, some CAE driven methods are used today, additionally local CAE teams have conducted CAE driven projects. For example, looking at a department level, local CAE is used for optimization, as explained before. The local CAE is conducted to better understand the own system and how to design it. However, there are no set deliveries or status reports in early phase. For example, if Body and Closure as well as Interior learns that the crash pulse will change in the future a local CAE work is started using different CAE methods (e.g. topology optimization and sensitivity analysis). This is done by building knowledge around alternative solutions in order to be better prepared when requirements are changed. By doing this local CAE, the CAD engineers get solid support from calculations into their designs. However, more often than seldom, when the design is sent to Complete Vehicle Development for verification the local CAE knowledge is not passed forward but forgotten. Hence the local CAE knowledge is usually not used in the complete vehicle analysis. Figure 15 illustrates this process. In this subchapter examples of CAE driven projects at VCC are described.

Figure 15. Illustration of the process from the local CAE work to CAE verification, highlighting that the knowledge from the local CAE never reaches the Complete Vehicle Development department.

4.2.1 Example of a CAE Driven Project when Developing the Front Structure in SPA

In 2007, when the strategy work started for SPA, a team started to look at the front structure in a project called NGF (Next Generation Front). The aim was to study many alternative load path configurations to identify the “optimal” architecture. However, it was identified that the amount of possible load path combinations was large and it was not possible to develop CAD concept models of all. To find a good architecture using the traditional work process was not possible. Instead it was agreed that topology optimization based on simplified beam structure should be performed to find an optimal architecture out of all possible combination. The frame topology optimization method used was developed by Harald Hasselblad during his PhD studies between 1999-2005. The knowledge generated by this optimization study served as the base for a new front structure architecture that was new in many ways compared to the existing front. It was also interesting to notice that potential in the new architecture had been identified already in 1997 by skilled engineers but at that time it was not possible to realize because of compromises that had to be made with e.g. the packaging of the car and the knowledge was not transformed and secured in the organization. One could say that the topology optimization study performed around 2007 reinvented the front structure studied already 10 years earlier. But now it was developed by a systematic optimization driven process with the aim of developing knowledge.

In parallel to this project there was also a project concerning the rear flooring. Here, the classical process of VCC’s way of working was used. The result was not radically different than how the rear flooring was designed from the beginning. The result of this was a rear flooring that met the requirements but where no knowledge regarding alternative solutions were created. However, the knowledge built around the front structure can be reused when developing a new platform or when upgrading SPA, which can save resource in the future. In the front structure project, by applying a CAE driven approach, time, workforce and weight was reduced compared to performing a traditional product development process.

4.2.2 Example of a CAE Driven Project at VCC to Minimize the Impact on the Lower Leg of a Human in the Event of a Crash

Another example is a project performed at crash-safety regarding low speed crashes. Many calculations (about a hundred) had been conducted in regard to a low-speed crash and the impact it would have on the lower leg of a human being if a collision would happen. The tests were made by colliding with a model of a lower leg (just above the knee and all the way down to the foot) and then calculating on the different forces and then optimizing the front structure in order to minimize the impact on the human. The main question was in regard to the stiffness of the front structure. However, the team was stuck, different type of calculations had been made but no common solution was obvious.

At this stage, a systematic CAE driven approach was adopted. The team pinpointed what aspect that was of greatest interest to examine. The aspect of importance was to minimize the shear force and momentum in the knee which was affected by the stiffness of the front structure. In a systematic manner, different thickness (from unrealistically thin to unrealistically thick) of all the plastic components in the front structure was tested through a parametric study. Many different combinations were looped in a systematic manner (DoE). From the DoE the team could evaluate what parameter that correlated most with what response surface, and the stiffness profile of the front structure was given that would minimize the collision impact on the lower leg. Hence, in this project parameters were systematically pinpointed to describe the stiffness of the front structure. Knowledge around how the system behaved and how it should be designed was built. After this CAD engineers could evaluate the result from the project and incorporate this into their designs.

4.4 Identified Key Factors and Methods that would Enable VCC to Works CAE Driven Development in the Early Phase

In this chapter, key factors and methods are presented. Interviews have been held with employees experienced in the early phases at VCC. The key factors and methods are listed in alphabetical order. Thus, the key factors and methods are not graded by importance (see chapter 2.2.2).

By conducting seventeen interviews with employees at VCC, key factors have been identified that would enable VCC to have a CAE driven development. These key factors are shown in Table 5:

Table 5. Key factors identified by interviews at VCC that would enable a CAE driven development.

Key factors	**Details**
Balancing of the entire car	OCA could have dedicated employees for this purpose.
Central database for storage of models and reuse of knowledge	A central database where models can be update and reached by different departments and teams. This is also a way to store knowledge which can be reused in the future. There is also a request for someone who is responsible for what models that exist and what status they have.

Concept engineers	A roll that would have an overall perspective. The concept engineer would neither be a CAE engineer nor a CAD engineer. Conditions for having a concept engineer are simplified models, load cases, parametrization, and a holistic mindset. It would be important to encourage the concept engineer to question exciting designs and solutions. The concept engineer should be working with CAE methods and tools.
Culture	Through OCA (Optimization Culture Arena).
Dedicated strategy/concept team	Dedicated team, consisting of the concept engineers and representatives from departments involved in the early phases. Grouping is important to avoid “us and them”-behavior and NIHS. The grouping can either be physical or digital - as long as everyone knows what is happening and that joint work is possible. Important to create a mindset that implies that the there is one joint product that requires a collaborative work. This group must also keep a strategic mindset and stay updated with strategic changes and forecasts.
Dimensioning requirement	Detailed requirements are not necessary in the early phases, however the dimensioning requirements necessary for building the architecture are essential.
Educated employees	Employees with knowledge about methods useful in the early phases (parameterization, sensitivity analysis, topology optimization etc.) and corresponding tools e.g. SFE that allow parameterization of sheet metal. Employees with this knowledge are needed for working with the CAE driven tasks but they are also needed at each department in order to enable a swift transaction to CAD engineers to minimize knowledge and information loss.
Encourage Creativity	The generic architectures can e.g. be made for a SUV, cabriolet, sedan and a station wagon. These generic architectures can be used as a virtual laboratory where different technologies can be tested and knowledge can be built. Architectures from competing manufacturers could also be created in order to create an understanding about their concepts. This also stimulates a creative environment.
Focus team	This team would be temporary and the constellation would depend on the project. The size of the team would depend on the project, however the size is not the most vital aspect, the most vital aspect is expertise and experience. This team should be able to work with different solutions and understand the CAE methods used.
Integration between CAE engineers and CAD engineers	Together group these two engineers on a department level.

Design deliveries from the strategic studies	Responsibility for making sure that models and other strategic studies have a certain level. If there are no delivery there is no responsibility for assuring that models (or other strategic studies) have a certain level. This also enables access to historical data. Today there are set deliveries in the later phases, however in the early phases there is a need for set deliveries of a smaller scale.
Responsibility for models	Someone who is responsible for what models that exist and what status they have.
Simplified models	In order to be able to work with CAE in the early phases there needs to be an access to simple models, that is models with fewer elements. When models are too detailed the calculations are very time consuming when testing different models.

By conducting 17 interviews with employees, methods have been identified that would enable VCC to have a CAE driven development. The methods are different, but the primary aim for all of them are the same in regard to the purpose for why VCC would use them, namely to build knowledge and comparing different solutions. These methods are shown in Table 6:

Table 6. Methods identified by interviewees at VCC that would enable a CAE driven development.

Methods	Details
Design of experiments (DoE)	A method for defining the relationship between factors that have an impact on a process. The aim is to find out how to structure a process and its input to optimize the output.
Parametric studies	Parametrization of different solution is possible, these can then be compared to each other. It is possible to investigate the potential of different solutions and their scalability. For example, different attributes can be investigated and how they interact through a pareto-diagram for different solutions.
Response Surface	Relates output variables (the so-called response) to design parameters.
Sensitivity analysis	Question addressed could be: - How do systems behave when requirements are varied? - What loads are dimensioning?
Topology optimization	Load paths and material distributions can amongst other things be investigated.

5 Case Company Studies

Five benchmark studies have been conducted in order to gain insight about how other companies work with CAE driven development and their thoughts about the concept. The case studies are presented below. First, the companies' take on CAE driven development, together with their current way of working, will be presented. Second, key factors and methods that supports CAE driven development (according to the interviewed representative) will be visualized in two different tables. Case studies have been made at CEVT, GKN Aerospace, Scania, Combitech, and Opel, the chapters are arrange in this order.

5.1 CEVT

In this case study Albert West was interviewed. Albert West works as a CAE director at CEVT. Albert West, states that the product development process at CEVT is similar to VCC's product development process since it, to some degree, is a heritage from VCC. A difference from VCC, in the product development process, is that CEVT does not use as developed templates (concept templates, engineering templates and part templates) as VCC does. The reason for this is that CEVT has not received templates from VCC. However, Albert states that he is not sure if CEVT would use the templates if they would have the chance to get them, because of the risk that templates could lead to an inflexible way of working.

CAE driven development is a term that is perceived differently depending on who you ask. When talking to Albert West he highlights this problem. He mentions that during the last decade, automotive companies have proudly used this term, without knowing the meaning of it. However, most companies have CAE supported product development. That is, most companies use CAE to analyze and find what is wrong with an already given construction. Also, even though CAE driven development is often mentioned as something to strive for, Albert says that CAE driven development also could be problematic. He mentions a competing automotive manufacturer as an example. This automotive manufacturer was early with CAE driven development but they experienced problems in the development. What they did was that they let CAE engineers develop a construction early in the product development phase. Simultaneously, construction engineers developed a construction parallel to the CAE engineers. The concepts developed by the CAE teams was not feasible when converting the result to a construction in CAD, where one reason for this was that manufacturing constraints forced big changes late in the development, but also that they experienced the Not Invented Here Syndrome (NIHS). The NIHS is a name for the tendency to neglect good external solutions (external in this case since it came from another department). Albert West mentions that CAE developers are usually skilled at developing with attributes in mind, they know NVH, crash, durability etc., but they do not know construction. The opposite is the case for construction engineers. When asked about if integration of CAD and CAE disciplines could be a possible solution to this problem, Albert states that it is hard to integrate whole teams with each other because of the size of the teams. However, Albert states that part of this problem is the integration of CAE and CAD disciplines but that the biggest part is the difference in competence between CAE engineers and construction engineers.

Albert West states that a pure CAE driven development is not anything he believes strongly in. Rather, he emphasizes the ability to support the development in the early phases as a complete vehicle is too complex for a pure CAE driven process. Limited sub-systems could, however, be developed CAE driven. By CAE driven in this case, Albert West means the phase of the product development process where there is no CAD design. Moreover, most vital in the strategy phase is to understand the pros and cons with different solutions.

One limitation to CAE driven development is that all components are not developed in-house. The effect of this is that even though components are developed using CAE tools, and with the most optimal structure, manufacturers might not be able to produce these certain designs. Furthermore, Albert West explains that a problem is that automotive companies often select suppliers by price which means that even though development has been done to improve a component, the supplier might not be able to produce it. Also, for a supplier to keep the price levels low and be competitive in the automotive industry, they need to utilize investments made in the past, and cannot build a new factory or create a new process for every optimized solution. However, the vehicle body (top hat) is one part of the car which is produced in-house and could therefore be a possible target for early CAE driven development.

Another problem with CAE driven development as Albert West sees it is the software tools that exist. There are CAE tools that can take manufacturing constraint into consideration when calculating and optimizing casted structures, but when calculating and optimizing sheet metal, CAE tools cannot handle these constraints in an effective way. Hence, topology optimization may many times only be used for inspiration. Moreover, regarding optimization Albert West states that in the early phases of the product development process different type of optimization can be made, however only topology optimization can be conducted without a basic construction - only a design space is needed. In addition, he states that out of the different optimization methods that are possible in the early phases, topology optimization is the one method that brings greatest value to the development at this stage. However, with the new way of working at CEVT - with parametric geometries - there is no focus on what type of optimization that should be used, but on investigating as many different solutions as possible during a specified time. In reality, the creative space is rather limited because of packing-space together with other already set constraints. Hence, the work in the early phases is more about finding the best compromise using a matrix of different solutions and to generate and evaluate as many of these solutions as possible (through e.g. DoE), rather than numerically optimize a concept.

5.1.1 The Development of the CMA Platform

The CMA platform was developed through a collaboration between VCC and CEVT. The project was initiated at VCC but when CEVT was founded development and the initiating team was moved to CEVT to develop the CMA platform. Even though most development has been done by CEVT, some support has been given by VCC regarding help with CAE calculation. Albert mentions that the development of the platform was not CAE driven. As VCC did with the SPA platform, the platform was first constructed in CAD and then CAE was used more as a support tool to improve the construction. However, to some extent the development might have been more CAE inspired since the company (at that time) consisted of 10 percent CAE engineers, which is higher than industry average.

5.1.2 New Initiative at CEVT Regarding CAE Driven Development

Furthermore, CEVT has an ongoing project with an aim to improve their CAE driven product development, and their integration between CAE engineers and construction engineers. The proposed solution is a small focus team (see Figure 16), in the strategy phase of the product development process. The team consist of one construction engineer (i.e. CAD engineer) from body & closure and one CAE engineer. The construction engineer and the CAE engineer will work with a software tool called SFE concept, a tool that supports CEVT when using parametric design when designing the car body. These two engineers will then be located with a team from packaging during the strategy phase of the product development. Albert highlights the importance of having engineers from these different disciplines, working together, to develop a car that has influences from more than one discipline and to avoid the NIHS. The reason they chose a construction engineer from body & closure was because CEVT saw improvement potential in this area, which they learnt from developing the CMA platform. Also, since the car body is developed and produced in-house and constraints from suppliers does not need to be taken into consideration.

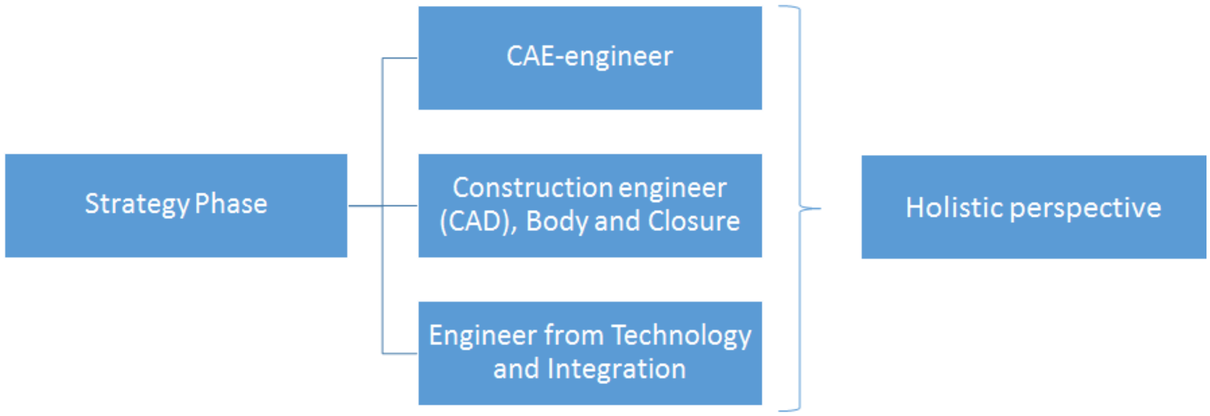

Figure 16. A small focus team will work in the early phases at CEVT to support a more CAE driven development.

5.1.3 Key Takeaways from CEVT

CEVT does not use as developed templates as VCC because of the risk of inflexible work. Moreover, there is an issue with competence difference between CAE-engineers and CAD-engineers which makes knowledge and data transition more difficult. A solution to this could be better integration, however it is difficult to integrate whole teams, mending the competence gap would be a better solution.

Furthermore, suppliers may not be able to produce the most optimal solution that has been designed, hence systems produced in-house may be easier to target for early CAE-driven development. There is a new way of working at CEVT, and that is working with parametric geometries. By working like this the focus is not on what type of optimization that should be used, but on investigating as many different solution as possible during a specified time in the early phases. However, the packaging-space and other constraints are limitations to the creativity when considering different solutions.

Pure CAE-driven development is not the focus, more importantly is the ability to support the development in the early phases. The most vital in the strategy phase is to understand the pros and cons with different solution alternatives. CEVT have introduced a small team in the early phases consisting of a CAE-engineer and a CAD-engineer that sit together with the packaging team, this to minimize the risk of NIHS and to get a more holistic development perspective.

5.1.3 Identified Key Factors and Methods that would Enable a CAE Driven Development in the Early Phase

Below are the identified key factors and methods which according to the representative at CEVT are important to enable a CAE driven development approach. The key factors and methods are listed in alphabetical order. Thus, the key factors and methods are not graded by importance (see chapter 2.2.2).

Table 7. Key factors identified by the representative at CEVT, which would enable a CAE driven development.

Key Factors	**Details**
Central database for storage of models and reuse of knowledge	This is not a key factor but will make the enabling of CAE driven development easier.
Concept engineer	These engineers should make out the concept team and be experts with in their tasks. This is a role of its own and not e.g. pure CAE engineers.
Concept team	The concept team should work with the layout and the balance of the car. CAE should support their work.
Requirements which are broken down	All complete vehicle requirements which are necessary for making a specific construction need to be broken down, e.g. for a specific system. If requirements are broken down then everything else will proceed much smoothly.
Small focus team	Put together based on the magnitude of the project to create a holistic view working with e.g. parametric studies. This minimizes the risk of NIHS.

Methods that would enable a CAE driven development are listed below in Table 8.

Table 8. Methods that supports CAE driven development according to the representative at CEVT.

Methods	**Details**
Design of experiments (DoE)	The most important method in the strategy phase in order to understand a design and its development possibilities/robustness.
Parametric studies	Not as important as DoE in the very earliest phase.
Structural optimization (topology optimization earliest)	Not as important as DoE in the very earliest phase and can mainly be used for inspiration.

5.2 GKN Aerospace

In this case study Phil Johanson (PhD) was interviewed. Phil has work at GKN Aerospace (GKN) since 2001 and is the technology lead for multidisciplinary design optimization.

In the early product development process, some basic and guiding strategies are decided at GKN, Phil Johanson explains. For example, what products to bid for in a new engine program or if additive manufacturing should be used. Next a simple prototype is made to make sure that the correct decisions have been made. The next step of the strategy phase at GKN is to work with design spaces and set-based design development. The design space can be divided into two spaces: a requirement space, and a solution space. The closer the product development process gets to freezing the design the narrower the requirement space gets and hence also the solutions space - as the solutions space must fit into the requirement space. Furthermore, the strategical work together with the set-based design is done by focusing on three aspects - aerodynamics performance, mechanical functions and producibility. When developing a new product, it is within the space where all these three parameters overlap that optimization is done (see Figure 17).

Figure 17. The three aspects that need to be balanced in the product development process at GKN.

Instead of deciding on a design by a point-based approach, several solutions are examined and evaluated through the set-based design development. A design is then decided upon by excluding less feasible solutions. In the beginning of a project there is a high degree of uncertainty and several ideas on different solutions. During the development process the project team learn about the solutions, how changes in parameters affect the solutions and what affects different attributes such as weight, cost, environment, lifetime etc. Most of the analysis that is done is not made to find an optimal design, but to learn what affects what and how. However, at some point a decision must be made, many times this is influenced by when decisions about suppliers have to be made. Hence it is important to gather as much knowledge as possible and learn as much as possible before picking a solution and freezing a design to be sure that it is feasible (see Figure 18).

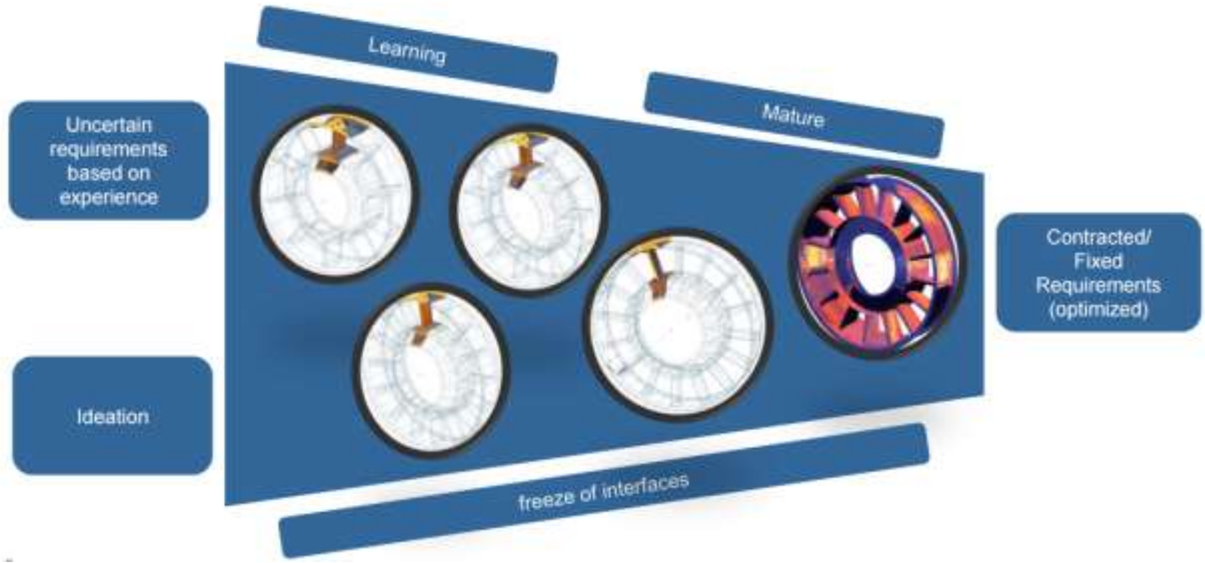

Figure 18. The set-based approach at GKN. It starts with ideation and requirements based on experience. The further the process goes the more has been learned, and as the design matures the interface is frozen. At the end of the process the design is optimized in regard to set parameters. This figure is taken from a presentation made by Phil Johanson at GKN.

GKN only develops parts of the engine (except RM12 for the Gripen fighter aircraft), hence there is the need to interact with other companies. In these projects, response surfaces can be used, Phil Johanson states. A response surface is statistical matrix of different solutions and the effect of parametric changes within the design space. When evaluating a response surface calculations can be made about what to investigate next, what parameters to keep, what to change and what to add. It is also interesting to see what parameters that do not affect the result at all. This can be repeated until all questions regarding a design are answered. The input to the response surface is data from different analysis. To create knowledge about the different solutions, data must be understandable and visualized. Different graphs and plots can be used for visualization, for example pareto-graphs, parallel diagrams and matrix. To understand the graphs, engineers need to be taught how to read them to make proper decisions. This is something GKN works with.

As stated in the beginning of this subchapter the set-based design development starts at GKN after basic and guiding strategies have been decided. Below is a description of the workflow that takes place just after these strategies have been decided until solution evaluation (visualized in Figure 19).

1. The first step after having set up basic and guiding strategies at GKN is to define problems and what needs to be explored in order to reach defined strategies and needs.
2. The second step is to make a set-up study. In the set-up study processes for different disciplines are described. This is done by first defining the product. Then creating a very basic CAD model. Next mesh, stress and fatigue, thermodynamics, aerodynamics and producibility is considered. The focus here is to numerically define as much as possible.

3. The third step is creating context and preparing for analysis. Create context means creating context through automated analysis models. These models can look very differently depending on the objectives of the project. Often there are different models for different aspects, for example one for strength, one for aerodynamics, one for cost, one for welding etc. What parameters that are going to be included in the analysis depends on needs and abilities within GKN.
4. When the preparations are done, the analysis can be performed, which is step four. At GKN, a thermic analysis is performed first, then durability, then lifetime and aerodynamics. Here, very simple flexible CAD templates are used.
5. When all analysis is completed they are compiled and different type of response surface are created and evaluation is made, which is step five. Depending on what the response surface shows it gives guidance about in what direction to optimize. For example, if weight is a critical parameter, the response surface shows what solutions that could work for a specific weight range and those solutions should be optimized further, which leads the process back to step two.
6. The last step is to make sure that the solution fits into the solution space defined by the three aspects aerodynamics performance, mechanical functions and producibility.

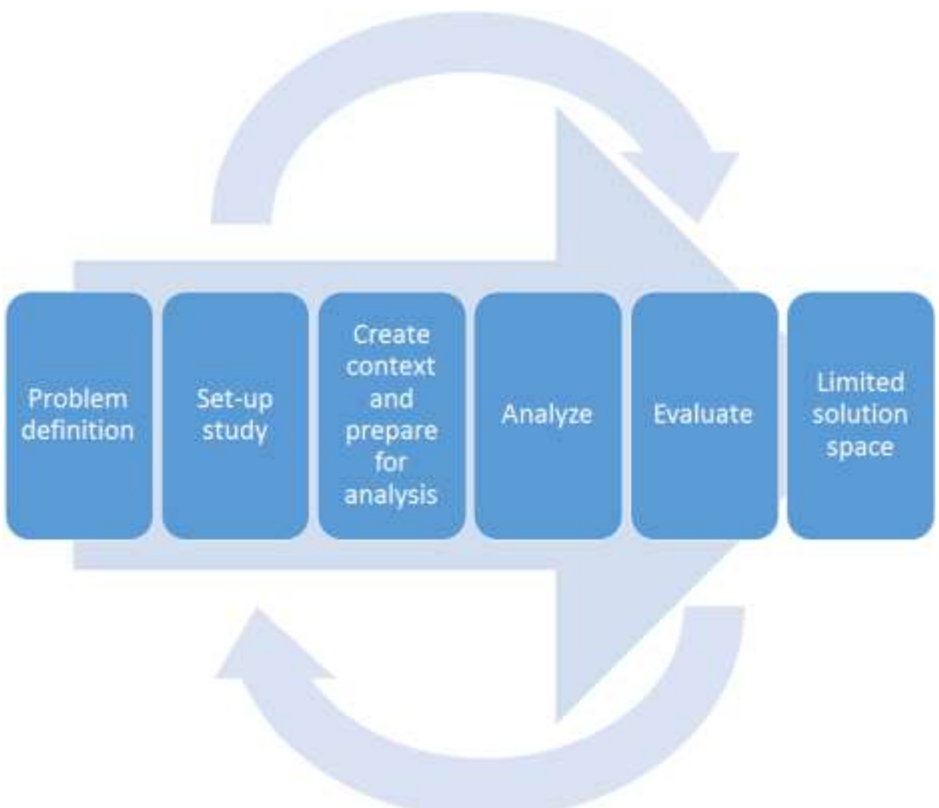

Figure 19. The workflow at GKN. This workflow starts after the basic and guiding strategies have been set and ends with solution evaluation.

Regarding work roles in the earliest phase of product development at GKN no detailed CAD work is involved because of the integrated tools. The focus is almost entirely on CAE, but there are employees that have both CAE and CAD skills that are involved. First when a design is frozen through the set-based approach, detailed design engineers are involved. The focus of the detailed design is more on validation and contact with customers and suppliers to make sure that the design will meet expectations and is producible. A problem for GKN is that there are very few CAD engineers that understand CAE and vice versa. Hence many times there is the need of cross-functional meeting for resolving issues that are not always so effective. Hence, the wish is for CAE engineers to learn some of the aspects of CAD (that influence their specific work) and for CAD engineers to learn some CAE (that influence their specific work). What is interesting is that GKN has started to investigate the opportunity of involving suppliers in the analysis models to create even more knowledge early in the product development phase.

What enables GKN to work set-based are statistical tools and the possibility to vary CAD geometries, together this creates the foundation of creating response surfaces. For GKN, it is important to work set-based for many reasons, but one of the most important reasons is that customers can change the thermal request for the product late in the product development process. This results in costly and timely redesigns. However, with a set-based approach this can be mended a bit as there is no need to start from scratch when redesigning. Moreover, GKN works a lot with integrating different tools for CAE and CAD to automatize the analysis process. Having an integrated tool for both CAE and CAD of course has its limitations because it will with today's technology not be as good as a CAD specific or a CAE specific tool. However, Phil Johanson continues, in the early phases there is no need of having too specific tools, however having integrated tools gives the opportunity to automate the analysis, which is crucial for the set-based design development to be time-efficient.

Lastly, Phil Johanson explains that some topology optimization is made in the early phases of product development at GKN to understand mechanical attributes. However, optimization is not as vital for GKN in this phase as for VCC. This, because the load bearing parts at GKN's product are mostly connected to aerodynamics. On the other hand, producibility is one of the most cost driving aspects at GKN and hence these aspects are important in the early phases.

5.2.1 Key Takeaways from GKN

In the strategy phase at GKN a design space is set, this is followed by working with a set-based approach. The set-based design development makes it possible to learn how different parameters affects a solution. Most analysis at GKN is not made to find the optimal design, but to learn what affects what and how. Many times, the decision about which supplier to use affect when the solution must be frozen, and GKN are investigating the opportunity of involving suppliers in the analysis models to create more knowledge in the early phases. Moreover, when working set-based, the data is made understandable and visible through different graphs, engineers must be trained on how to read them and make decisions based on them.

In the early phases at GKN the focus is almost entirely on CAE. However, some employees have both CAE and CAD skills, these are also involved in the early phases. The integrated tools that GKN use gives an opportunity to automate the set-based analysis. What further enables GKN to work set-based, are statistical tools and the possibility to vary CAD geometries. Costly and time consuming redesign can be minimized with a set-based design. Lastly, the focus in the early phases should be on cost driving aspects.

5.2.2 Identified Key Factors and Methods that would Enable a CAE Driven Development in the Early Phase

Below are the identified key factors and methods which according to the representative at GKN Aerospace are important to enable a CAE driven development approach. The key factors and methods are listed in alphabetical order. Thus, the key factors and methods are not graded by importance (see chapter 2.2.2).

Table 9. Key factors identified by the representative at GKN Aerospace, which would enable a CAE driven development.

Key Factors	Details
Educated employees	Employees that can understand response surfaces and graphs created in the set-based development. They should be able to make decisions based on them.
Integrated CAE- and CAD tool	Used to automatize the analysis process, the integrated tool is good to work with in the early phases as high accuracy is not needed and the analysis is made much easier. Not a key factor but makes the enabling of CAE driven development easier.
Simplified models	This is needed to enable the evaluation of alternative solutions and not lock the development to one design early on (a set-based approach). This, to not overlook a good solution, but also to not lack alternative solutions when requirements are changed. When requirements are changed, the chosen solution may not be suitable anymore.

Methods that would enable a CAE driven development are listed below in Table 10.

Table 10. Methods that supports CAE driven development according to the representative at GKN Aerospace.

Methods	**Details**
Design of experiments (DoE)	A combination of methods is preferred. Phil proposes DoE with parametric studies and response surfaces. This enables optimization between several disciplines, it also enables a set-based approach.
Parametric studies	See DoE.
Response surface	See DoE.
Topology optimization	This is suitable in the early phases for to create an understanding for how load paths can/should be placed.

5.3 Scania

One interview was conducted with two representatives at Scania via telephone where the representatives were Karl Jakobsson, Senior Technical Advisor for product simulations and Magnus Tapper, Technical Manager, responsible for structural optimization at Scania R&D.

The product development at Scania differs from the automotive product development. As described earlier (in literature and by explaining the product development at VCC), product development in the automotive industry is based on the development of a platform, from where different projects run corresponding to different car models, using the same platform. However, when developing trucks, new models are usually based on customer requests and from benchmark studies on competitors. Furthermore, new regulations from governments or other regulations that require the company to update their existing model, or that the company have developed a new technology they want to implement, also drives the development to some extent. Furthermore, compared to when developing cars, the platform is not redesigned and reconstructed when a new model line is released. Instead, parts of the platform, where an update is required or where Scania have made technological progress, are updated.

According to the representatives at Scania, the way Scania use CAE driven development has changed during the last decade. Before, CAE driven development was used as a method to complement testing and to verify existing designs/constructions. Today, CAE driven development is, to some extent, used as a method to actually develop new solutions, through simulation and optimization, by inspiring construction engineers when designing. Also, CAE driven development is used to build knowledge around designs and alternative solutions to better understand what the outcome will be and what options exist. Other benefits that the interviewees consider with CAE driven development is shorter development time and less problems in the later phases of the product development. The risk that components does not fit with each other and that the quality of the components is not sufficient, is lowered.

Today Scania use CAE driven development in the early phases of the product development. However, the use of simulation and optimizations in the early phases are only used to some extent. Initiatives that include this way of working are driven bottom up, i.e. initiatives are taken by the employees. Both representatives request that the initiative should come from management, thus a top down approach. When the requirements, or key factors, of having a CAE driven product development is discussed with the representative from Scania, different key factors are mentioned:

- Management need to request a CAE driven product development process. A big factor for CAE driven product development is that management create processes and roles that makes it mandatory to use CAE driven development where possible. Also, management need to secure resources for these activities.
- When implementing CAE driven development, do not change the whole organization at once. Start by creating small cross-functional teams which will lead a trial project before implementing CAE driven development in the whole organization.
- There need to exist tools where knowledge can be stored and reused.
- Using integrating software tools (for integration between CAE and CAD) can be good in order to lower the gap between these departments and to create a better understanding of each other. Also, tools that do not have CAD geometry as a base, e.g. SFE Concept, is preferred to use in the early phases of product development.

Even though the representatives at Scania states that the area where they can improve their way of working with CAE and optimization is in the strategy phase, projects have been done where CAE driven development have been used in the early phases of product development. When developing the cabin in their new truck, the time pressure forced Scania to work with simulation and optimization in the early phases of the development. The representative from Scania states that it would not have been possible to develop the new cabin as fast as they did if they had not used this approach.

5.3.1 Key Takeaways from Scania

Management need to request a CAE driven development, they should also create processes and roles that will standardize the CAE work as well as secure resources for these activities. When changing to a CAE driven development, do not change the entire organization at once. A suggestion is to start by creating a small cross-functional team as a pilot-project. When working CAE driven knowledge is created, hence a tool where knowledge can be stored and reused is important. A suggestion is also to use an integrated tool for CAE and CAD in the early phases to mend the gap between the disciplines and to create a better understanding of each other's work.

5.3.2 Identified Key Factors and Methods that would Enable a CAE Driven Development in the Early Phase

Below are the identified key factors and methods which according to the representatives at Scania are important to enable a CAE driven development approach. The key factors and methods are listed in alphabetical order. Thus, the key factors and methods are not graded by importance (see chapter 2.2.2).

Table 11. Key factors identified by the representatives at Scania, which would enable a CAE driven development.

Key factors	Details
Central database for storage of models and reuse of knowledge	Tools must exist where data and knowledge can be stored and reused.
Culture	Create a culture that supports CAE driven development. Courage is also important when transforming a traditional product development to a CAE driven product development.
Integration between CAD and CAE tools	Software tools that can lower the gap between CAE and CAD engineers, and create a better understanding of each other's results.
Management involvement	A top down approach. Initiatives must come from management, who should create processes and roles that makes it a part of the development and not only something that comes via initiatives from employees.
Small expert team (focus team)	Start by creating small cross-functional teams which will lead a trial project before implementing CAE driven development in the whole organization. Moreover, by doing this you can show the benefits from using a CAE driven approach, which creates trust in the organization.
Tools that do not have CAD geometry as a base	A CAE tool that can work with CAD geometries as an input and not only CAE models, e.g. SFE-Concept.

Methods that would enable a CAE driven development are listed below in Table 12.

Tabell 12. Methods that supports a CAE driven development according to the representatives at Scania.

Methods	**Details**
Parametric studies	Most important in the early phases as it enables sensitivity analysis and optimization.
Sensitivity analysis	See Parametric studies.
Topologi Optimization	Topology optimization can be performed earliest.

5.4 Combitech

In this case study Tobias Svensson at Combitech was interview. Tobias has approximately 25 years of experience in the automotive industry within the CAE area. Before starting at Combitech in 2012, Tobias worked at SAAB Automobile with product development as responsible for the CAE department (safety, NVH, durability analyses etc.) within the scope of CAE. Tobias explains that CAE driven development from his perspective is that decisions are based on calculations using CAE tools. The key is to be active in the early phases of the product development process where dimensioning systems have not reached a detailed design yet. Tobias takes the car body as an example where different options can be simulated and evaluated by the use of CAE tools before a final decision is taken.

5.4.1 Lessons Learned from Tobias Experience at SAAB Automobile

When Tobias worked at SAAB Automobile they used a small team in the early stages of the product development process. This team consisted of persons from different departments (Tobias mentions body, interior, chassis, styling and CAE as some of the active participants) and worked as a focus group in the early stages. One part of this way of grouping was that SAAB Automobile chose experienced people from these different departments and had them work together, in the same location. In one project that SAAB Automobile was participant of, together with FIAT, they even relocated this team to another location outside the SAAB Automobile office. The advantage of working like this was that decisions could be taken faster. Furthermore, Tobias stresses that this group should not have to double check with their corresponding department when taking decisions since one of the reasons with this way of organizing is that different options can be tested faster without too much bureaucracy, and that new ideas and solutions are more likely to appear without the groupthink that might appear when consulting with the home department.

When working in the early phases of product development different approaches can be used to access the data necessary for simulations and optimizations. One approach is to reuse an old construction (i.e. using the former car models and making changes to those), whereas another approach could be to request CAD data that match good enough to build new models. It is important that the overall dimensions and specifications, (vehicle size, weight, engine type, front or rear wheel drive etc.) do not change, because if they change, simulations and calculations done on new concepts and solutions could go to waste.

From a software perspective, the software tools used in the early phases of product development are not as important as tight integration between the different departments. Moreover, in the early phases of product development it is important that there are gates where all necessary data are collected and when reaching this gate, concepts and solutions are analyzed. Tobias states that the data that the CAE engineers retrieve from construction (CAD data) must be accurate when reaching these gates, since this will save resources. Tobias takes an example from his time at SAAB automobile. A project was done in collaboration with Opel where five models of the car body was developed. The time it took for this development was 440 hours and the reason for this was that the CAD data was 80% accurate. However, 2011, still at SAAB automobile, a similar project was done. The time for development this time was 140 hours, and the only reason for that was that the data retrieved from construction was 100% accurate. Tobias says that this show that, by doing right from the beginning, time and resources can be saved. However, it is important that there are not too many gates since this will risk to lower the creativity and removing the “fuzzy” of the front end of the product development. In the early phases of product development, there is not always time, or even a possibility, to assess all parts of the vehicle. However, by focusing on parts of the car where the manufacturer sees improvement possibilities or where the manufacturer know that they have had problems before, resources can be focused on areas which requires it the most.

Management's role is also an important part when looking to transform the product development to be more CAE driven. Management need to inform and make it clear that all departments work in the early phases so that the right assumptions can be made, and furthermore, so that simulations performed are reliable. As mentioned earlier, having gates in the early phases of product development, where necessary data is collected, is important. At these gates, management needs to make sure data is evaluated and that CAE calculations are done. However, between these gates, management must also give freedom to the developers in order to keep creativity flowing.

According to Tobias it is crucial to use CAE in developing vehicles, as well in the early phases as the later. When asked about using CAE in early phases in order to gain weight reduction, Tobias says that he thinks that there is an over-confidence on how big of an impact CAE in early phases will have on weight reductions if only the car body is considered. However, he adds that if CAE driven development is used on all systems and components, (chassis, interior, seats etc) and by suppliers for purchased components, the total weight reduction could be considerable.

5.4.2 Key Takeaways from Combitech

It is important to be active in the early phases in order to be able to simulate and evaluate (through CAE) before a final decision about a solution is taken. At SAAB Automobile, a small focus team with experienced employees from different departments worked together in the early stages of the product development process. This enables fast decisions with a holistic project perspective. Tight integration between departments is important in the early phases. Moreover, gates are important in the early phases of product development in order to collect data, in addition concepts and solution can be analyzed in these gates.

The management has a vital role when introducing a more CAE driven development. They need to involve all departments in the early phases in order to be able to make the correct assumptions and reliable solutions. They also need to check the gates and make sure that CAE has been performed. Lastly, CAE driven development should not only be implemented in-house (systems and components) but also on supplier level to reach full effect.

5.4.3 Identified Key Factors and Methods that would Enable a CAE Driven Development in the Early Phases

Below are the identified key factors and methods which according to the representative at Combitech are important to enable a CAE driven development approach. The key factors and methods are listed in alphabetical order. Thus, the key factors and methods are not graded by importance (see chapter 2.2.2).

Table 13. Key factors identified by the representative at Combitech, which would enable a CAE driven development.

Key factors	Details
Central database for storage of models and reuse of knowledge	Enable data-exchange between different models in a simple manner.
Creativity	Creativity is important in the early phases to develop new solutions.
Dimensioning requirement	Requirements must be set so that valid work can be done and to minimize the risk of doing unnecessary work. Requirements that need to have been set are e.g. size of the car, weight, engine alternatives, battery size, distance to the ground etc.
Educated employees	Employees with knowledge about CAE methods e.g. parameterization, sensitivity analysis, topology optimization etc. and corresponding tools e.g. SFE Concept that allow parameterization of sheet metal. This, together with talented CAD engineers that quickly can produce CAD models that can be used for CAE.
Focus Team	A team with independent experts from different departments that can make decisions fast and create an integration between departments.
Integration between CAE and CAD engineers	Integration between CAE and CAD is important. However, it is important that other departments (styling, packaging, electric department etc.) are involved as well in the early phases of product development.
Management involvement	Management needs to involve all departments in the early phases to enable correct assumptions and reliable solutions. The management should also initiate and make sure that CAE is used through e.g. gates. The virtual gates can also be checked from time to time in order to gather different ideas around a common base.
Simplified models	Enables a fast CAE work, e.g. optimization, and testing of different ideas. Having a simple model enables testing of many ideas in a short time. Important to remember is not to make the models too simple. This, because the result needs to be relevant to the end product (which may differ from a too simplistic model), and because it takes time to update the result to more detailed models it will be time consuming if the model is too simple.

Methods that would enable a CAE driven development are listed below in Table 14.

Table 14. Methods that supports CAE driven development according the representative at Combitech.

Methods	**Details**
Design of experiments (DOE)	Suitable, but first in the concept phase.
Parametric studies	Suitable, but first in the concept phase.
Response Surface	Can be made based on the parametric studies and DoE.
Sensitivity analysis	Sensitivity analysis should be made in the early phases of product development to avoid that the solution developed is not just an optimal solution, it should also be feasible if changes are made later in the development.
Topology Optimization	The most important method in the early phases as there still is a large freedom to impact the final product.

5.5 Opel

Two interviews were conducted with representatives from Opel. Both interviews were conducted with Dr. Herman Becker, Director Vehicle CAE and Hans Bartling who is Manager CAE for Strategy and Operations at Opel where Hans is involved with the process links between CAE and the overall vehicle development, a role which is cross-functional where he reports for all disciplines working on the development.

5.5.1 The Opel Virtual Vehicle Development

The virtual development process (see Figure 20), which is organized by the central CAE department, is running alongside the vehicle development. In the virtual development, gates exist where people from the central CAE department get together for four to five hours, and complete the status of the vehicle. These gates are called virtual vehicle assessments. Roughly eight weeks prior to that, Opel have synchronization point. This is where all data, mainly focused on CAD data and geometry data, is stored in Opel’s DMU (digital mock-up), and based on this Opel build models for performance simulations, crash simulations, structural simulations and manufacturing simulations as well as complete vehicle integration so that packaging work can be done. The synchronization points are not only about freezing data, it is also about going through it together with the departments responsible for the data to agree that this is the data Opel want to use in the further development. From the beginning of the development, starting in the initial assessment, Opel uses data maturity levels to show the organization what data is needed in different stages of the development and how mature that data needs to be (classified as distinct maturity scale). Having a central CAE department makes it easier to give a harmonized status to the organization, but it is also important for the optimization in the early phases. Below is the generic process for Opel's virtual vehicle development. The first three phases are the phases that corresponds to the early phases of product development, which is the phase researched in this thesis.

The initial phase is where Opel gets an understanding of architecture concepts, to understand what is feasible and what is not feasible. The architecture phase is where load path strategies are defined. Furthermore, the lower architecture is defined in this phase (not completed). It is important in this phase to look over the requirements which are enabling the architecture to fulfill the complete bandwidth, which is used with all different kind of vehicles developed on the platform. To understand what is inside and outside the scope is important since it is hard to adjust to larger changes later in the development, both because it is costly but also because it is time consuming. The concept phase is where the new styling is put into a virtual vehicle. During this phase, the number of concepts proposals is reduced to one final proposal.

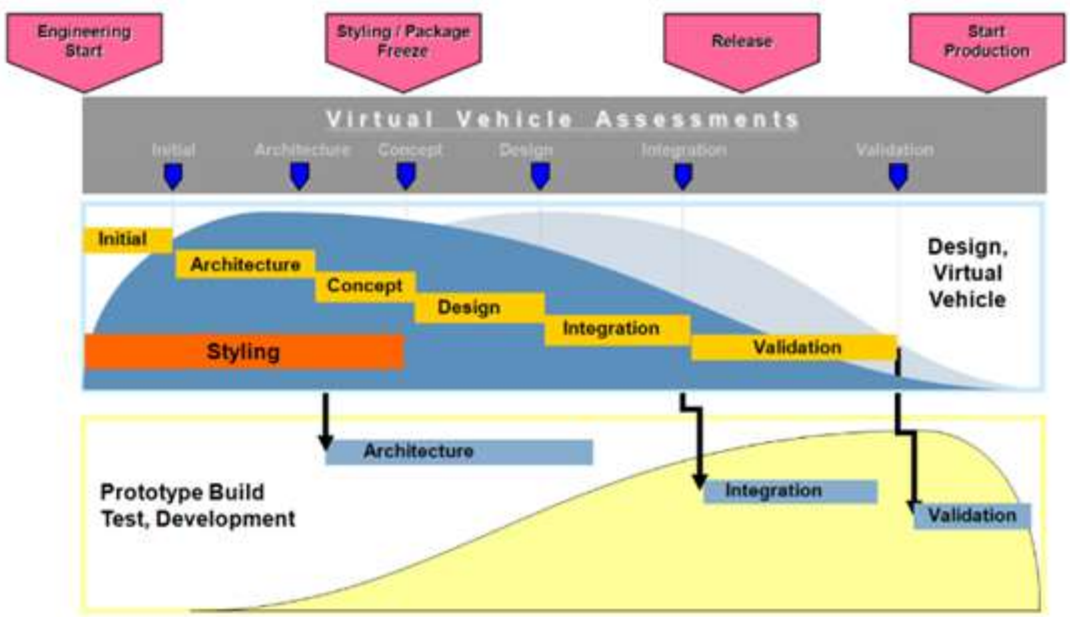

Figure 20. A generic process for Opel's virtual vehicle development. The figure is taken from a presentation made by the representatives at Opel.

Herman argues that it is important to have good knowledge about the type of vehicle and which market that is going to be targeted with the platform. Experience have shown that if this is not assessed and the platform is based on an incomplete bandwidth (i.e. the scope of the platform is not evaluated enough), problems will occur when additional cars outside the bandwidth is developed on the same platform. Furthermore, theoretically all the requirements can be put into the architecture, to satisfy everything, but this tends to make the architecture heavy, which is why only dimensioning requirements is considered in the early phases.

When developing the architecture, Opel try to develop alternative solutions to fit the scope of different markets if they decide to put the vehicle on a market with different requirements. If they have not done this they add an additional architecture development phase in the beginning of such a project, to make the scope of the platform suitable for that specific market. This additional architecture development phase build on the first architecture development and is only there to adjust for the new market (see Figure 21).

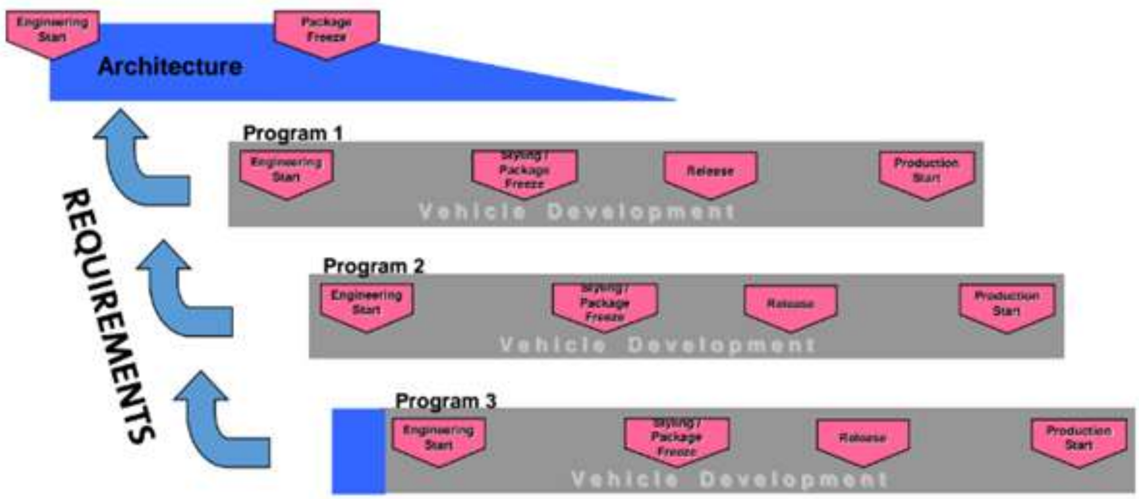

Figure 21. The architecture development at Opel and the development of architectures suitable for different markets. The figure is taken from a presentation made by the representatives at Opel.

Before any kind of optimization is done Opel typically takes old vehicle models and apply them to new load cases. This is to see what needs to be improved in the new vehicle models. As mentioned earlier, it is important to know your requirements and upcoming requirements. For example, new crash requirements are usually known years in advance, why it is important to simulate these load cases early in the development. Topology optimization is used in the early phases to build initial models already in the end of the initial phase. Before Opel is able to do topology optimizations, stability on the package is needed, thus, topology optimization is used as early as possible and preferably before CAD engineers start their design work. Hans highlights the importance of having both manufacturing and design engineers in the loop while doing this.

"The key for optimization in the early phases is CAE driven design, where design proposals are inspired by calculations."

A decade ago there were a lot of best practices where CAD engineers took the best practice solution, designed a component or a system, and then used simulations to evaluate it. Today, it is the other way around Herman explains. Via the virtual vehicle assessment, CAE engineers develops an optimal design proposal which is then converted into a CAD design. This is why it is so important with integration between different disciplines. Not only for practical reasons but also for psychological reasons. That is, to avoid the NIHS, integration is key. When developing the vehicle in this way it is important to have a loop prior to when the CAD engineers take over the design development where solutions are evaluated to give the organization confidence in the developed solution. Experience during the last years have showed that CAE driven design with optimizations in the early phases of vehicle development, have been generating solutions that look different from the "best practice designs" and where big weight reductions have been made possible. This is of course good for Opel because of the new CO2 regulations coming up. Opel Astra is one example where Opel have managed to reduce the weight with 200kg between the old model and the new model, keeping the same requirements.

Integration between different departments (Herman mentions CAE, styling and packaging) is, as earlier mentioned, a key factor for a CAE driven development. Working in small teams in the early phase, where you locate the involved employees together, is the best option since it is hard to integrate a whole organization and everybody does not need to be involved in the early phases of product development. The team size is depending on the scope of the project. When developing a completely new platform a bigger team is required than when just changing a part of the platform. Also, in organizations where styling has a tradition of having the final word on design it is a lot easier to optimize new solutions so that it fits into the perspective of the styling department. Solutions tend to be accepted more often in these cases. Therefore, to enable a CAE driven development it is important to show reliable results to earn the trust from both top management and the styling management. Also, by showing that the CAE department can produce reliable results top management will understand that a CAE driven development can create both cost savings and time savings in the development.

5.5.2 Key Takeaways from Opel

In the early phases integration between different departments is important for Opel. A team is created where employees from different departments are grouped. The size of the team and the participants depends on the project. Furthermore, at Opel a virtual development process with synchronization points (organized by the CAE department) runs in parallel with the platform/vehicle development. Opel works with different solutions until the concept phase where a final solution is proposed. Working with different solutions is not only about building knowledge about their behavior but also to make sure that the final solution will fit all markets.

Before any optimization is done, Opel typically takes old vehicle models and apply them to new load cases to understand what needs to be improved. Moreover, only the dimensioning requirements are needed in the early phases to go forward with the development. To perform topology optimization, only the stability of the packaging is needed. Furthermore, the CAE engineers develops an optimal design proposal which then is converted to CAD. This makes integration between the two types of engineers essential to make the process smoother but also to avoid the NIHS. Before the transition from CAE to CAD there is a loop where the solution is evaluated to give the organization confidence that the new solution works. Lastly, it is important to gain the trust from management and styling management.

5.5.3 Identified Key Factors and Methods that would Enable a CAE Driven Development in the Early Phases

Below are the identified key factors and methods which according to the representatives at Opel are important to enable a CAE driven development approach. The key factors and methods are listed in alphabetical order. Thus, the key factors and methods are not graded by importance (see chapter 2.2.2).

Table 15. Key factors identified by the representatives at Opel, which would enable a CAE driven development

Key Factors	**Details**
Central database for storage of models and reuse of knowledge	Consistent reuse of CAE models (knowledge).
Confidence in CAE models	In order to gain trust from management, and other involved departments, it is important to show good results and create confidence in the CAE models used
Cross-functional focus team	It is important to have both CAD, CAE, manufacturing and design engineers involved in the early phases. Working in small teams in the early phases it is good to locate the involved employees together.
Culture	Traditional design areas need to accept the new CAE driven process, this requires a change in mindset from the engineers.
Dimensioning requirements	Important to look over the requirements which enable the architecture to fulfill the complete bandwidth. Too complex requirements tend to make the architecture too heavy
Integration between CAE- and CAD engineers	Important not only for practical reasons, but also for psychological reasons. This to avoid the NIHS. Furthermore, it is important to have a consistent clear strategy to derive the CAE models from CAD, and the other way around.
Management involvement	To enable CAE driven development the trust from management is vital

Methods that would enable a CAE driven development are listed below in Table 16.

Table 16. Methods that supports CAE driven development according the representatives at Opel.

Methods	**Details**
Topology Optimization	Topology optimization is used in the early phases to build initial models already in the end of the initial phases. Stability on the package is needed before doing topology optimization, thus, topology optimization is used as early as possible and preferably before CAD engineers start their design work

6 Analysis

In this chapter, an analysis is presented. The analysis is based upon the interviews made at VCC and the information gathered at the case companies, this is put in relation to the literature study. Firstly, an analysis of the current product development approach at VCC is made and compared to the literature regarding CAE driven development and set-based design, this leads to an argumentation of whether a change of the current development process at VCC is preferable or not. Secondly, key factors and methods that are most important to enable a CAE driven product development is presented. These key factors and methods are based on the conducted interviews at the case companies and VCC, and then supported by the literature. Thirdly, a suggested process and workflow is presented which is based on the literature as well as the interviews with a focus on the key factors and methods. Lastly, a discussion about important factors to consider when making an organizational change is made.

6.1 Is a Change of the Traditional Product Development Process Preferable or not?

Considering VCC's current way of working in the early phases of product development, VCC uses an approach that is more similar to a point-based approach than a set-based approach. Furthermore, the approach VCC uses is centered around CAD. Roughly, VCC's development process can be compared to the generic traditional vehicle product development process presented by Schelkle (2006) in chapter 3.1. The point-based design process is time consuming and the final product may not be the optimal solution (Inoue et al., 2010). Working with a CAE driven approach, however, enables evaluation of alternative solutions and creating knowledge about the behavior of the design (Flager et al., 2009; Schelkle and Elsenhans, 2001; Schelkle, 2006; Autosim Consortium, 2007; Donders et al., 2008; Bordegoni & Rizzi, 2011). In addition, the development time and cost is reduced while the quality of the product is improved (Donders et al., 2008; Autosim Consortium, 2007; Yan et al., 2011; Schelkle, 2006). Working with a CAE driven approach enables a set-based development as it allows variation of parameters and building knowledge around alternative solution in a set design space. As a CAE driven development and a set-based design are related to one another so are the gains. Oosterwal (2010) highlights that the gains of a set-based design is shorter lead times in product development and the ability of building knowledge around alternative solutions. As mentioned before, VCC have a problem that *one* solution is investigated in-depth before consequences have been understood. This current process is time consuming. A consequence to this is that investigation is made on a detailed level too soon and unsystematically. Instead, through a CAE driven development approach investigation of several solutions at the same time could be performed, but on a general level in order to create knowledge around different alternative solutions. To achieve the ability of building knowledge and evaluating alternative solutions through a CAE driven development before deciding on a solution is what representatives at VCC have underlined the most during interviews (the case studies also show that building knowledge and evaluating alternative solutions is one of the main purposes with a CAE driven development). The literature clearly states that solving this through a CAE driven development is achievable. In addition, so did all the case studies. Building knowledge around solutions enables reuse of knowledge (from earlier projects) and less risk if something goes wrong later in the product development process as the knowledge can be used for learning how to proceed without making new simulations or tests (Autosim Consortium, 2007; Thomke & Fujimoto, 2000). Based on this background, a CAE driven development with a set-based design approach is recommended.

Moreover, the focus of this research has been on the early phases of the product development process. Khurana and Rosenthal (1998) argues that the largest benefits are reached when the work done in the front-end is improved, this argument supports a change of the early phases at VCC, or at a resembling company. Furthermore, the actions taken in the early phases have the greatest impact on the design work later in the process (Yamamoto et al., 2007; Verganti, 1997), and if changes are necessary in the later phases they are of high cost and consumes much time (Verganti, 1997). Hence, the choices made in the early phases ought to be as correct as possible as it has a direct impact on the success of a product (Kim and Wilemon, 2002). This is enabled through CAE, because evaluation can be done before deciding on a design. This speaks in favor for introducing a CAE driven development in the early phases of product development process. However, there are two more reasons for why a CAE driven development in the early phases of product development should be introduced. The first one is that the room for changes and creativity is large in the early phases (Schelkle, 2006; Schelkle and Elsenhans, 2001; Donders et al., 2008; Autosim Consortium, 2007) and can be made to a lower cost (Autosim Consortium, 2007). The second reason is that the knowledge created through a CAE driven development makes it possible to solve engineering problems early in the design phase (Donders et al., 2008; Thomke and Fujimoto, 2000; Autosim Consortium, 2007) which saves both time and money (Autosim Consortium, 2007; Donders et al., 2008). As stated by all the interviewed representatives at VCC, the possibility of evaluating more concept proposals would be possible with more CAE resources in the early phases of product development. This is also stated by the representatives at the companies where case studies were performed.

> "[...] the cost of fixing a problem that designers should have corrected in the planning and concept phase increases 10 times if the company discovers it in the testing phase, 100 times if it finds the problem in the production phase, and 1000 times if the customer discovers it."
> (Autosim Consortium, 2007, p.3)

Moreover, a paradigm shift is taking place in the automotive industry (Schelkle, 2006; Moser & Schweiger, 2007) which means that VCC needs to put effort on exploring a CAE driven development process in the early phases in order to stay competitive. The case studies also highlight this, as all the interviewed companies are starting to work, more or less, CAE driven. Furthermore, Wheelwright and Clark (1992) explains that there are three main forces that drive product development: intense international competition, fragmented and demanding markets, and diverse and rapidly changing technologies. The automotive industry is exposed to all three forces and, hence, the need to cut lead time, lower development costs, and raise the quality of the products is vital. CAE driven development is a tool for improvement in all three areas (Donders et al., 2008; Autosim Consortium, 2007; Yan et al., 2011; Schelkle, 2006), which is why a CAE driven development approach is suggested.

6.2 Identified Key Factors that would Enable a CAE Driven Development

Identified key factors that would enable a CAE driven development according to representatives from VCC, CEVT, GKN, Scania, Combitech and Opel are presented in this subchapter. These key factors are also compared to the literature study. An important notification is that the key factors mentioned by the different representatives are the key factors they consider to be *most* important. However, this does not mean that the representatives consider the key factors, where they have not made a reply, to be negative when having a CAE driven development approach. Hence, the amount of YES does not have an impact on the importance of the key factor. The reply *partly* means that the representatives have mentioned this factor as an important one but not as a key factor. These factors have been derived from the texts presented in chapter 5. Some of the key factors mentioned in the empirical findings are not included in this table since they are closely related to another key factor and, hence, these are combined in the table below. However, the excluded key factors are mentioned in the description of each correlating key factor. A summary of the key factors is shown in Table 17, and are listed in alphabetical order. Thus, the key factors are not graded by importance (see chapter 2.2.2).

Table 17. A summary of the most important key factors mentioned at the studied companies to enable a CAE driven development approach.

Key factors	**VCC**	**CEVT**	**GKN**	**Scania**	**Combitech**	**Opel**
Central database for storage of models and reuse of knowledge	YES	YES		YES	YES	YES
Concept engineers	YES	YES				
Confidence in CAE models						YES
Cross-functional focus team	YES	YES		YES	YES	YES
Culture	YES			YES		YES
Dedicated strategy/concept team/expert team	YES	YES			YES	
Dimensioning requirements	YES	YES			YES	YES
Educated employees	YES		YES		YES	
Encourage creativity	YES	YES		YES	YES	
Integration between CAE- and CAD engineers	YES	PARTLY			YES	YES
Integration of CAE- and CAD tools			YES	YES		
Management involvement				YES	YES	YES
Simplified models	YES		YES		YES	
Supplier engagement	PARTLY	PARTLY	PARTLY		YES	
Tools that do not have CAD geometry as a base (e.g. SFE)	PARTLY	PARTLY		YES	PARTLY	PARTLY

Central Database for Storage of Models and Reuse of Knowledge

As stated by Thomke and Fujimoto (2000), knowledge is the most important precondition for effective front-loading problem solving. The reason is that stored knowledge, and the reuse of knowledge minimize the number of problems that have to be solved in the early phases of product development. Thus, time and resources can be spent on other, more value adding, activities. This is something that several of the interviewed companies agrees with. The representatives at Opel argues that a managing data is important to reuse CAE models and creating knowledge. Representatives at Scania and CEVT argue that there need to exist tools where knowledge can be stored and reused, and Tobias Svensson at Combitech agrees that this simplifies data exchange between different attributes and disciplines. Hilmann (2014) also argues that a database is important for having a CAE driven development, this to enable storage, backups, information exchange and for sharing models. However, as Autosim Consortium (2007) mentions, to have an effective CAE driven development, data does not only need to be stored, it must also be easily accessible. Moreover, both Moser and Schweiger (2007) and Schelkle (2006) states that a simulation data management tool is effective when implementing a CAE driven development. The tool creates the infrastructure for managing CAE data, the results can easily be made available for usage.

Several of the interviewed representatives at VCC have mentioned the importance of creating knowledge and saving it for further reuse. Something that VCC lacks today is a central database for models, which enables a faster information flow when changes in models occur. Therefore, in order to fully utilize the benefits of CAE driven development, VCC need to have a central database where models can be stored. The need for creating a shared mindset when developing a new product is requested by the interviewed representatives at VCC. This means that there should be one joint product, and the different departments should work on a joint model so that extra work is eliminated. This requires a collaborative work process. However, an additional solution brought up by representatives at VCC is to use a central database where one central model is used as input to calculations/optimizations/verifications. This request stems from the issues that CAE calculations from time to time are performed on models that are sent from CAD engineers, but when calculations have been performed this model is outdated since CAD engineers have made changes in their models. This means that new calculations have to be done, which creates extra work. Representatives from VCC have also requested that someone should be responsible for what models that exist and what status they have in order keep a controlled overview of what exists and what needs to be updated. An evaluation should be made if this type of role would be necessary to have, however literature (Kotter, 1995; Moser & Schweiger, 2007) emphasizes the importance of standardizations when conducting a change in an organization, hence a role that is responsible for the models could impact the change positively.

Concept Engineers and Dedicated Strategy/Concept Team

Both representatives from VCC and CEVT considered that a concept engineer would be important to enable a CAE driven development. According to representatives these engineers should be experts within their tasks and use CAE methods and -tools. The representatives from VCC argue that it is important that these engineers keep a holistic mindset (both the mindset of the complete car and the business and product strategy), which is supported by Donders et al. (2008), and Khurana and Rosenthal (1998). A Senior Analysis Manager at Complete Vehicle Development at VCC and Albert West from CEVT states that these engineers should make out a strategy/concept team. As VCC do not have dedicated employees that should work with the CAE methods and tools in the early phases a concept engineer is recommended. This to create standards and routines by introducing a new role, standards are necessary when making a change in an organization in order for the change to be successful (Kotter, 1995; Moser & Schweiger, 2007). Albert West (representative at CEVT) suggest that a concept team ought to be responsible for balancing the entire car. However, as VCC have the OCA, employees at the OCA could be appointed the responsibility for balancing the car (as was suggested by one of the OCA members). However, where the responsibility for balancing the car should be placed is something VCC will have to evaluate.

Confidence in CAE Models

Autosim Consortium (2007) states that creating confidence around the CAE models is essential, otherwise choices will not be based on the CAE models. Confidence can be built through educated staff, the validity between the digital model and the physics of the problem, accurate material data, and the complexity of the model, as well as the mesh density that should be adjusted to the problem in investigation and the resources at hand. In addition, during the interviews at VCC, an issue was brought up about the lack of CAE models. Because of this lack, it is important to remember to create confidence around the CAE models when introducing them on a larger scale. The representatives at Opel also agrees with this, as they highlight that confidence in CAE models are important in order to gain trust from management, and other involved departments in the early phases of product development.

Cross-Functional Focus Team

Bordegoni and Rizzi (2011) states that focus teams are important to utilize knowledge. Donders et al. (2008) also states that in the early phases a few engineers work together and these should have a holistic approach. Khurana and Rosenthal (1998) states that companies that experience the greatest success are the companies that have a holistic approach in the early phases activities, including not only a holistic approach concerning e.g. the complete vehicle, but also business and product strategy, something that Kates and Galbraith (2007) agrees on. Hence, a recommendation is that the cross-functional team should balance the three main areas that are of concern when developing a new product at VCC, namely business, customers and technology. Moreover, Hilmann (2014), also argues that to develop new ideas and solutions a cross-functional work is needed. Representatives from VCC, CEVT, Scania, Combitech and Opel states that a focus team is a key factor that enables a CAE driven development. The representatives agree that the constellation and size of this team would vary depending on the project (to create a holistic approach) and the most important aspect is the team members’ expertise and experience. However different departments and disciplines should be represented. The team should also be able to handle the evaluation alternative solution and understand CAE results. Moreover, representatives at VCC have argued that styling and packaging have a great impact on the development before CAE have had the possibility to make an impact. With a cross-functional focus team this could be solved as an environment is created where discussion and idea exchange is possible in the early phases of the product development process. Albert West (representative from CEVT), the representatives from Opel and McAfee et al. (2012) also highlights that a small cross-functional focus team can minimize the risk of NIHS. Tobias Svensson (representative from Combitech) also argues this by stating that a small cross-functional focus team enables integration between the departments, he says that it enables a faster decision making process. However, the grouping could be physical or virtual as long as everybody knows what is happening. The two representatives from Scania argues that a small cross-functional team can be used as a trial project before implementing a CAE driven development in the whole organization. As VCC experiences difficulties with NIHS a focus team is important, the focus team can therefore help to achieve a mindset implies that there is one joint product that requires collaborative work. In addition, as the focus team enables a holistic approach (which is important both according to the literature and the case studies) and integration between different type of engineers and departments. Hence, a focus team is regarded as an important key factor.

Culture

Lakos and Phipps (2004) argues that the outcome of an organizational change is very much dependent on cultural transformation lead by the management. If changes, or other initiatives, are made without reflecting upon how the culture of the organization needs to be changed, unexpected and possibly even negative consequences often occur (Lakos and Phipps, 2004). During the interview with Scania the two representatives pushed for culture as a key factor for a successful transformation to a CAE driven development. As a first response to what key factor that is most important when enabling a CAE driven development, the answer was that courage and the belief in CAE as a tool for product development was a key factor in order to convince the organization to push in a certain direction. This is in line with Autosim Consortium (2007) statement about the importance of building confidence in the CAE models. As the uncertainties in the early phases of product development are high it is easy to work in the same manner as before, since the risk of making mistakes in the early phases can be costly and time consuming (Autosim Consortium, 2007; Wehrle, 2015). Opel also highlights that traditional design areas need to accept the new CAE driven process, this requires a change in mindset from the engineers.

At VCC, a culture that promotes CAE in the early phases is starting to appear. Depending on the people asked at VCC, different answers were given. Some of the interviewees stated that there is a culture that promotes CAE in the early phases but that there is not enough individual ambition within the different departments to change the current way of working, of course with some exceptions. However, in 2014 VCC started an initiative called Optimization Culture Arena (OCA), with the goal to promote the benefits of optimization and create a network of cross technical knowledge within the company. Furthermore, OCA wants to create a culture that drives optimization and implement more CAE driven product development. By collaborating with other Swedish companies, the hope is to learn from each other and create a network of competence that can be used within the organization. OCA within VCC works with smaller projects in order to show positive results of optimization. As mentioned earlier, this is a way to create trust in optimization within the organization, and to show the benefits with optimization. Moreover, as described in chapter 4.2, there are CAE driven project happening at VCC today, this implies that employees are getting aware of the fact that this is important. By showing the positive result from these project a base for a growing culture is set. However, as described in the literature framework, the potential for good optimization results is larger in the early phases of product development, why it is important for VCC to create a culture within the whole organization to give optimization a bigger part in the early phases of product development. In addition, all interviewees at VCC stated that CAE should take a larger role in the early phases product development, and that more decisions should be supported by CAE.

Dimensioning Requirements

As Pisipati et al. (2016) argues, the requirements that are used as input to CAE are often detailed since they are based on detailed CAD templates. In the early phases of product development, there is a value in less complex requirements as input to CAE. This, because in this stage, one of the benefits with CAE is the possibility to evaluate different concepts fast (Pisipati et al., 2016). Representatives from VCC, Combitech and Opel discussed the importance of defining what requirements that are dimensioning, this because all requirements are not necessary in the early phases and increases the complexity. The representatives from Opel states that too complex requirements tend to make the architecture too heavy. Tobias Svensson (representative from Combitech) also highlights that requirements are necessary in the early phases to minimize the risk of unnecessary work. Moreover, Albert West (representative from CEVT) also mentions requirements as a key factor, but not the dimensioning ones. He emphasizes that all complete vehicle requirements, which are necessary for making a specific construction, need to be broken down to enable a smooth process. As VCC have problems today with too complex requirements for enabling a smooth CAE analysis in the early phases, this is an important key factor for enabling VCC to work CAE driven.

Educated Employees

Schelkle (2008) argues that creating an understatement and acceptance of the new tools and methods through e.g. trainings and education is necessary to make sure that the new methods are used consistently. This is supported by Jensen and Friche (2007) that argue that education lowers the risk of employees not adapting to new methods, and by Moser and Schweiger (2007) that implies that education is important for those that will use the new methods. Hilmann (2014) states that in order to develop new ideas, make concept developments, analyzing data and coming up with a conclusion expertise is needed. Also, the representatives from VCC, GKN and Combitech highlights the importance of education in CAE methods and tools so that the employees can understand the results and base decisions on them. Making sure that the methods and tools are used consistently could also be done by applying gates in the product development where management can check that CAE has been done which was suggested by Tobias Svensson (representative from Combitech). Moreover, as both the literature and the case studies suggest education is vital, otherwise employees will not be able to use methods and tools necessary for having a CAE driven development nor making decisions based on the result. Hence, this is an important key factor. However, it is not only education within in the CAE methods and tools that is important, as Tobias Svensson (representative from Combitech) highlights. It is important to have talented CAD engineers that understand what input the CAE engineers need.

Encourage Creativity

Moser and Schweiger (2007) argues that encouragement of creativity is important to achieve a CAE driven development in order to be able to develop new solutions. Tobias Svensson (representative from Combitech) also emphasizes this and states that this is a key factor for enabling a CAE driven development and to stimulate creative development of solutions. Also, Hilmann (2004) argues that this is very essential to develop new ideas and concepts. He also state that creativity is important for analysis and making conclusions. With this in mind, a creative environment stimulates the creation of ideas and solutions, and as evaluation of alternative solutions is the essence of a CAE driven development encouragement of creativity is considered to be a key factor for enabling a CAE driven process. However, as Albert West mentions, limitation in terms of packaging, styling and other constraints are limitations to creativity even in the early phases. Moreover, a representative at VCC that has experience in working with CAE driven project as a local CAE engineer emphasizes that creating generic architectures as a virtual laboratory is something that stimulates creativity and building of knowledge, hence, this is something VCC is recommended to consider.

Integration Between CAE Engineers and CAD Engineers

Integration between CAE- and CAD engineers has been brought up as an issue by all interviewees at VCC. The issues mentioned during interviews have been the lack of close collaboration, long waiting times and NIHS. The two representatives from Opel argues that to enable a smooth transition between the CAE engineers in the early phases and the CAD engineers that use CAE engineers' result as an input to the CAD models, integration is important. Tobias Svensson (representative from Combitech) states that integration between departments is very important. Deng et al. (2002) states that if there is no integration CAE engineers and CAD engineers work separately followed by iterations. However, by integrating the two disciplines and applying a CAE driven approach the product development can be done faster. In addition, there is an opportunity to minimize cost and weight while performance is improved (Park & Dang, 2010). The process time is reduced because fewer iterations between analysis and redesign are needed and because each iteration takes less time (Maier et al., 2009). When integrating these engineers, they need to work closely together, hence collaboration and communication is important as well as having one common goal (Maier et al., 2009), this is also good for reducing NIHS (McAfee et al., 2012; Ragatz, 1997). Albert West (representative from CEVT) and the representatives at Opel argues that integration between CAE- and CAD engineers could lower NIHS, however he also states that he considers that the competence difference between the engineers has a larger impact on NIHS. However, Bordegoni and Rizzi (2011), states that tacit knowledge is harder to transfer if there is a physical distance, hence closer collaboration could also improve the competence gap to some level. Maier et al. (2009) argues that in order to produce a product that is satisfying both in geometrical structure and function, CAE- and CAD engineers need to understand each other's way of working and communication between them is vital (Maier et al., 2009). Based on the information brought up here, an integration is vital, where the engineers working with CAD and CAE are given the opportunity to exchange knowledge and give input to each other's work to save time, cost, weight, reduce NIHS and improve performance of the product. The local CAE engineers are a good example of a CAE and CAD integration, and as the empirical studies have shown the local CAE engineers have a great impact on local CAE driven developments. Hence, this type of grouping is recommended to introduce on a larger scale. However, this is more applicable in the later phases of the product development process. In the early phases, the cross-functional focus group together with the dedicated strategy/concept group provides an integration between engineers and departments.

Management Involvement

As mentioned in the literature framework, the involvement of management is important for several reasons. First, to create a change, the involvement of management and the creation of a vision is a key factor (Kotter, 1995). Furthermore, in many organization CAE supported processes in form of optimization and simulation is not always trusted (CIMdata 2016). This creates a problem where a two-sided solution is needed. As mentioned by representatives at Scania and Combitech, engineering teams need to show good simulation and optimization results in order to gain trust from the management. However, they also mention, as do the representatives from Opel, that management must support and create processes and roles for optimization and simulation in order to gain the benefits from CAE driven development. Furthermore, as Scania argues, it is up to management to secure these resources. It cannot be dependent on employees' initiatives and their network within the company.

As several interviewees at VCC mentions, resource allocation does not come from management in the current workflow and people depend very much on their network within the organization. Hence, this way of working is driven bottom up, i.e. initiatives are taken by the employees, just as the representatives from Scania labels their own situation. Both representatives from Scania request that the initiative should come from management, thus a top down approach, which also is suggested for VCC. The representatives at Opel highlights that it is important to gain the trust from management to enable a CAE driven development approach. In order to improve the optimization and simulation capabilities of the organization, management need to create processes and roles where optimization is more prioritized. However, the attempts to optimization projects performed at VCC (two examples mentioned in chapter 4) and the initiatives taken by the OCA are examples of initiatives that are heading in the right direction. By showing good results, the trust from management will be higher and more resources can be spent on optimization and simulation, moving the organization to be more CAE driven.

Simplified Models

Autosim Consortium (2007) as well as Bordegoni and Rizzi (2011), recommend working with simple models in the early phases. This, because there are many uncertainties in the early phases which makes a complex model fragile (Autosim Consortium, 2007), and because the uncertain environment the need for high accuracy is low (Bordegoni & Rizzi, 2011). In addition, simple models enable more knowledge and insights in a shorter time-period than if the model would have been complex, this as analysis can be made faster (Autosim Consortium, 2007; Bordegoni & Rizzi, 2011). Representatives from VCC, GKN and Combitech strongly agrees with this and find simplified models essential in order to make faster analysis and testing alternative solutions. Phil Johanson (representative from GKN) highlights the aspect that simplified models enable evaluation of alternative solution and hence also a set based-design. With this in mind, simplified models are an essential key factor that VCC need to focus on especially as there is a lack of simplified models at VCC today.

Supplier Engagement

Moser and Schweiger (2007) states that communication with suppliers is important when changing to a CAE driven development as the virtual development will become much more complicated, organizations that are involved need to be on the same page. Albert West (representative from CEVT) states that suppliers in the automotive industry usually are decided upon based on price, which interviewees at VCC also have stated, which means that even though development has been done to improve a solution, the supplier might not be able to produce it. Phil Johanson (representative from GKN) also highlighted the fact that the decision about what supplier to choose greatly influences when a design has to be frozen and when. Tobias Svensson (representative from Combitech) states that the suppliers need to be involved in the CAE driven development in order to reach full effect of on the product. However, this has not been considered to be a key factor by any of the case studies. Nevertheless, as many of the interviewees at VCC have mentioned the suppliers as a limitation to realizing the solutions made with a CAE driven approach, this aspect is considered to be important to enable VCC to fully work CAE driven.

Tools that Support CAE Driven Development

Exchanging methods and tools, so that they enable a CAE driven development, is a key factor according to Schelkle (2006). An analysis of methods is presented in the following subchapter, evaluation of CAE tools, on the other hand, has not been within the scope of this thesis. However, some conclusions can be made based on the case studies and literature, hence, a brief analysis is made.

The two representatives from Scania consider tools that do not have a CAD geometry as a base (e.g. SFE-concept) as a key factor for working CAE driven. When speaking to the representatives from CEVT, Opel, Scania and Combitech they all speak positively about this type of tool for parametric modeling and evaluation. Moreover, representatives from GKN and Scania speak about integrated tools for CAE and CAD. The two representatives from Scania states that having an integrated tool the gap between the engineers can be lowered (a gap that Albert West at CEVT highlighted as an issue to be able to minimize NIHS), and Phil Johanson (representative from GKN) argues that the integrated tools help atomizing the analysis process. He also explains that having integrated tools means that the quality is compromised, however in the very early phases the integrated tools gives an enough accurate answer. These two type of tools (SFE and CAE-CAD integrated) have also been covered in several articles studied during this thesis, however, as tools were not within the scope these articles have not been covered.

Apart from the above key factors that have been identified by the case studies, and now also supported by literature, there are two key factors that solely have been identified in articles. These are presented below.

Involve People that will Be Affected By the Change as Early as Possible

Moser and Schweiger (2007) argues that people which will be affected by the change should be involved as early as possible in order to achieve good results when changing to a CAE driven development. This is also highlighted by Hudgins and Macklin (2000), they argue that early involvement of affected people is important in order to make sure that all important aspects have been taken into consideration as these employees may carry information that e.g. management do not. Kotter (1995) states that involvement is positive by arguing that announcing positive results is important early on to increase the devotion of employees and creates a culture where individual performance is important.

Standardization of Processes and Routines

Moser and Schweiger (2007) argues that standardization of processes is important to reach a CAE driven development. This is supported by Kotter (1995) that states that it is important to establish the changes by introducing standards and routines to make the changes a natural part of the organization and its long-term way of working. Looking at VCC current way of working there are clear standards and routines in the later stages, however, the early phases are lacking clear standardization of processes in regard to CAE. This was brought up as an ongoing issue in chapter 4.1 and it is therefore very important for VCC to create standards around how to work. However, as Tobias Svensson mentions (representative from Combitech) it is important to not remove the fuzziness of the front-end to make sure to enable creativity, hence standardizations and routines have to be made with this in mind. This is also supported by Koen et al. (2001). An example at VCC is that there is a lack of defined methods, processes and tools in the early phases for working CAE driven. Another example is that there is no model or other strategic study delivery that are set in the early phases, something that representatives at VCC brought up as a key factor for enabling a CAE driven development in their organization. A suggestion is that VCC should evaluate what these early deliveries should cover and how many they should be. However, as the lack of defined methods and processes for how to work in the early phases has been brought up as an issue at VCC, it is important to investigate this. Moreover, the result from this thesis is a start for how VCC can work with standardization and routines in the early phases in regard to a CAE driven development.

In total, 17 key factor have been identified through this research. These key factors can enable a CAE driven development approach, but as mentioned before, there have not been any analysis of the relative importance between the key factors. However, even though no analysis of the relative importance has been done, 15 of these key factors are strengthened by VCC and some of the case companies, as well as in the literature. As mentioned above, two key factors are only based on the literature, but for a holistic approach, they are considered to be important in this analysis.

6.3 Identified Methods Needed at VCC to Enable a CAE Driven Development

Through interviews with representatives from VCC, CEVT, GKN, Scania, Combitech and Opel methods have been identified that are of value in order to enable a CAE driven development in the early phases. What can be concluded is that the main purpose with these methods, according to the interviewees, is to build knowledge around alternative solutions before deciding what concept to go for. An important notification is that the methods mentioned by the different representatives are the methods they consider to be most important. However, this does not mean that the representatives consider the methods where they have not made a reply to be negative, when having a CAE driven development approach. The reply *partly* means that the representatives have mentioned this method as an important one but not as a key enabeler. A summary of the methods identified during the interviews is shown in Table 18l, and are placed in alphabetical order. Thus, the methods are not graded by importance (see chapter 2.2.2).

Table 18. A summary of methods mentions by the studied companies to enable a CAE driven development approach.

Methods	VCC	CEVT	GKN	Scania	Combitech	Opel
Design of Experiments (DoE)	YES	YES	YES		PARTLY	
Parametric studies	YES	PARTLY	YES	YES	PARTLY	
Response Surface	YES		YES		PARTLY	
Sensitivity analysis	YES			YES	YES	
Topology optimization	YES	PARTLY	YES	YES	YES	YES

Kojima (2000), together with all of the case studies, cover the same methods, he argues that these methods can be divided into two optimization approaches. One optimization approach combines DoE, parametric studies, sensitivity analysis and response surfaces (here on called *combination approach*), and another approach is topology optimization (here on called *topology approach*). These methods in the combination approach enable evaluation of alternative solutions in a set design space (Kojima, 2000). Because of this, the methods also enable a set-based development (Hannapel & Vlahopoulos, 2014) which Phil Johanson highlighted in his interview when stating that statistical tools and the ability to vary geometries enabled GKN to work set-based. Flager et al. (2009) states that DoE can be used as an input to topology optimization. Topology optimization is a type of structural optimization and it is used to find the optimal way to structure material to sustain loads in the best way (Christensen et al., 2009). As a result, time, material and cost savings can be made (Yildiz, 2012). Time can be saved as the need for iterations later in the process is lower than without optimization (Schramm & Arold, 2006). Yamamoto et al. (2007) also highlights that using topology optimization in the early phases can improve performance and lower the weight of the product. Furthermore, this will be even more important in the future since new environmental requirement will be introduced 2020, which will put more emphasis on the fuel efficiency of the car. Thus, using topology optimization to find a lightweight structure can prepare VCC for the upcoming requirements.

However, an iterative process can be created between the two optimization approaches (the combination approach and the topology approach). For example, while conducting a parametric study a topology optimization study can be done in parallel where information is exchange (the output from the parametric study becomes the input to the topology optimization study, next the output of the structural optimization study is used as an input to the parametric study and so forth), (Autosim Consortium, 2007). Looking at the "Conceptual Design Process" presented by Moser and Schweiger (2007) and Schelkle (2006), they recommend starting with Symbolic CAE that enables investigation of the physical layout through very basic layout concepts (combination approach) and design grammars (topology approach), followed by parametric concept model (both optimization approaches). This approach enables the creation and parametrization of CAE models in the early phases, something that was brought up as a request during the interviews at VCC.

Looking at the case studies, Albert West (representative from CEVT) argues that DoE is the most important method in the early phases to understand a design and its potential. Phil Johanson (representative from GKN) advocates, just as Kojima (2000) a combination of methods (he suggests DoE with parametric studies and response surfaces) to enable optimization between different disciplines, and to separately conduct topology optimization to understand how load paths can be placed. The two representatives from Scania highlight the importance of parametric studies as it, enables sensitivity analysis and optimization. In contrary to the other case studies, Tobias Svensson (representative from Combitech) states that topology optimization is most important method followed by a sensitivity analysis. DoE, parametric studies as well as response surfaces are suitable but first in the concept phase according to Tobias Svensson. The representatives from Opel agrees that topology optimization is most important by stating that topology optimization is used to build initial models. Stability on the packaging is needed before doing topology optimization, thus, it can be used as early as possible and preferably before CAD engineers start their work.

In total, five methods have been identified that would enable a CAE driven development approach. This has been strengthened by literature and interviews. Based on the analysis above symbolic CAE (combination approach) together with design grammars (topology approach) is suggested to start with. This is then followed by parametric concept modeling (both optimization approaches). This should then be used as an input to the CAD models (i.e. the concept templates).

6.4 Process and Workflow

The current process and workflow in the early phases of the product development process at VCC lack clear definitions and standards for how to work with CAE, as described in chapter 4, and especially for category two CAE. Bordegoni and Rizzi (2011) states that the purpose of having a CAE driven development in the early phases is to support the decisions about material and architecture by quantitatively examining the structural performance, make feasibility- and what-if studies, estimating weight by increasing accuracy, evaluate and creating knowledge around alternative solutions. The aim of this subchapter is to propose a process and workflow for how VCC can achieve this by working CAE driven in the early phases of the product development process, with a focus on enabling to run faster and more analysis as well as building and reusing knowledge. This proposal is described below. However, what is important to highlight before going through the proposal, is that the purpose of this proposal is that it should be used as an inspiration for VCC when transforming the product development process to a CAE driven development process. The proposed process and workflow below is a combination of the findings above (hence, a combination of the data gathered at VCC, the case companies and literature), which is why VCC might need to customize the proposal so that it fits their current way of working and their future goals. As described in chapter 4.1, the perception of to which degree the product development should be CAE driven varies depending on the representative interviewed, which is why the proposal must be considered as an inspiration. To what degree the development process should be changed is up to VCC to decide.

According to Georgakopoulos et al. (1995) a workflow can be modeled based on communication or on activities. The focus in this analysis is on the activities, see Figure 22. Moreover, according to Lin et al. (2002), a process consists of customers, activities that create value for the customers, humans or machines operating the activities, and finally a business process usually involves different organizational units. The organizational units involved in this new process will be the same units that work with the product development process today, namely: Complete Vehicle Development, Technology and Implementation, Vehicle Hardware as well as Vehicle Software and Electronics. In addition, also the Design unit will be involved as they are responsible for the "styling" design. The customers in this process are internal, that is, the output for one employee is the input for the next. Below is a suggestion for how the activities could be arranged in the early phases, and to an extent who/what that is going to operate the activities. Figure 22 summarizes the proposed process and workflow.

To start with, to enable a CAE driven development approach 17 key factors have been identified. According to this research these are vital to enable a transition from a product development process that is centered around CAD to a process that is CAE driven. These key factors can be categorized according to:

- Key factors that enables an organizational change. Hence, key factors that set the basis for creating a change towards a CAE driven development. These key factors are presented in the blue board situated to the left in the Figure 22.
- Key factors that enable working CAE driven. These are key factors that are necessary to enable an organization to work CAE driven, however these are not essential in order to create an organizational change. These key factors are presented in the blue board in the bottom of Figure 22.

Furthermore, Figure 22 depicts the Annual Process together with the early phases at VCC (the strategy phase together with the beginning of the concept phase). Starting with the Annual Process, Hilmann (2014) states that to work CAE driven a problem or question needs to be identified, this is also the first step made by GKN. This problem or question identification is comparable to VCC current gap-identification process, however in this scenario it needs to be of a CAE evaluation character. Hence, the first activity suggested in a CAE driven development approach is a gap definition that can be used as an input to an investigation. Today at VCC, gaps are identified in the first phase of the Annual Process through the PAP. A suggestion is to use these gaps and base problems and question on those. In the second phase of the Annual Process, the aim is to understand how to close the identified gaps, either by new technical solutions or by developing existing solutions. This is also where CAE actions have been taken today and are made on individual initiative. As stated in chapter 4.1, CAE has in this phase a go or no-go function but occasionally (if requested by an employee) subsystem MDO (multidisciplinary optimization), load case sensitivity studies, concept studies and refinement optimization have been made. With this in mind, a suggestion is to start the CAE driven development in this phase as it has naturally been practiced here without the need for defined standards or routines. Moreover, one of the key factors is to introduce a new role, a concept engineer. These engineers should be educated to work with CAE methods, which was recommended above, to evaluate alternative solutions and building knowledge around the solutions. These engineers would make out the dedicated strategy/concept team. Hence, by identifying gaps, concept engineers will investigate these gaps using CAE methods (both the combination approach and topology approach) that are suitable for the specific evaluation. This gap identification together with the concept engineer and dedicated strategy/concept team, are the proposed new roles and activities in the Annual Process, illustrated by the dark blue box to the left in Figure 22.

Moving on to the strategy phase. As described in the key factors, a cross-functional focus team is necessary. The suggestion is that the cross-functional focus team (whose constellation and size should depend on the project) should work together with the dedicated strategy/concept team in the product development process at VCC. This, to enable a holistic approach to the development, integration between different type of engineers, and the reduction of NIHS that otherwise could arise in the departments. This constellation would appear in the strategy phase of the product development process at VCC (and would use the input from the Annual Process as described in chapter 4.1.1 as basis for their CAE work). As described in chapter 4.1.3, VCC is currently working with a cross-functional focus team in the early phases (however this has not been practiced before and hence the approach is new at VCC) but based on the information gathered in this research a cross-functional focus team is recommended and hence a suggestion is to make this team into a standardized procedure. The dedicated strategy/concept team together with the cross-functional focus team would make out the necessary resource allocation for the CAE driven activities. This is depicted in Figure 22 by the dark blue box in the middle of the figure.

As described before, in the Annual Process the suggestion is to identify gaps and investigate these using different types of CAE methods. However, when entering the strategy phase there is a need for clearer standards and routines. Hence, based on the analysis made in chapter 6.3 a proposal has been made for how to structure the early phases regarding CAE methods. Figure 22 illustrates what methods to use and in what order to use them in the early phases (symbolic CAE, design grammar and parametric concept modeling). With this workflow, CAE can be used as an input to and support the development of CAD templates as well as enable evaluation of alternative solution and knowledge building.

Furthermore, Hilmann's (2014) “Circle of CAE driven development” explains that for each defined problem or question a CAE loop is be started. Hilmann's (2014) process starts with concept modeling, next it moves on to analysis and learning about the system and finally a conclusion which either ends the loop or starts the investigation all over again. This is also described by Schelkle (2006), where the start of a product development should consist of many iterations between concept modelling and CAE simulations. This is illustrated in Figure 22 by the double arrows pointing between the CAE methods and the concept modelling, this also illustrates that CAE results are used as an input to the CAD models. In addition, each verification at VCC is time consuming today, with a faster iteration process, more, but quicker, loops are possible instead of a few time-consuming. This is enabled through the integration of engineers and departments in the collaboration between a dedicated strategy/concept team and a cross-functional focus group. Moreover, as the figure depicts, concept modelling in CAE and CAD is later in the process exchange to regular CAD design.

Figure 22 also visualize two blue diamonds marked with the numbers one and two. These diamonds illustrate deliveries of models or the outcome of other strategic studies. As mentioned a need have been identified during the interviews at VCC for defined deliveries already in the early phases. However, the number of deliveries is to be decided by VCC. Lastly, Figure 22 also depicts when the concept template development would start at VCC and when the project would start – illustrated by two blue diamonds.

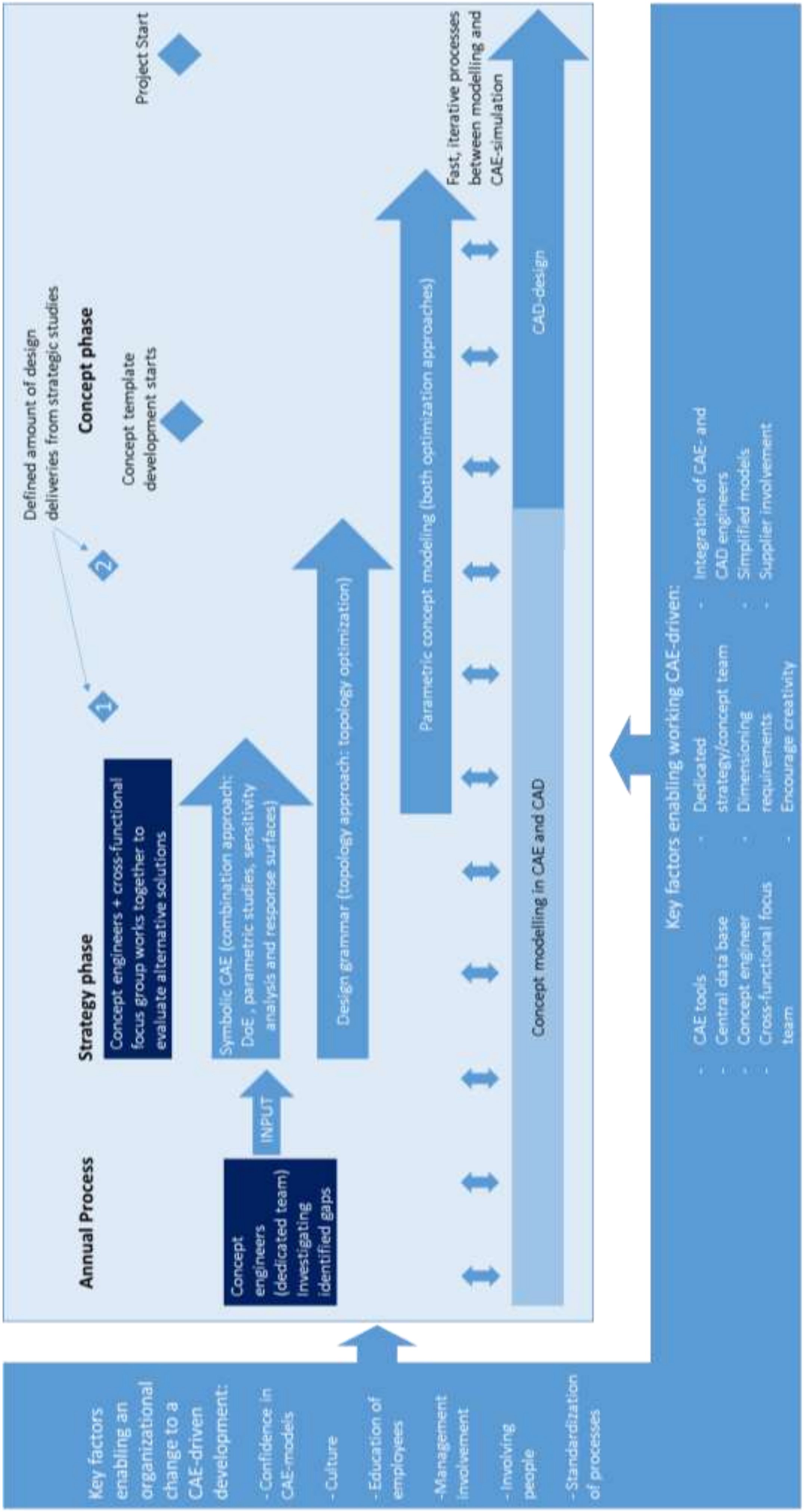

Figure 22. A visualization of the proposed process and workflow containing the defined methods and key factors.

6.5 Changing the Current way of Working and what to Think of when Doing So

This thesis does not cover any implementation phase, however, a couple of issues connected to implementing a change in an organization is highlighted in this subchapter. This, to discuss some aspects that are important in order to reach a successful result when making a change. As stated in the key factors (chapter 6.2) above, management plays a crucial role when introducing a CAE driven development, below are some aspects that are important to keep in mind.

In general, it is hard to handle change. However, there are situations where change is essential to the company because of new legislations or for the company to stay competitive (van der Aalst & Jablonski, 2000; Wheelwright and Clark, 1992). One risk when introducing new methods and work tasks is that employees will not adapt them. A way to reduce this risk is by making sure that the new tasks and methods are taught properly to the employees, and to make sure to put aside time that is intended to be used for trying the new task or method (Jensen & Friche, 2007). This is also important because the satisfaction of the employees influences the success of the change (Cima et al., 2011). Hence, it is important to look after the involved employees. One other issue that is important is getting all the involved employees to agree and actively participate in the change as early as possible, this can be managed through change management (Grover et al., 1995; Moser and Schweiger 2007). Kotter (1995), discusses the importance of creating an understanding and acceptance among the employees that will be affected by the change, this can be done by e.g. involving them in the decision process and give them an opportunity to give propositions. In addition, this is a positive way of acting as the employees may have more knowledge about a specific task then the management. Kotter (1995) states that change should occur stepwise to maximize the chance of succeeding, which he has summarized in eight steps, which are recommended to consider before conducting a change:

1. Create a sense of urgency for change
2. Create a strong and influential group that can take the lead of the change
3. Create a vision for the change
4. Communicate the vision
5. Get others to act according to the vision
6. Plan to create short term wins
7. Consolidate the improvements and produce more changes
8. Institutionalize new way of working

The first step is already starting to happen on a natural basis at VCC. As described previously, pilot projects that are CAE driven are already happening which is an evidence that some employees have realized the importance of a CAE driven development. The OCA is also a proof that a sense of urgency is felt. However, both as the literature show and what the case studies pinpointed, to achieve a change, management involvement is needed.

Moreover, when trying to achieve a radical process change BPR can be applied (Motwani et al., 1998). Hence, apart from practicing change management to reach a successful change, BPR is also recommended. The two main tasks of BPR is mapping existing activities and processes as well as modelling the new process (Lin et al., 2002). Kettinger (1997) describes a framework for BPR consisting of six steps: envision, initiate, diagnose, redesign, reconstruct and evaluate. Each step consists of different activities which are depict in the Figure 23. The first step of the BPR is envision, and the first activity is establishing management support. Hence, this is a crucial next step for VCC (e.g. the OCA) - to engage management. In this thesis, a basis for step three and four has been made (diagnose and redesign). Hopefully, this thesis, together with results from pilot projects and further benchmarks can be used to create a sense of urgency also for the management.

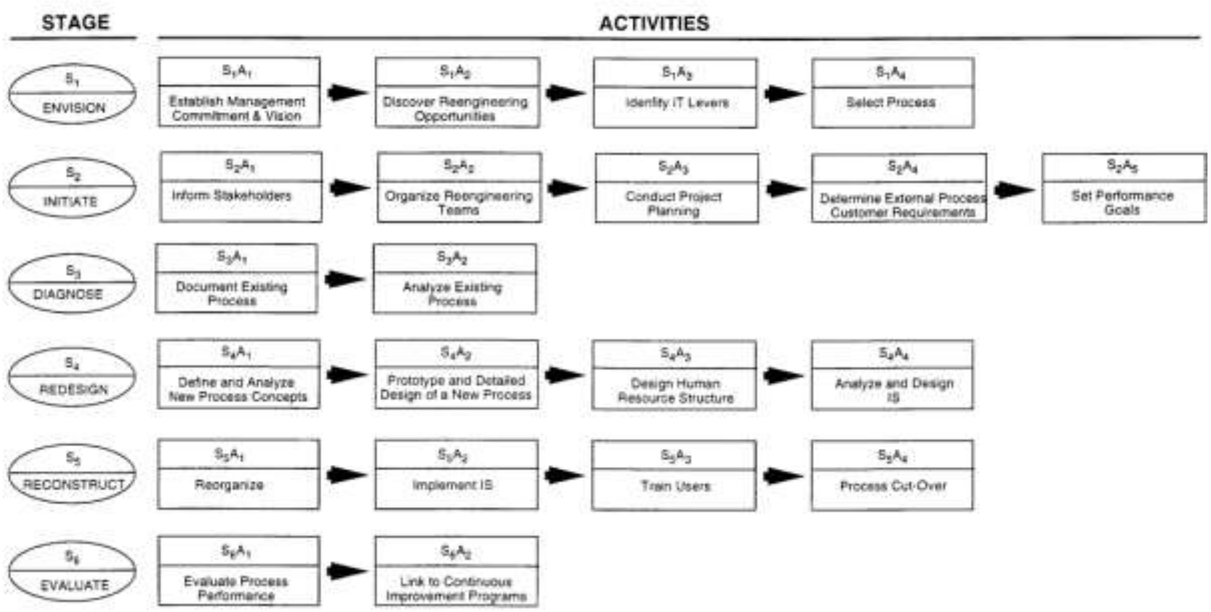

Figure 23. Kettinger's framework for performing BPR including six stages and 21 activities [Source: Kettinger, MIS quarterly, 2007].

7. Conclusion

This thesis proposes a process and a workflow together with key factors and methods that could enable VCC, or a resembling company, to work CAE driven in the early phases of product development. It also highlights the possible benefits of having a CAE driven development approach. To do so, two research questions have been investigated, namely:

- What key factors and methods does an automotive manufacturer need to consider to enable a CAE driven product development approach in the early phases of product development?

- How can an automotive manufacturer structure its process and change the workflow so that a CAE driven product development approach can be incorporated in the early phases of the product development process?

The first research question was investigated through interviews at VCC, a literature study and interviews at case companies. The result from each data collection was combined and analyzed in comparison to each other. Seventeen key factors that would enable VCC to have a CAE driven development approach have been identified and these can be divided into two groups: key factors that enable an organizational change and key factors that enable a CAE driven development. When it comes to the methods, two approaches have been identified – the combination approach and the topology approach. These can be categorized in to Symbolic CAE, design grammars and parametric concept modeling.

To investigate the second research question, the current way of working at VCC was examined together with the way of working with CAE in the early phases of the case companies and the literature study. In addition, issues with VCC current way of working were identified. This, together with the identified key factors and methods enabled the construction of a proposed process and workflow.

However, to start working CAE driven a suggestion is to start on a small scale and with a few elements at a time. This, in order to make a smooth implementation and to minimize the risk of resistance. Moreover, the understanding of the importance, and the cultural spread of, CAE driven development has already begun at VCC. Employees are taking own initiative to work with a CAE driven development approach and the current paradigm shift in the automobile industry will put further pressure on the automotive companies to improve their development processes in the form of cost, time and quality. But what is most important to focus on in the near future? What is most important for the organization to focus on in the long run? Hence, in this chapter a recommendation is made for how to proceed with the results of this research and what to focus on. This will be made by proposing what VCC should focus on in the short term, what to focus on in the long-term perspective as well as highlighting the possible benefits with a CAE driven product development process.

7.1 What to Focus on in the Short-Term

Even though the OCA have started their work to spread the benefits of CAE driven development, this must continue, and new culture bearers must be found within the company. This is one of the most important key factors since the spread of culture also creates a sense of urgency for change. Employee participation plays a role when creating this urgency. Culture is a key factor that is important in the short run, but also in the long run. Therefore, the continuation of OCA and search for other employees that can spread the culture of CAE driven development is recommended for a possibility to reach a CAE driven development within the whole organization in the future. Not only to spread the culture within the company, but also because of the possibility to learn from other organizations which will decrease the transaction cost when introducing CAE driven development.

A suggestion for VCC is to start by focusing on simplified models and dimensioning requirement. This, because VCC are lacking in these areas today and because both literature and the case studies highlight that this is essential to enable a CAE driven development approach. If VCC work with simplified models and dimensioning requirements in the early phases of product development CAE calculations and optimizations can be performed faster and with higher accuracy. However, without these two key factors, CAE in the early phases is difficult to perform, and can be too time consuming. Furthermore, having simplified models enables more knowledge and insights in a shorter time-period as analysis can be made faster, and it lays the foundation for a set-based approach, as stated in chapter 6.2. Dimensioning requirements also have an impact on the development time as unnecessary work can be avoided. Hence, without these key factors, two crucial aspect of automotive development is not reached to a sufficient level: *time* and *cost*. Through interviews at VCC it has been identified that creating knowledge around alternative solutions, and base decisions on CAE results to support a feasible development is of great need. The knowledge created through a CAE driven development approach makes it possible to solve engineering problems early in the design phase (Donders et al., 2008; Thomke and Fujimoto, 2000; Autosim Consortium, 2007) which saves both time and money (Autosim Consortium, 2007; Donders et al., 2008). This is possible if simplified models and dimensioning requirements are created. With these two key factors as a foundation, alternative solutions can be evaluated in the early phases. Moreover, there is also a need to have employees that understand and has the knowledge about how to work with identified CAE methods (combination approach and topology approach). VCC needs to allocate resources that have knowledge about CAE methods or educate employees to make sure that CAE can be performed in the early phases. If there is no knowledge about CAE methods or how CAE can contribute, it is difficult to have a CAE driven development approach, both in the short and long term. The proposition is to introduce this (a small number of employees working with simplified models and dimensioning requirements to perform CAE) in a small scale. This, to create results that can imply on the positive effects of a CAE driven development approach.

As stated in the analysis, the importance of management involvement is crucial, if not vital, in order to create an environment where the product development process is CAE driven. Also, management must allocate resources for CAE activities in the early phases of product development and create roles and process that makes it possible to reach the benefits of CAE driven development in the early phases. However, to get the support from management, good results and the benefits from CAE driven product development must be available and shown to management. This is something that the representatives from Opel agrees with by stating that by showing that the CAE department can produce reliable results top management will understand that a CAE driven development can create both cost savings and time savings in the development. Therefore, it is the key factors mentioned above (simplified models, dimensions requirements and educated employees) that should be prioritized first, as these, according to this research, can enable the creation of positive results. Furthermore, as shown in chapter 4.2, local CAE driven projects have been undertaken at VCC. In the front structure project, by applying a CAE driven approach, time, workforce and weight was reduced compared to performing a traditional product development process. This together with the OCA, are perfect examples of initiatives from employees that both creates trust in CAE driven development and spreads the benefits, and the culture, of CAE driven development. To start with small pilot projects is something we recommend VCC to continue with before trying to completely change the product development process.

Hence, the suggestion is to start with simplified models, dimensioning requirements and educate employees (in CAE methods and a CAE driven development approach). This, to start a CAE driven development on a small scale to produce positive results (shorter development time, less costs and increased quality and at the same time building knowledge around the solution). These results, together with the results from local CAE projects, should then be shown to management in order to demonstrate why they need to participate.

7.2 What to Focus on in the Long-Term

Having the support of the management lays the foundation of a more long-term focus and a wider organizational scope. This is important in order to achieve the suggested process and workflow (suggested in chapter 6.4). Kotter's (1995) eight steps recommend the creation of a strong and influential group that can take the lead of the change. Hence, a suggestion is that with the help of the management, appoint a group that can be responsible for the change and create a vision for it. A recommendation is to involve the OCA and its network for this. Moreover, the suggestion is to, with the support of the management and the appointed team, firstly focus on standardization and routines, the development of the concept engineer role, the establishment of a dedicated strategy/concept team, the formulation of how to form and work with cross-functional teams, education of employees (in CAE methods and a CAE driven development approach) and the involvement of the employees that will be affected by the change. Without the support of the management these key factors are difficult to realize, however they are important to enable a CAE driven development approach. With a focus on these areas, a foundation for the suggested process and workflow can be built.

In the long-term it is also important to focus on creating confidence around CAE-models so that decisions are based on the results, and to encourage creativity to stimulate the development of new solutions. These two key factors, together with a culture that supports a CAE driven development, needs to be emphasized on an ongoing basis, to make sure that they become a natural part of the new product development process and workflow.

A next step would be to introduce a central data base. This is not necessary in order to start working CAE driven, but it is necessary when the new way of working has been introduced in order to e.g. store knowledge and models, make backups and share information. Hilmann (2014) argues that having a central data is vital for achieving success. Engage suppliers is also a key factor that is not necessary in order to start working according to the suggested process and workflow, however it enables the assurance that a supplier can produce the developed solution.

7.3 Possible Benefits with a CAE Driven Development Approach

Through interviews at VCC it has been identified that there is a need to create knowledge around alternative solutions, and base decisions on CAE result to support a feasible development. This research has shown that having a CAE driven development approach, enables evaluation of alternative solutions and creates knowledge about the behavior of the design (Flager et al., 2009; Schelkle and Elsenhans, 2001; Schelkle, 2006; Autosim Consortium, 2007; Donders et al., 2008; Bordegoni & Rizzi, 2011), and hence support a feasible development which was supported not only by literature but also by all of the case studies. In addition, the development time and cost is reduced while the quality of the product is improved (Donders et al., 2008; Autosim Consortium, 2007; Yan et al., 2011; Schelkle, 2006), this was also supported by the local projects at VCC and three of case studies (GKN, Opel and Scania). In addition, by utilizing the early phases the room for changes and creativity is large (Schelkle, 2006; Schelkle and Elsenhans, 2001; Donders et al., 2008; Autosim Consortium, 2007) which GKN, Opel and Combitech agrees with, and can be made at a lower cost (Autosim Consortium, 2007). Moreover, the knowledge created through a CAE driven development approach makes it possible to solve engineering problems early in the design phase (Donders et al., 2008; Thomke and Fujimoto, 2000; Autosim Consortium, 2007) which is agreed by the all of the five case companies. This also saves both time and money (Autosim Consortium, 2007; Donders et al., 2008). With this in mind, the possible benefits that representatives from VCC wished for with a CAE driven development approach, which were described in the introduction, have been supported through this research and can hence be achievable through the suggested key factors, methods as well as the process and workflow (see Figure 24).

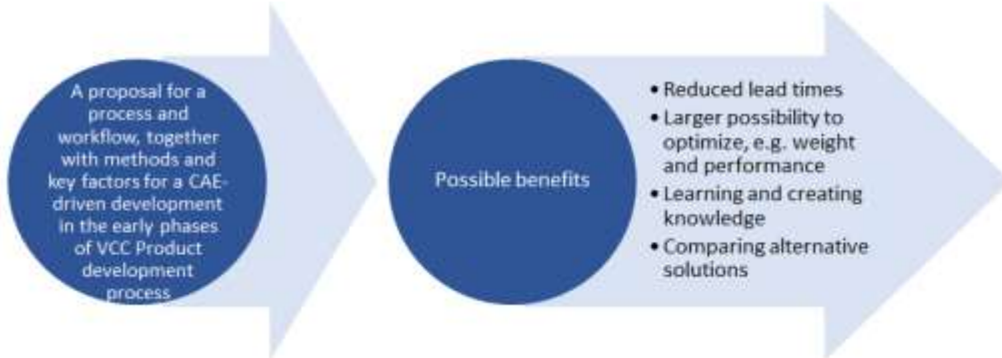

Figure 24. An illustration of possible benefits with a CAE driven development approach, which were depict in the introduction. The possible benefits have been supported in this research and are, hence, achievable.

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Appendix I – The Semi-Structured Interview Guide Used at VCC

1. What is your role at VCC?
2. In what phases of the product development process are you active in?
    a. What are your tasks in the different phases?
    b. How does the cooperation work between you and other employees in the different phases?
3. What are the activities in the early phases that you are involved in, and what roles and departments are involved?
4. What benefits/issues do you experience in the current way of working (in regard to the current CAE activities)?
5. What is a CAE driven development according to you?
6. What are the benefits/issues of having a CAE driven development according to you?
7. How do you think a CAE driven development at VCC could contribute?
    a. What are the current needs?
    b. What issues would it solve?
    c. What is needed in order to introduce a CAE driven development at VCC?

Question to the employees with deeper knowledge about CAE:

1. What key factors do you consider to be necessary to enable a CAE driven product development process in the early phases?

2. What methods do you consider to be necessary to enable a CAE driven development in the early phases?

Appendix II – The Semi-Structured Interview Guide used During the Case Studies

1. Could you describe the strategy phase of the product development process at Company X (from a workflow perspective)? With strategy phase, we mean the very first stage of the product development, before the concept has been set (and where you, possibly, work with more than one design option).

2. How do Company X work with CAE driven development in the early phases of the product development process (from a non-technical point of view, but a more value-adding and organizational point of view)
    a. If you can answer, please state how you define a CAE driven development.

3. How would Company X want to improve the work in the strategy phase of the product development regarding:
    a. CAE driven development
    b. Integration between CAE engineers and CAD engineers

4. Do Company X have any yearly process in parallel to the product development process where strategies and technologies are developed and improved? If so, then:
    a. Is there a CAE driven development in this process? How does it look like from a workflow perspective?
    b. Is the integration between CAE engineers and CAD engineers satisfying or do you see this integration as a bottleneck for CAE driven design?
    c. If bottleneck, do you see any ways to solve this by changing the workflow or the processes?
    d. Is there any improvement that you would like to see in this process in regard to the two aspects above?

Emailed questions:

1. What key factors do you consider to be necessary to enable a CAE driven product development process in the early phases?

2. What methods do you consider to be necessary to enable a CAE driven development in the early phases?