Simulation Driven Product Development

How it can be combined with Lean Philosophy to achieve increased product development efficiency.

Master of Science Thesis in the Master Degree Program Supply Chain Management

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ABSTRACT

During the last decades the product lifecycle has been shortened and as a consequence the majority of manufacturing companies have focused on decrease the time to market. Several companies within the automotive industry have during the last years implemented *Simulation Driven Product Development* as a method to reduce lead time, increase quality and reduce development cost for their products.

This study is divided into three areas; (1) Investigate the applicability of Simulation Driven Product Development in a Lean Product Development environment. (2) Examine the preconditions for implementing Simulation Driven Product Development. (3) Study the possible effects in a product development process of using simulations performed by design engineers.

By studying available literature in the area of Lean and Simulation Driven Product Development the consistence of the two product development philosophies are rather high. Simulation Driven Product Development tends to support the principles of Lean as well as reduce different kinds of waste that normally is present at a R&D department.

In order to implement a Simulation Driven Product Development a number of preconditions were identified; e.g. knowledge and experience within both physical and virtual testing, cross functional synchronizations, trust for simulation results and incentives from management. These factors, among a couple of others, are according to the theory and case studies preconditions for a successful implementation where the primary case is based on Scania, but Saab Automobile AB, Jaguar Land Rover and AB Volvo is also analyzed in the benchmarking study.

Simulations performed by design engineers will increase the potential of Simulation Driven Product Development in several ways. A major finding from the study is that it enhances the understanding for properties of the items among design engineers. The increased understanding also increase the knowledge and decrease the learning cycle time for the design engineers. It also seems to be a resource efficient way since waiting times are reduced. The need of support from simulation groups might also reduce the communication barriers between different groups and increase the cross functional work.

Keywords: Simulation driven product development, Simulation driven design, Lean Product Development, Virtual testing, Automotive, Lead time, Scania, knowledge, Product Development Process.

SAMMANFATTNING

Eftersom produktlivscykeln blir allt kortare har utvecklingstiden för produkter fått ett ökat fokus. Inom fordonsindustrin har *simuleringsdriven produktutveckling* använts som en metod för att reducera ledtid samtidigt som kvaliteten förstärks och den totala utvecklingskostnaden sänks.

Detta examensarbete är uppdelat i tre olika områden: Det första utreder huruvida simuleringsdriven produktutveckling är förenligt med Lean produktutveckling. Det andra området fokuserar på förutsättningar för att kunna implementera en simuleringsdriven utvecklingsprocess. Det tredje och sista området fokuserar på konstruktörssimuleringars inverkan på produktutvecklingsprocessens effektivitet.

Förenligheten mellan Simuleringsdriven produktutveckling och Lean produktutveckling är hög, enligt befintlig litteratur. Simuleringsdriven produktutveckling stödjer flertalet av principerna till Lean samtidigt som det bidrar till att reducera slöseri på forskning och utvecklingsavdelningen.

De två andra forskningsfrågorna angrips med hjälp av litteratur såväl som fallstudier. Den huvudsakliga fallstudien genomförs på Scania, men även Saab Automobile AB, Jaguar Land Rover och AB Volvo studeras i syfte att öka examensarbetets generaliserbarhet. Studierna identifierar ett antal viktiga faktorer för att kunna implementera en simuleringsdriven produktutveckling: incitament för en förändring från ledningen, kunskap inom både fysisk och virtuell provning, tvärfunktionell synkronisering, en tydlig och framtung produktutvecklingsprocess och tillit till simuleringar.

Konstruktörssimuleringar kan på flera sätt höja potentialen hos simuleringsdriven produktutveckling. Det ger konstruktören en ökad förståelse för sin komponents fysiska egenskaper. Tät feedback från simuleringarna kortar inlärningstiden hos konstruktörerna och resulterar även i mer genomarbetade produkter. För att lyckas med dessa simuleringar krävs ett nära samarbete mellan konstruktion och beräkning vilket bidrar till att öka det tvärfunktionella arbetet och minskar kommunikationsbarriärerna mellan konstruktions- och beräkningsgrupper.

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PREFACE

This Master of Science thesis was conducted during the spring in 2012 on behalf of Scania CV AB. The study was a collaboration between the master programs Production Engineering at KTH Royal Institute of Technology and Supply Chain Management at Chalmers University of Technology.

We would like to thank our supervisor at Scania CV AB, Kent R Johansson for giving us the opportunity to conduct this study and for his support and continuous feedback on our work. His belief in this subject and our study has helped us getting valuable input and strengthen the importance of the research. We would also like to thank all the members of the steering group, Emil Axelson, Magnus Bergman, Hans Holmlöv, Patrik Karlsson and Johan Tingström, since they have has been a great resource for us to gain a broader understanding and a way to discuss our theories and results.

Further on, we would like to thank our supervisor from KTH, Per Johansson, who has helped us to assure the academic content and the scientific contributions. Thanks are also directed to Ola Hultkrantz, examiner at Chalmers, and Per Johansson, at KTH, for their approval to a collaboration between the two universities and that we have had the possibility to conduct the thesis together. It has been very valuable for us to address this study with two different academic backgrounds.

We would also give thanks to Tomas Sjödin, former employee at Saab Automobile AB, Jesper Blixt at AB Volvo, Lars Tengelin and Neville Johnson at Dassault Systèmes for their contribution to a broader perspective of this subject outside of Scania.

Finally, thanks to all the employees at Scania CV AB that have participated in the interviews and have taken their time to give an honest imagination of the current situation and contributed with suggestions for improvement. It is because of the open minded employees at Scania we fell proud to present this thesis.

This study has given us great insight about simulations within product development, but also about Scania and their organization and it will have a great value for both of us in the future.

Södertälje, May 2012

Sara Johansson

David Sätterman

CONTENT

1 INTRODUCTION

This chapter provides a background to the subject of this master thesis project. It also conducts the problem analysis and delimitations as well as an outline of the thesis.

1.1 Background

The product lifecycle has during the last decades been shortened, therefore time to market has been more crucial for all parties related to the product development process (Johannesson et al., 2005). Due to the increased focus on a shortened development phase of products, several companies have put effort to create efficient product development processes. Lead time is not the only important parameter; quality and cost are examples of other parameters that can be influenced by the product development process.

From a quality perspective the focus is not only to perform the tasks in an accurate way, it is also important to focus on the right tasks (Bergman & Klefsjö, 2010). In today's organizations it is common that they try to build in quality into the system. The Lean enterprise, originated from Toyota, uses the Japanese word Jidoka to describe how quality is achieved in production (Liker, 2004). Jidoka contains several different activities; e.g. automatic stops, error proofing, and in-station quality control. When Swedish enterprises talk about Lean, the Jidoka uses to be replaced by the expression "right from me", which also relates to build in quality into the system.

Another cornerstone of the Lean philosophy is the waste reduction; to achieve a Lean production several different types of waste needs to be minimized. The waste reduction in combination with the built in quality and continuous improvements is an important part of generating a high performing production site. A lot of attention is put into the production process and create efficient flow in production. However, the Lean enterprise has potential in several different areas outside production, e.g. product development and services (Liker & Morgan, 2006). Waste is not only present among blue-collar workers, it is likely that the waste awareness is at least equally important in the area of white-collar workers as well.

By studying the learning process of an engineer, trial-and-error cycles are important for the learning outcome (Jacobs & Herbig, 1998). An engineer in the field of mechanical engineering for instance needs to test a solution in order to get a feeling for how to handle strength behavior of different geometries. The learning-by-doing process gives the engineer the opportunity to enhance its skills over time and is a part of creating a learning organization. It is very seldom that the first solution to a problem or a task is the right one. Almost all solution is a result of an iterative process with a mixture of synthesis and analysis (Johannesson et al., 2005). Nowadays, Computer Aided Design, CAD, in combination with simulation tools can be used to create virtual models of the item. By using virtual model instead of physical prototypes the lead time has a potential of being shortened significantly (Johannesson et al., 2005).

The shortened lifecycle in combination with increased cost awareness and high demand of quality are driving forces to develop an efficient product development process. Both the philosophy of the Lean enterprise and simulation tools has potential to achieve increased efficiency in the product development processes. However, by combining them the product development process can probably be even more efficient.

Scania CV AB is one of the world leading manufacturers of heavy vehicles and marine and industry engines. The usage of its modular product system allows it to offer a big variation of products and a high degree of customization while keeping down the cost to its customers (Scania CV AB, 2011). To be as efficient as possible, Scania continually needs to improve their methods and processes to keep being profitable and competitive.

One of the most important demands for Scania's products is dynamic strength durability to achieve as high quality as possible. It is therefore a big focus on testing with physical prototypes in rigs and on test tracks in their product development process. To use physical prototypes is both expensive and time demanding. One way to become more effective is to reduce the numbers of physical test in the development projects. At the same time Scania aiming to achieve superior quality on their products and reduced lead time for the development projects.

1.2 Purpose

The purpose of this study is to investigate the current product development process at Scania and find benefits and drawbacks in the existing structure of the process regarding simulations and lean product development. The study also investigates how Lean principles and simulation driven product development can be integrated and what the limitations can be with these methods.

1.3 Problem Analysis

One of the biggest wastes for the R&D department of Scania is likely the rework made due to bad and uncertain designs of the components. The root cause can be the lack of knowledge when the design engineer needs to take decision about concepts in an early phase. This uncertainty can often be avoided by using an iterative simulation driven product development process.

Based on the background, problem analysis and purpose, three research questions are formulated in order to be answered in the result chapter of the thesis.

RQ1: How can iterative simulation driven product development be integrated with Lean product development concepts?

RQ2: What are the preconditions for a simulation driven product development?

RQ3: In what way can simulations performed by the design engineers improve simulation driven product development?

1.4 Delimitations

The study focuses on the mechanical engineering track of the product development process at Scania CV's R&D department in Södertälje, Sweden. The insights and potentials in the embedded system and software engineering processes will therefore be delimited. The reasoning of choosing the focus on the mechanical track is related to the university study background of the authors.

The study will primarily have the design engineers' point of view and investigate the need for simulation tools in the product development process. How engineers in the technical simulations process and the testing processes can use iterative simulation will not be investigated since this processes can be looked upon as supporting processes to the design process. Therefore will this study mainly involve interviews with design engineers, though both simulation engineers and engineers within physical testing will be involved.

The simulations that will be investigated in this study are mainly calculation focused simulations, especially Finite Element Analysis. Simulations within digital manufacturing and other areas outside of the Research and Development organization at Scania are excluded.

The study will investigate preconditions for implementing simulation driven product development. A *Yes-or-No* question regarding if simulation driven product development should be implemented or not is not the focus of the study since it already seems obvious to recommend it. Though, advantages and disadvantages regarding simulation driven product development will be analyzed and discussed.

1.5 Outline of the Thesis

This section comprises an overview of the structure and information of content for each chapter headline in the thesis

1. INTRODUCTION

This chapter gives an academic and corporate background to the subject of the study as well as clarifies the research questions who are supposed to be answered by the study. It is also aiming to emphasize why the topic of the study is of interest.

2. METHODOLOGY

This chapter provides the different methodologies used to achieve the output of the three research questions. It also comprises a reliability and validity discussion of the study.

3. THEORETICAL FRAMEWORK

This chapter provide a deeper understanding for the topic of the thesis. It gives an overview of Lean Product Development and Simulation Driven Product Development as well as introducing Scania specific theory in order to give an enhanced understanding for the specific circumstances for the study.

5. RESULTS FROM CASESTUDIES

This chapter is divided into two different subchapters. The first subchapter provides an case study used to analyze the current situation of Scania regarding the processes and usage of simulations. The second subchapter provides case studies from three other companies within the automotive industry, which is aiming to increase the generalizability of the study.

5. ANALYSIS AND DISCUSSION

This chapter concludes the analysis and striving to come up with output to the research questions. Findings from the theoretical framework and the results from case studies are used as basis for the analysis. The first section of the analysis has a general approach and investigates primarily RQ1 while the second part is more business specific and focus on RQ2 and RQ3.

6. CONCLUSIONS

This chapter comprises the result of the study. Each one of the three research questions are answered as well as it provides some specific recommendations for Scania of how to proceed with a simulation driven product development approach.

7. FURTHER STUDIES

This final chapter aims to provide recommendations of areas feasible for further studies where the thesis lack in depth or areas which has not been included in the study.

2 METHODOLOGY

This chapter is going to highlight the different research methods that will be used during the project and connect each method to academic theories.

2.1 Method Model of the Study

This master thesis project is performed at the R&D department of Scania CV AB and emphasize the possibilities of implementing a simulation driven product development process. In addition to Scania, other companies implementation of simulation tools are being studied both through primary data, i.e. data collected in the study through interviews and written correspondence, and secondary data, i.e. data and information collected by someone else accessible through articles and conference material (Björklund & Paulsson, 2007). Due to the company focus, the research design of the study is a case study. Davidsson and Patel (2003) emphasize that the case design is useful when studying a process and possibilities of change, which is analogous to the objective of this study. By using a case study approach it is possible to use several different methods to collect data such as interviews, document and observations (Yin, 2008). Wallen (1996) emphasizes that a case study gives the possibility to gain knowledge and great depth understanding for the focal company.

A case study has limitations and drawbacks as well, Wallen (1996) highlights that it usually is very time consuming and it might be difficult to finish the study. Another disadvantage is that if the study is too closely connected to a certain case it is a risk to lose its general applicability. To handle the time issue, the delimitations are a key by delimiting the scope of the outcome within appropriate time. The theory framework as well as benchmarking cases from other companies give the scope of this thesis a broader perspective than it would had if it only would have been a case study of Scania.

The method model, see Figure 1, describes the procedure of how data and knowledge is gained in order to answer the three research questions; RQ1, RQ2 and RQ3.

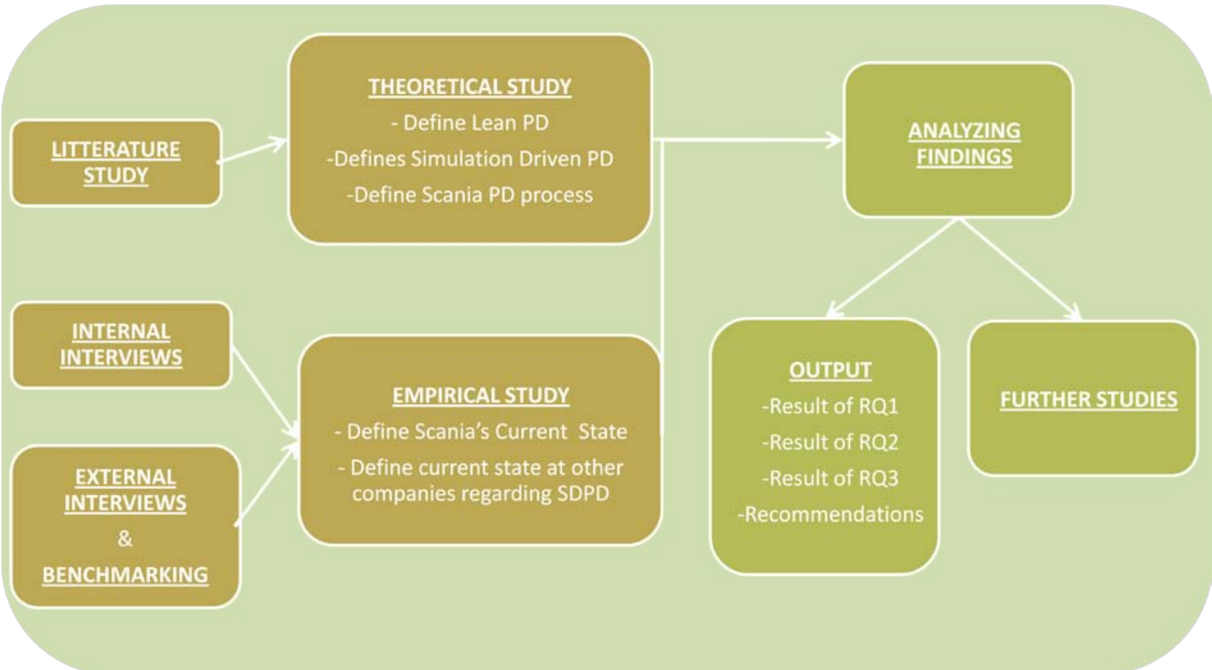

Figure 1 Method model for the Study

The procedure to generate the output of the research questions differ some depending on the questions, therefore the method is presented individually in following sections.

2.1.1 Method to find output to RQ1

RQ1 is not company specific and has more of an academic approach than the other research questions. Therefore, the answer to the questions is found by a literature review, which is carried out to develop the theoretical framework. A literature review is a cheap and rather quick method to gather information for a study (Björklund & Paulsson, 2007). To get an enhanced understanding for Lean Product Development, several different kinds of sources is used describing the philosophy in different ways. It is easy to find sources about this subject so the challenging part is to filter what sources that actually contributes to the framework. Since the research within simulation driven product development is limited, it is more difficult to find accurate literature about the area. Therefore the subchapter about this field in the literature review is more related to best practice examples than academic reports. A simulation driven product development's impact on the values of Lean product development are then analyzed in order to find out whether the Lean and Simulation Driven Product Development is consistent or not.

2.1.2 Method to find output to RQ2 and RQ3

RQ2 and RQ3 share the same methodology to receive the output to the questions. The study has its origin in the theory chapter. Based on the theory, conclusions from the specific areas presented in the results from case studies chapter are drawn. This kind of research there theory is used as a starting point for principles followed by conclusions for a specific case is known as a *deductive* research approach (Davidsson & Patel, 2003). The results are based on the case study concluding qualitative interviews with in total 63 participants. A qualitative study has the advantage of providing as depth of understanding for the specific situation (Holme & Krohn, 1997). Another advantage is the flexibility of the method; it is easier to adapt a qualitative study during a project than to adapt a quantitative. However, a qualitative research might be influenced by the interpretations when transferring information between the interviewee and the researcher (Bryman & Bell, 2011). When using qualitative research instead of quantitative it is also an increased risk of decreasing the study's generalizability (Björklund & Paulsson, 2007).

2.2 Data Collection

According to Andersen (1994), there are three ways to collect data: *(1) Document studies*, *(2) Observations* and *(3) Interviews.* Which method that should be used should depend on the purpose of the investigation, the case background, the length of the study and available resources.

2.2.1 Document Study

The purpose of the document study is to use data that is already spoken, written or published (Andersen, 1994), e.g. literature, annual reports and articles. The documents used in this study are mainly books and articles from journals, but master thesis reports, webpage information, conference documentation and internal documentation at Scania is also used when there is not any book or journal article in the specific subject. According to Andersen (1994) more general documents should be used in the beginning of the study to than narrow the subject and read about more specific areas. Therefore are books about lean in general first read to than later narrow the subject for the literature, i.e. journal articles about simulations within product development and lean product development.

2.2.2 Observations

Through observations, either *participating observation* or *non-participating observation,* the social behaviors can be seen directly (Andersen, 1994). The researcher is always in direct contact to the objects been observed and observations are preferably used in the beginning of the study to create a more clear view of the problem (Andersen, 1994).

This study includes different types of smaller observations, all non-participating, to get a better overview and understanding for different areas regarding simulation and development projects. The observations sometimes lead to some supplementary questions in order to deepen and secure data from the observed situation. Examples of observations are pilot projects regarding simulation performed by design engineers, interference analysis secession and project planning meetings.

2.2.3 Interviews

An interview can be performed either verbally or written through a survey (Andersen, 1994). All interviews for this study are verbally while some follow-up questions are answered through written correspondence.

To gather information about the product development process at Scania, interviews are made in three rounds; Pre-study, first round and second round. Interviews can be divided into *structured, semi-structured* and *unstructured* (Björklund & Paulsson, 2007). The pre-study interviews are made with a selected few people to get an overall picture of the process and most of this interviews are unstructured since the authors has not knowledge enough at this time to define areas and relevant questions. The first round of interviews is then with many more people in different areas at R&D to get a both broader and deeper perspective. Here are the interviews semi-structured since a semi-structured interview has the discussion area predefined and the interviewer has prepared some open questions (Björklund & Paulsson, 2007). All the semi-structured interviews in this study are recorded and one person will lead the interview and ask questions while the other interviewer will take notes and make sure that no questions are forgotten.

The last round of interviews are more of a discussion based type where different conclusion made from the first round are discussed and analyzed together with mostly the same persons from the pre-study interview round. These interviews are sometimes unstructured and sometimes semi-structured depending on the subject.

There are also interviews and reference visits hold at other companies than Scania. This interviews and visits are made after the first round of interview at Scania so a comparison can be made more easily and what is relevant to study at the other companies is clearer. The reference visits are made within the automobile industry since it is an industry that has applied simulation driven product development and Lean product development in a larger scale and have used it for a longer period of time. For Saab Automobile AB and AB Volvo, the interviews are made directly with the employees while for Jaguar Land Rover, they are held through Dassault Systèmes.

All interview rounds are qualitative and not quantitative since knowledge and understanding about the product development process are more important than a large number of data. Although some quantitative questions might be used during the first round if there is a desire to compare different departments internally or with external companies regarding working hours or economical aspects of product development.

2.3 Reliability and Validity

Regarding validity, it is divided into internal and external validity (Bryman & Bell, 2011). The external validity is how much the study can be generalized (Bryman & Bell, 2011) and the internal validity is about the methods used to really measure what was intended to measure (Gripenberg, 2006) and this can be achieved by triangulation (Bryman & Bell, 2011).

Since this study does not only contain the case study at Scania, but also a literature review and benchmarking at other companies the external validity is fairly high. The internal validity is ensured by continuously having a dialog with both the supervisor and the steering group members about methods used for the study and by letting them read both the theoretical framework and results from case studies during the study to cover up gaps or correct misunderstandings.

According to Bryman and Bell (2011) the reliability is whether a study is repeatable or not. The reliability to this study does depend on the way correspondents to the interviews are chosen and how the questions and answers can be interpreted. When correspondents are chosen, a conscious the selection should be made regarding what would give the best result (Creswell, 2003). In this study, all the correspondents chose to participate or not and when choosing persons to the interviews, it will be employees with a good analytic skills and an aptitude to express opinions be preferred.

The language used at the interviews at Scania does include internal terms. When using these terms in the thesis, first translated to a more general language and than from Swedish to English it might be more difficult to interpret. Therefore the reliability of this thesis is also dependent on how well the internal terms are described.

3 THEORETICAL FRAMEWORK

This chapter is aiming to give a deeper understanding for the subject and current research. The chapter starts by describing traditional product development and Lean product development. Next section describes simulation driven product development and its precondition. It also comprises a briefly introduction to different simulation methods. Finally the chapter introduces the specific circumstances for product development at Scania CV AB.

3.1 Product Development in General

The product development process at different companies has developed during the last century. In the beginning of the 20th century it used to being more of single craft man role to develop a product from scratch until it reach fulfill the needs of the customer. Nowadays product development to comprise large complex organizations there several individuals are experts in a more specific field.

3.1.1 Traditional Product Development Processes and Methodologies

According to Ward et al. (1995), the traditional U.S. product development process is influenced by Shingley's book *Mechanical Engineering Design.* Shigley (1963) suggest an approach based of stepwise iterations. The engineer should start by understanding a problem and when the problem is understood a solution is generated. Based on next step the solutions is adapted to fulfill the targets it did not reach in the first run, see Figure 2. Even though the upcoming phases are not involved in the previous steps, Shigley puts effort to the importance of making decision based on knowledge. Shigley's approach use to be named Point-Based Concurrent Engineering (Ward et al., 1995).

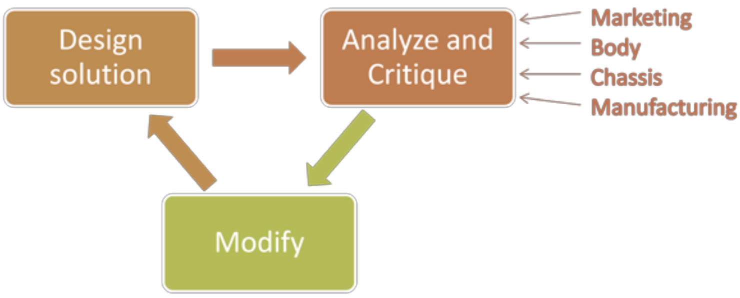

Figure 2 Example of Point-based engineering approach

Johannesson et al. (2004) introduce some different methods for development processes common in Swedish industries. One example of a process is the axiomatic product development process. It contains four different sub-processes; (1) *A problem definition process* in which the customers' needs are defined and transformed to functional requirements and constraints. (2) *A creative synthesize process* where design parameters are generated in order to fulfill the functional requirements from previous phase. (3) *An analysis process* there the different alternatives are evaluated by simulations. (4) *A validating process* there the final solution is verified to fulfill all requirements in the specification. Johannesson et al describe a stepwise approach where different phases are quite separated from each other and there is a lack of cross-functional work, except for phase shifts when the knowledge is transferred between departments.

Another process described by Johannesson et al is the systematic product development process. The first step in this approach is the product specification phase in which the specification and needs for the product are created. Next phase is the concept generating phase. In this step, several possible solutions are combined and compared in order to find the best one. A concept is often chosen from matrices where the designer compares benefits and drawbacks of each one to finally choose one concept. Since the cost for changes is low in the start of a project it is important to evaluate the concepts early (Johannesson et al., 2004). The concepts are evaluated with the specification in mind and have to fulfill the requirements to not be eliminated. The design engineers tend to do the concept generation and elimination with only limited support of cross functional competence. Firstly after the concept generation phase has come to its end the cross functional functions are involved in order to improve and validate the chosen concept, see Figure 3.

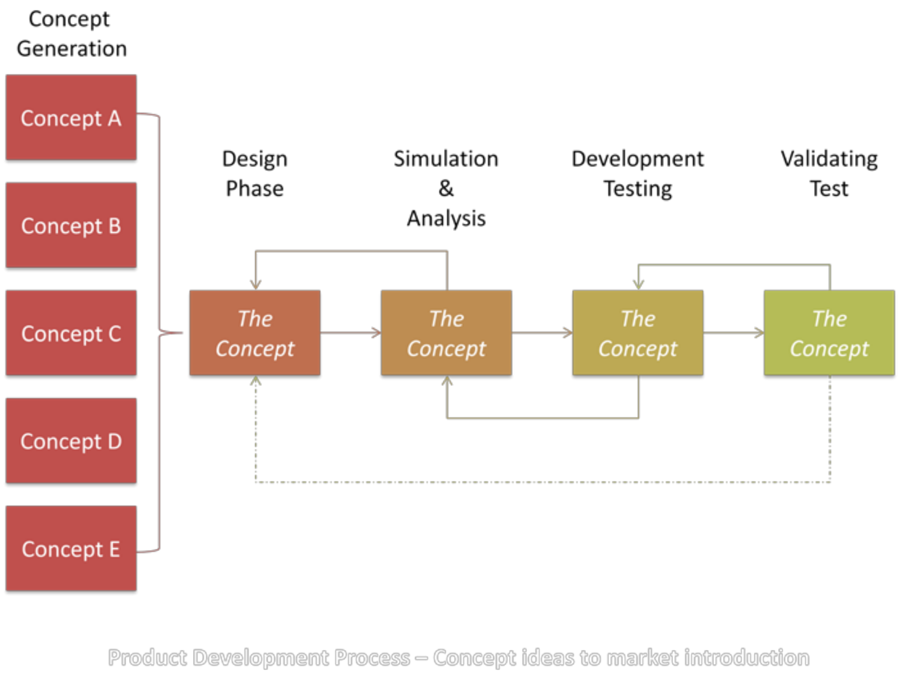

Figure 3 Illustration of traditional Swedish approach of product development processes

Johannesson et al. emphasizes the importance of frontload decisions in the processes due to increasing cost along the timeline. Both processes described above do suggest an approach where the concept is chosen primarily on the basis of the design engineers knowledge and skills.

3.1.2 Different Roles in the Product Development Process.

The engineer role was founded during the industrialization, in the 19th century (Johannesson et al., 2004). Before the industrialization took place it was all about handcraft. One single person used to be responsible for the styling, design and manufacturing for a product. During the industrialization, the styling and design became separated from the manufacturing and the engineer as a profession took place. However, even though the engineer has become more specialized than what craft work used to be, it had a wide spectra of tasks and responsibilities. On other areas, the same individual was in charge to secure the supply of raw material and choosing manufacturing techniques. The origin in craft also made the design of the products quite artistic; one example is the old steam locomotives from the 19th century that is both functional and very esthetic (Johannesson et al., 2004).

During the 20th century the role of the engineer has changed (Johannesson et al., 2004). Since the development project has grown in range it is a need for more specialized competence, see Figure 4. Examples of new roles connected to engineering were for instance; design engineer, simulation engineer, testing engineer, styling engineer, material expert, production engineers, purchaser and project manager.

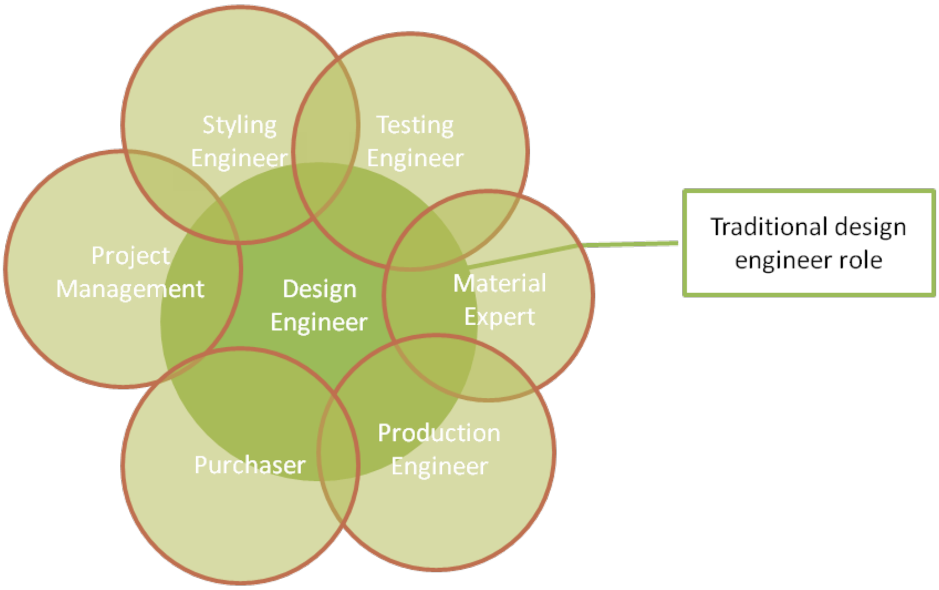

Figure 4 The new roles of engineering

The *design engineer* has focus on the design and it needs to interact with all other functions. The *simulation engineer* has together with the *testing engineers* often a shared responsibility to validate the durability of the design. The *styling engineer* focus on the esthetic part of the design, they often also have the responsibility for the ergonomics. *Material engineers* have core competence in material properties, it is often a research function that supports the design engineers with feasible alternatives when it comes to the choice of raw material. The *production engineers* are responsible for the manufacturability of the design and how it will be manufactured. The *purchaser* source raw material as well as have the contact with sub-contractors when outsourcing is used. Since the projects have become more complex and involve lots of different functions, a coordinator is needed; this is the role of the *project manager.*

The roles in the product development process has changed during the last centuries, from a individual job with a wide spectra of different kinds of responsibilities, to complex team activities where each individual's core competence is needed in order to success with a development project.

3.2 Lean Product Development

The Lean enterprise originates from Toyota Motor Company, but the term *Lean* was first introduced in 1991 in the book "The machine that changed the world" (Morgan & Liker, 2006). In this book, Jim Womack and Daniel Jones (1991) used the term *Lean manufacturing* as doing more of everything with less of everything. The Lean manufacturing system was described as a better, faster and cheaper production system with less inventory and labor hours required (Womack & Jones, 1991). Womack and Jones are though fast to point out that Lean manufacturing is just one part in the Lean enterprise, which also includes marketing, distribution, accounting and product development. Although, most companies has just focused on the manufacturing part of Lean (Morgan & Liker, 2006). It is a good first step, but according to Morgan and Liker (2006), you need to take the second step upstream to product development in order to become a Lean enterprise. However, in the book about Lean product development at Harley-Davidson, *"The Lean Machine",* Womack points out that you should not bring Lean manufacturing upstream to product development, (Oosterwal, 2010). Womack emphasize that the Lean aspects within manufacturing and product development are very different and even though they might seem similar at first sight he recommends that an expert in Lean manufacturing should not give advice within Lean product development (Oosterwal, 2010).

According to Allen Ward, Lean product development is about knowledge-based product development which has its origin from Orville and Wilbur Wright (Oosterwal, 2010). The dream about flying was an obsession among humans during the 1900's and Ward therefore saw it as astonishing when the first ones creating a flying machine operated by humans did not come from a university, government or big company, but from two uneducated brothers. Ward emphasize that the Wright brothers did not just invented the first airplane, but they also invented a new way of developing products. They created a wind tunnel to test different air foils in order to create trade-off curves and gain knowledge about aerodynamics (Oosterwal, 2010). Instead of first designing an idea and then test it, the Wright brothers first gained knowledge about wing profiles, power application and dynamics of the airplane which they used to design a possible solution. This approach resulted in a process that took them about $1000, five years and a powered flight at the third attempt (Oosterwal, 2010). According to Ward the Wright brothers' method was then used during World War II to create airplanes with a very short lead time and those engineers later ended up at Toyota Motor Company after the war ended (Oosterwal, 2010)

Liker and Morgan (2006) wanted to find the answer to what the underlying principles of product development were that had made Toyota so successful. They identified 13 principles built on three subsystems: (1) Process, (2) Skilled People and (3) Tools and Technology, see Figure 5.

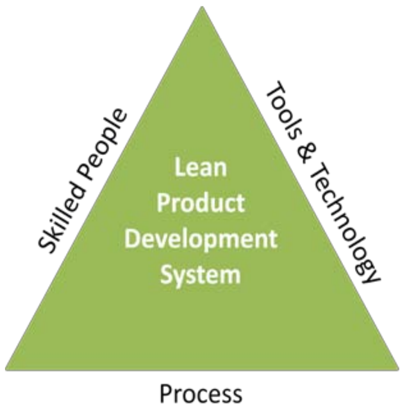

Figure 5 Coherent systems approach to product development (Morgan & Liker, 2006)

These three subsystems are further defined with 13 principles, see the box below.

THE 13 PRINCIPLES OF LEAN PRODUCT DEVELOPMEMT SYSTEM (MORGAN & LIKER, 2006)

The Process Subsystem: Includes all the activities and the order of the activities required to bring a product from idea to start of production. Starts with the raw material, information of customer needs, competitive product data and engineering principles, which is being transformed to the engineering of a product built by manufacturing.

- ***Principle 1:*** *Establish Customer-Defined Value to Separate Value-Added Activity from Waste.* Define your customer is always the starting point in a Lean system. Than define what your customer wants. Everything that is not of value for your customer is waste. In product development, waste is divided in to two broad categories: *Waste created by poor engineering* and *Waste in the product development process itself*.
- ***Principle 2:*** *Front-Load the Product Development Process While There Is Maximum Design Space to Explore Alternative Solutions Thoroughly.* The earlier several alternatives are explored, the more opportunities are still possible. Therefore, Toyota puts most of the work and effort as early as possible, also known as front-load, in its projects. The problem solving is made with several possible designs and by using this set-based (parallel solutions) approach, it increases its chance of finding the optimal solution.
- ***Principle 3:*** *Create a Leveled Product Development Flow.* Once value is defined, waste can be reduced from the process in order to achieve a waste-free Lean Product Development System. A Lean Product Development System is a knowledge work job shop which can be continuously improved by eliminating waste to level workload, synchronize cross-functional processes and to reduce rework to a minimum.
- ***Principle 4:*** *Utilize Rigorous Standardization to Reduce Variation, Create Flexibility and Predictable Outcomes.* There are three types of standardizations used by Toyota: (1) *Design standardization*; achieved through common architecture, modularity and shared components. (2) *Process standardization;* made by designing components based on a standard manufacturing process. (3) *Engineering skill set standardization*; used to have a flexibility in their staff and project planning.

The People Subsystem: This subsystem covers recruiting, training engineers, leadership, structure of the organization and the culture including language, symbols, beliefs and values.

- ***Principle 5:*** *Develop a Chief Engineer System to Integrate Development from Start to Finish.* The Chief engineers role is to be the project manager, the leader and technical system integrator. Since the chief engineer has the full responsibility of the project, this person knows exactly the status of the project as it also knows all the technical details.
- ***Principle 6:*** *Organize to Balance Functional Expertise and Cross-Functional Integration.* This principle is how to find the balance between functional expertise combined with a seamless integration between the different disciplines. Toyota is functional organized and is integrated through the chief engineers, module development teams and an *obeya* (big room) system, where cross-functional meetings are held.

- ***Principle 7:*** *Develop Towering Technical Competence in All Engineers.* Since the automobile is such a complex system it is of great interest to have a lot of technical excellence in many different areas, like aero and fluid dynamics, mechanics, electronics and computer technology. Although many automotive manufactures put more effort into broaden their engineers rather than encourage them to deepen in their subject. Internal courses and training can sometimes be so general that it value can be questioned. At Toyota the focus lies in learning more core engineering in their own area, rather than getting a MBA.
- ***Principle 8:*** *Fully Integrate Suppliers into the Product Development System.* Since suppliers usually provide more than 50 % of the vehicle, they need to be a part of the Lean Product Development System. The same way a company manage and nurture their own manufacturing and resources should the suppliers being managed and nurtured. Suppliers are involved form the earliest stages in the development process and provide Toyota with guest-engineers to work full-time at Toyota in order to integrate them more with the company.
- ***Principle 9:*** *Build in Learning and Continuous Improvement.* The most sustainable advantage a company can have is the ability throughout the organization to learn and improve.
- ***Principle 10:*** *Build a Culture to Support Excellence and Relentless Improvement.* Since the core values are seen in the Toyota work, the culture supports the principles and makes it a living part of how Toyota gets things done.

The Tools and Technology Subsystem: This subsystem consists of the CAD systems, digital manufacturing and machine technology as well as the “soft” tools used for problem solving, learning and best practice.

- ***Principle 11:*** *Adapt Technology to fit your People and Processes.* Adding new technology tools must be made so it becomes integrated with the already existing process or it will probably retard the work rather than help. Toyota works hard to adapt its design software and digital simulation to the Toyota way.
- ***Principle 12:*** *Align your Organization through Simple, Visual Communication.* One main tool used is *hoshin kanri*, known as breaking down big corporate goals into meaningful objectives at working level. It is also used to break down vehicle objectives down into system objectives for performance, weight, cost and safety. Toyota also use simple, visual methods for communications like A3-sheet reports with only the most important, knowledge-based information on them.
- ***Principle 13:*** *Use Powerful Tools for Standardization and Organizational Learning*. In order to work with *kaizen,* continuous improvement, standardization is required. This occurs on all levels from the overall design process down to individual engineering check-lists.

The principles should be seen as points to discuss rather than rules and they would not explain how Lean product development works in reality. To learn the principles and the Lean product development process should be done step by step, like peeling of one layer at the time from an onion (Morgan & Liker, 2006). The more layers you had peeled away, the sooner you will discover the basis of both Lean manufacturing and Lean product development: *the importance of integrating people, processes, tool and technology to add value to the customer and society* (Morgan & Liker, 2006).

3.2.1 Knowledge-Value

Compared to Lean production, Lean product development is focused more on knowledge flow than the flow of physical objects. While manufacturing creates the actual products, development creates the operations how to manufacture the products and usable knowledge. Therefore the biggest value adding activity in development is to create new knowledge(Ward, 2007). According to Ward(2002) missing or unused knowledge is the reason to project failure and knowledge is created by three types of learning:

- *Integration learning* is about your customers, supplier, manufacturing, the product usage and environment, etc. From here the knowledge can be found of how to develop regarding to other criteria and the surrounding environment.
- *Innovation learning* is the knowledge of how to create new concepts and possible solutions to problems.
- *Feasibility learning* is about taking the right decisions and chose the best concept or solution regarding to cost, quality and time.

Ward mentions that useful knowledge from both the integration learning and feasibility learning is a critical part of the development process since it is here you can gain time and effort by avoiding mistakes (Ward, 2007). By turning data into readable and understandable information the results from analysis and test can be more widely spread and understood.

One way to transforming data to be more easily understood is to use trade-off curves for different product preferences (Ward, 2007). They are used to see how close to the limit you are by letting a parameter differ (Holmdahl, 2010) and these curves should be the center of the development activities (Ward, 2002). One example could be a diagram, depending on a screw dimension, with curves showing how it will affect bearing stress, sheer stress and tensile stress, see Figure 6. By displaying it as curves instead of tables makes it easier to reuse the knowledge gained from the test by others not familiar with the original test. The strength with the curves is how easy it is to see if you are beneath a safety zone or not, by drawing red lines, limit curves, for the mandatory criteria (Holmdahl, 2010), see Figure 6.

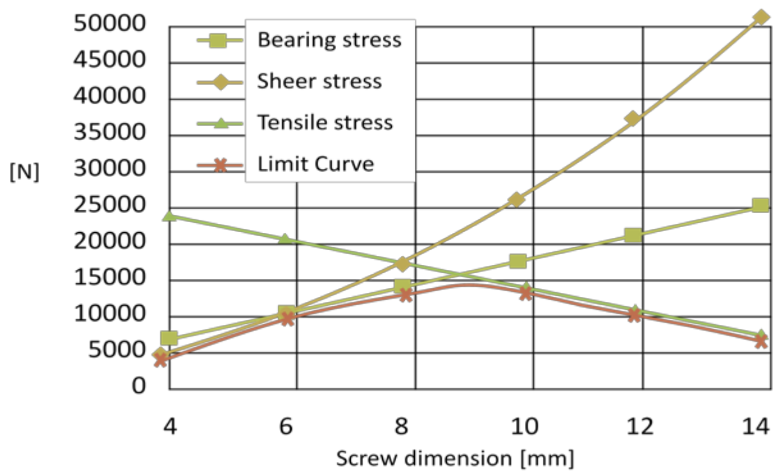

Figure 6 Example of trade-off curves

Since the methods today are more specialized, engineers are either a design engineer working with Computer-Aided Design, CAD, or a calculation engineer working with Computer-Aided Engineering, CAE, i.e. Finite Element Method, FEM and Computer Fluid Dynamics, CFD (Holmdahl, 2010). It is more important to be able to understand the different needs. However, the role of the design engineer might change over time since different CAE tools are becoming more integrated with the CAD-programs. Many software providers believe that the next generation of design engineer does, except for specific product areas, need more insight in CAE tools (Honeywill, 2008).

Ward has two learning cycles which can be used to create knowledge. One is the value-adding cycle, see Figure 7, and the other on is the LAMDA™-cycle, see Figure 8. The cycles are similar in many areas and both of them handle how to handle problems and gain knowledge from them.

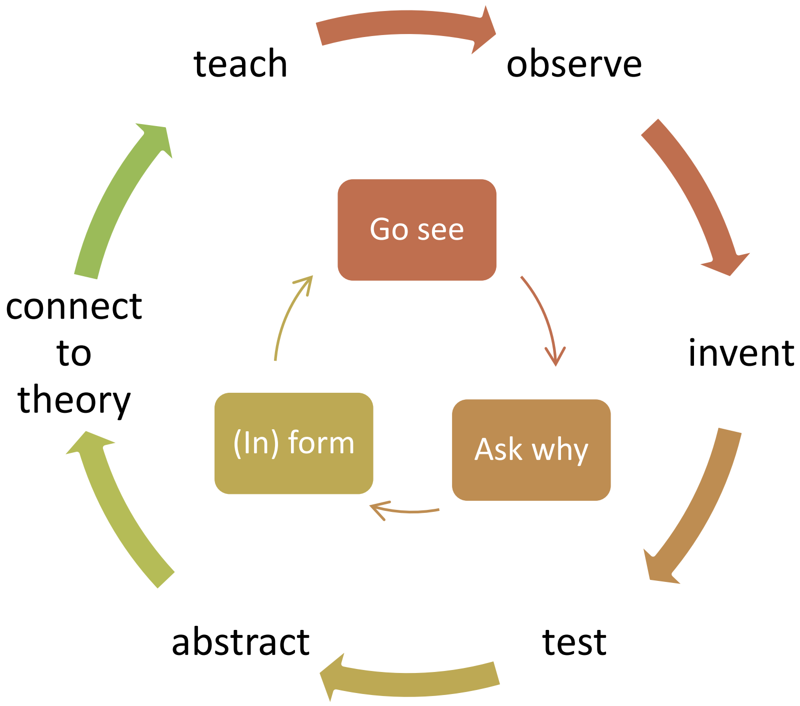

Figure 7 The value-adding cycle (Ward, 2007)

Go see can also be referred to as *Genchi Genbutsu*, *go and see* or *go to the gemba*. Literally *Genchi Genbutsu* means to focus on the actual part, the actual place (Morgan & Liker, 2006). It means that you should go to the place (or person), the gemba, where the problem or work actually happens to understand with own eyes the current reality (Liker, 2004). This activity is called *Look* in the LAMDA™ cycle (Ward, 2002), see Figure 8. For a design engineer the *go and see* activity can be to walk through the assembly line, talk with a customer or see an experiment (Ward, 2007). Many engineers today dedicate their working hours to either meetings in conference rooms or working at their desk, very few get to see the actual products, especially while it becomes more common with outsourcing manufacturing and virtual engineering without any physical prototypes (Morgan & Liker, 2006). One important *Genchi Genbutsu*-activity, according to Liker and Morgan, practiced by Toyota is the prototype building phase (2006). Early in the project the engineers themselves get to mount on their prototypes to the vehicle in order to get knowledge about the surroundings and get a feeling of their own design.

Ask why, also referred to as *The Five Why:s* or *Ask* in the LAMDA™ cycle, is meant to find the root cause for different problems (Liker, 2004). According to Liker, Toyota asks *Why* five times to go down all the way from there the problem started in order to get rid of the real problem and does not just do a quick-fix solution. Ones you reached the root cause, it is time to find a solution for it. This can be done by the next step, *(In)Form* or *Model-Discuss-Act,* see Figure 7 and Figure 8. The *"Five why"* process has unfortunately become a *"Five Who"* process of blame at many companies, including Harley-Davidson and it is important that the learning process stays around the "why" and not the "who" in order to be effective (Oosterwal, 2010).

The *(In)Form* part in the cycle is there we *form* the information gained from the other steps (*Go see* and *Ask why)* into something usable like a drawing, prototype, report or equation. These are also used to inform others (Ward, 2007). According to Ward, many organizations fail with the value-adding cycle for two reasons. The first reason is that not all steps in the cycle are performed, or sometimes not even aware of, all steps of the outer cycle, see Figure 7 . The second reason is that you are taught in school that you learn by repeating the teacher and very few lessons is about inventing something new yourself. We learn that scientific and mathematical principles are already known and there is nothing more to discover, but since all the competitors also know Newton's laws, engineers have to learn how to discover and learn new knowledge in order to gain competitive advantages (Ward, 2007). Therefore Lean companies know that they have to teach the engineers how to learn besides the traditional educational system and that is the primary source of Lean competitive advantage (Ward, 2007).

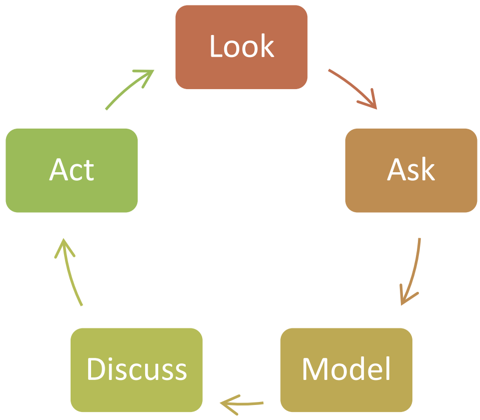

Figure 8 LAMDA™ cycle (Ward, 2002)

Model in the LAMDA™ cycle can be the same as the form in the value-adding cycle. The important thing is to create easily understandable models that are clear and visual (Ward, 2002). *Discuss* can be replaced with the Inform activity which has its purpose to spread the knowledge and get opinions from many different areas. When all the information has been found, analyzed and discussed, you can finally *Act* and implement a solution for the problem (Ward, 2002).

3.2.2 Definitions of Waste

In order to work with continuous improvement you need to define value and waste, so waste can be eliminated (Morgan & Liker, 2006). Ward (2007) categorizes the activities in product development into three different kinds; *(1) value adding*, *(2) non-value adding but necessary* and *(3) waste*. If activities should be classified as value adding or not depends on what the process is supposed to deliver. It might be a drawing, a solution or knowledge to the operation. What waste is, depends on the expected outcome, the company and the department. For product development, waste has been explained by both Ward (2007) and Morgan and Liker (2006) in different ways.

3.2.2.1 Waste according to Morgan and Liker

Morgan and Liker (2006) define waste in product development as any activity in a process that needs resources without adding value for the customer. They have divided waste activities into seven categories, see Table 1. These categories are originally mentioned in the Toyota Way (Liker, 2004) for Lean production, but with some changes it can be used for product development as well (Morgan & Liker, 2006).

Table 1 Seven categories of waste (Morgan & Liker, 2006)

Waste category	**What does it mean?**	**Example in product development**	**Example in manufacturing**
Overproducing	Producing more or earlier than the next process needs	Unsynchronized concurrent tasks, too much information in the report	Producing ahead what is actually needed by the next step or the customer
Waiting	Waiting for material, information or decisions	Waiting for simulation results, prototypes or decisions	Operators waiting for material, waiting while an automatic machine is running
Conveyance	Moving material or information from place to place	Unnecessary hand-offs, information changing hands by word, pictures or data	Moving parts or products unnecessary long distances
Processing	Doing unnecessary processing on a task or doing an pointless task	Engineering errors, reinvention, simulation on the wrong model – lack of standardization	Unnecessary or incorrect processing
Inventory	A build-up of material, models or information that is not being used	Information waiting in queues to be processed, hides problems in the information	Direct result of overproduction. Having more in stock than the required minimum for a pull system
Motion	Excess motion or activity during task execution	Long travel distances, unnecessary meetings and project reviews	Unnecessary movement for the operators. Reaching or looking for tools and parts
Correction	Inspection to catch quality problems or fixing an error already made	Rework, late changes, excess tool tryout	Inspection, rework and scrap

The goal for Lean is not only to eliminate waste, *muda,* but to eliminate the three dimensions of waste, *muda, mura and muri* (Morgan & Liker, 2006).

THE THREE M:S (MORGAN & LIKER, 2006)
Muda *(non-value added):* Includes all the seven wastes mentioned in Table 1. Any activity that add cost or lengthen the lead time to a product without support from the customers need is should be considered as *muda.*
Muri *(overburden)***:** When a machine, process or person is pushed to work beyond it natural limits. Can cause quality problems and safety risks which will lead to rework.
Mura *(unevenness)***:** Sometimes it is too much work for the engineers right before deadlines, which usually follows by a calm period with little to do. An uneven workflow will create *muda* and *muri.*

3.2.2.2 Ward's Definition of Product Development Waste

Ward (2007) has a different definition of waste in product development compared to other studied authors. The focus is on waste of knowledge, where Ward uses three different categories to describe it, see Figure 9.

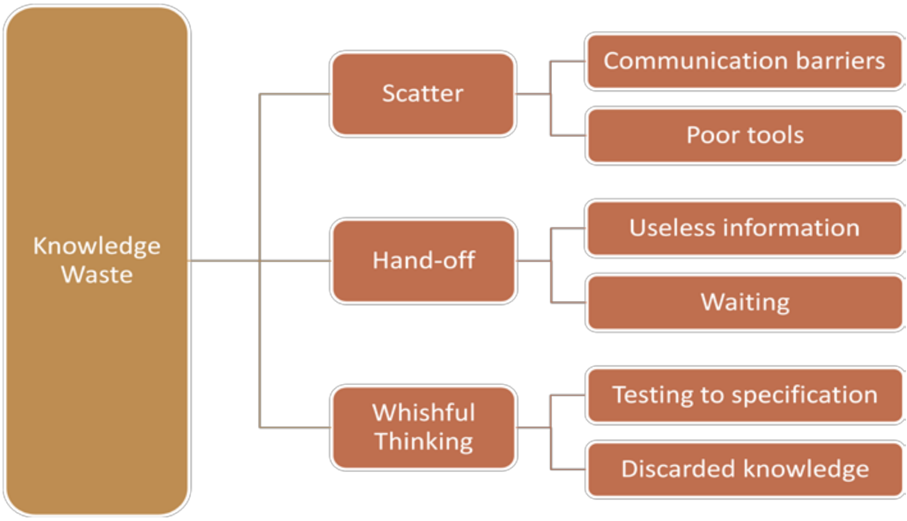

Figure 9 Knowledge waste in product development processes adapted from Ward (2007)

Waste caused by Scatter

Scatter is common in the processes in many different ways. It can be from a time perspective; employees' time is scattered among different tasks and a set up time is required each time an employee is interrupted. According to Ward (2007), it is a common contra productive behavior when a project is delayed. Imagine a design engineer waiting for a prototype, when it is worried about the delayed delivery it calls the purchasing department several times a week. Due to that, the purchasers are interrupted in their work by answering calls from worrying engineers and they cannot focus on their main task. Ward highlights two main root cause categories for scatter; *Communication barriers & Poor tools.*

Communication barriers

Lack of communication is a common source of scatter waste. It might be *physical barriers* that make it impossible to share knowledge, e.g. incompatible computer software or departments located far away from each other. Another issue in communication is the *social barriers,* these might be caused by lack of vertical and/or horizontal integration within the organization. However, too many meetings will keep the engineers busy and slow down the process (Ward, 2007). *Knowledge barriers* drives communication issues, if the receiver does not have sufficient knowledge to understand the information it receives, the message is lost and the knowledge will be wasted. A fourth category of communication barriers is the *information channels,* it is related to how information is distributed and stored in the organization.

Poor tools

If the process is too detailed, the engineers are forced to use tools that are not sufficient for their certain situation (Ward, 2007). However, according to Ward standardization should be used to create a robust process. The same task should be performed in the same way every time. But the focus should be on how to transfer data to knowledge, not a detailed step-by-step instruction.

Waste caused by Hand-Off

This category is about separating knowledge, responsibility, feedback and action from each other (Ward, 2007). The effect of *Hand-off* is that decision making is made by people that either have a lack of knowledge in the subject or not having the authority to carry out the decisions (Ward, 2007). An example of hand-off is when companies divide the responsibility for the engineering design among CAD-operators and analysts. Ward introduces two different root cause categories for Hand-off; *useless information* and *Waiting.*

Useless information

A lot of time in a developer’s working day is used to pursue useful information among useless information, a result of scatter. Sometimes useless information is related to overproduction. Some engineers tend to get stuck in endless optimization for a project or designing new products when the old ones were good enough to keep.

Waiting

In production, the sequence thinking is obvious an item that flows through the processes. However, Ward (2007) emphasizes that the sequence thinking is not suitable for a product development environment. In product development the next process has to influence the previous one to create a successful solution. Ward suggest cross functional teams from the earliest phase in the projects to create an enhanced understanding and broader perspective of possible solutions. Involving an analysts too late in the project might cause a lot of rework.

Waste caused by Wishful thinking

Many developers come up with a specification in an early phase of a development project. However, due to development lead times it is uncertainties in the customer demand and often the customer does not really know what it wants at this stage (Ward, 2007). Actually, the design decisions are then based on speculation and guesses instead of data and facts.

Some design engineers tend also to stick with a concept or solution from a very early stage. If this happens it is impossible to ensure that the solution actually is the best possible solution to fulfill what the customers really wants (Ward, 2007). Wishful thinking is derived to two root causes; *Testing to Specification* and *Discarded Knowledge*

Testing to Specification.

Ward (2007) doubts the behavior of testing to specification. A test cannot verify that a product is ready for the market, it is impossible to do enough tests to check e.g. fatigue issues. When U.S. car manufacturers were benchmarked to Toyota, Ward found out that Toyota uses 70-90 percent less prototypes. However, Toyota still outperforms the U.S. manufacturing regarding quality.

Testing is necessary during the product development process, but should be used in the right way. According to Ward it should be used to gain the knowledge in order to avoid traps. Testing engineers and simulation engineers should come up with the answer and knowledge of why a concept breaks down and suggest improvements to the design engineer even if it actually fulfills the specification. Ward suggest two different kinds of testing. The first category is tear down testing where the test runs until the item breaks in order to gain knowledge, notice that the test should not be stopped when specification is fulfilled. The second one is validating testing in the final state of the development process in order to validate the concept as well as the manufacturing process.

Discarded Knowledge

According to Ward (2007), it is crucial for the knowledge development how knowledge is handled and created during a project. Focus is often on the lead time and getting the product to market, not how to sustain the knowledge. If more attention would be put on sustain gained knowledge, the lead time could be shortened next time a similar project is in progress. Tests, performed with focus on specifications, make it difficult to reuse the gained knowledge in another project. Data and information that comes up during the project have to be transferred into knowledge, the data in itself does not develop excellent engineers (Ward, 2007).

3.2.2.3 Scania R&D Factory's Definition of Waste

In the compendium *R&D factory* Scania introduces guidelines for how to make decisions towards a robust product development process (Scania CV AB, 2010). Different kinds of waste in the Product Development process are defined, these are presented in the box below. Scania CV AB (2010) identifies seven different possible types of waste at the R&D department:

DIFFERENT CATEGORIES OF WASTE IN PRODUCT DEVELOPMENT ADAPTED FROM SCANIA CV AB (2010)

1. Doing more than necessary: It can for instance be the creation of documentation with more content and information than necessary, or order more prototypes than actually needed for a test. This kind of waste can also be present in meetings if more people than actually need to participate at a meeting are invited or the more PowerPoint slides than necessary are prepared for a presentation.

2. Not helping others If you have finished your part of a project you should help others instead of try to optimize a solution more than good enough. To not support others is a waste of your own resource and knowledge.

3. Not finding necessary information easily: When it is a lack of accessibility to information a waste occur. It can for instance be a homepage that is difficult to navigate or not divide responsibility clear enough. It can also be related to excess scattering of information; instead of only send an email to the individual that need the information the information is sent to everyone

4. Missing or unclear decisions: To not respect taken decisions about deliveries cause waste. It can also be a lack of decision in the cadence, the manager might be unavailable when a top down decision is needed, which cause uncertainty.

5. Excessive lead times in the planning stage: Excessive lead times tend to hide issues and cause a false sense of security. It also causes waiting time in the process due to that an item, which drawings are ready for simulation or testing too early, has to wait for the next step.

6. Having excessive wait: This kind of waste is related to both waiting for physical prototypes such as waiting for late people attending a meeting. Excessive waiting cause idling and unused resources. It is often related to disturbances in one way or another.

7. Not using everyone's competence: Every individual's competence should be used to gain the performance.

These seven categories are introduces in the folder as examples of waste, however, it is a possibility to have more categories of waste in the process.

3.2.3 Set-Based Concurrent Engineering

Set-Based Concurrent Engineering, SBCE, is an important part of Lean product development and is described as a cornerstone and success factor in the philosophy (Ward, 2007; Kennedy, 2003).According to Morgan and Liker (2006) SBCE is a part of the second Lean product development principle; *Front-Load the Product Development Process While There Is Maximum Design Space to Explore Alternative Solutions Thoroughly.* The target is to avoid early development decisions that cause late engineering quick fixes to cope with the demanded market launch. These quick fixes cannot be viewed as continuous improvement, actually, they should be treated as waste (Morgan & Liker, 2006). The basis from SBCE is that all cross functional stakeholders of the new product starts generating alternative solutions by their own. These alternatives are combined into possible sets of solutions (Ward, 2007). The solutions are eliminated one by one based on facts from, for instance, simulation and analysis related to shortcomings in the solutions. However, parallel solutions are carried along almost the entire product development process. When the narrowing process is finished the overall best solution is left and the decision is knowledge based see Figure 10 (Sobek et al., 1999).

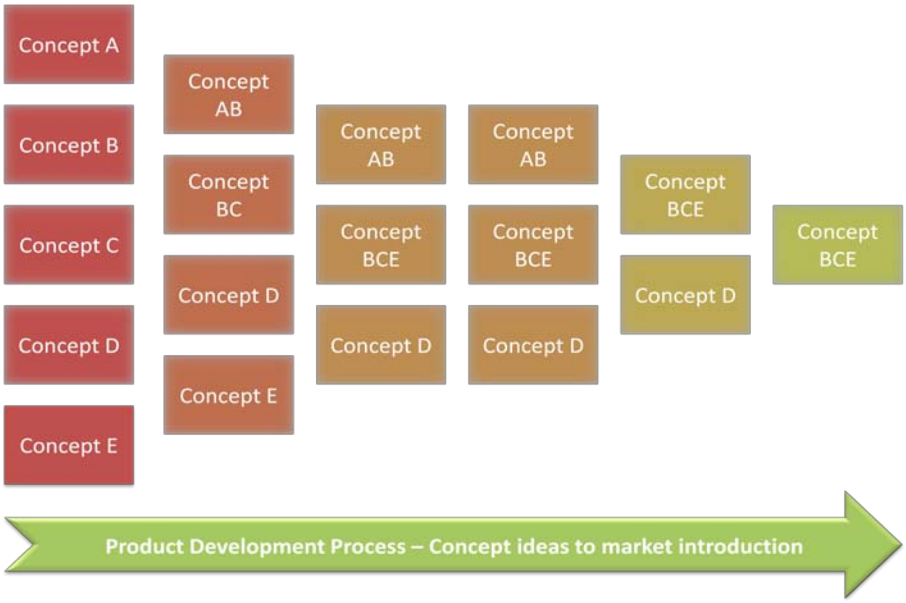

Figure 10 Concept narrowing in Set-Based Concurrent Engineering

3.2.3.1 Framework for Set-Based Concurrent Engineering

Three of the four fathers of the terminology Set-Based Concurrent Engineering, Sobek, Allen Ward and Liker launch in the article *Toyota's Principles of Set-Based Concurrent Engineering* a framework for SBCE. Since they are the owner of the expression SBCE (Morgan & Liker, 2006), the framework can be viewed as it is representative for SBCE in general. Sobek et al. (1999) identifies three principles as a basis for the SBCE; (1) *Map the design space,* (2) *Integrate by intersection* and (3) *Establish feasibility before commitment.* These principles together with some implementation principles for each one of them creates a framework for working with several concepts in parallel and knit them together, the framework is described in detail in Appendix B.

Sobek et al. (1999) emphasize that it is impossible to do a step-by-step guide how to success with SBCE. As much of the Lean Enterprise, it is all about culture. The tools might be helpful, but to success with Lean a pure cultural change has to occur (Liker, 2004). Therefore, the success factor of a SBCE implementation is more about the implementation of the ideas than the principles themselves (Sobek et al., 1999).

3.2.3.2 The Economics of Set-Based Concurrent Engineering

The main idea with SBCE is based on the fact that the cost for a change increases for each step closer to market launch a project takes (Johannesson et al., 2004). By maximize the learning in the early phase and minimizing late changes, it is a potential of saving a lot of money (Ward, 2002). SBCE is more or less a methodology aiming to decrease risk and increase quality. In almost all projects, it is a risk of a concept failure where rework is necessary. By base the decision on facts and investigate several different solutions, this risk is minimized and the probability of rework and failure decreases exponentially when the number of possible solutions increases (Reinerstein, 2009).

However, it is a tradeoff between minimize the risk of rework and cost for investigating several solution paths. Increased number of investigated subsystem increases costs for simulation, testing and physical prototypes. Reinerstein (2009) introduced an adapted variant of the Wilson formula, also known as Economic Order Quantity, EOQ, formula, aiming to give the "break even" for number of solutions versus risk of failure. Reinterstein highlights the importance of cost awareness among engineers using SBCE in order to optimize the profit.

3.2.4 Cost Awareness

Usually, continuous improvement and *kaizen* is focused on enhanced quality or reduced lead time, but when Toyota faced a great loss caused by the oil crises and great recession in 2009 they started to work with Kaizen from an economic perspective (Liker, 2011). In production, different costs were tracked on billboards and all effort was put in how to reduce scrap and use junk to rebuild the plants. Some plants and production lines had to be rebuilding in order to become more flexible and produce smaller vehicles. Carts and racks that would normally have been purchased were built in-house by scrap metal instead. Old overhead catwalks were made into carts. One production line budget on originally $4 million was trimmed down to $700 000 (Liker, 2011).

A common issue in product development is the lack of cost awareness at the R&D department (Reinerstein, 2009). The management has often clear targets regarding cost and several KPI:s are related to cost, but the engineers, who actually are the ones that have the direct impact on the expenses, does not bather of cost at all. Instead the design engineers tend to focus on proxy variables, e.g. robustness, functionality and style. If the economic connection is absent, the design engineer does not manage to understand its Cost of Delay, COD (Reinerstein, 2009). Due to the lack of insight in COD, the prioritization between different projects is based on feeling rather than fact.

If the duration and COD is known for a project, Reinersten (2009) suggests that a weighted factor should be used in order to evaluate the order of project execution. If the COD is divided by duration, the project with the largest fraction should be given the highest prioritization. Table 2 gives an example of a fraction calculation of three different projects.

Table 2 Example of prioritization by a weighted value

Project number	Duration	Cost of delay	Weight = $\frac{\text{COD}}{\text{Duration}}$
1	1	3	3
2	5	9	1,8
3	10	27	2,7

To illustrate the impact project implementation order has on cost, the generated cost is visible in Figure 11. In this example, it is assumed that all three projects will be delayed with at least its duration time.

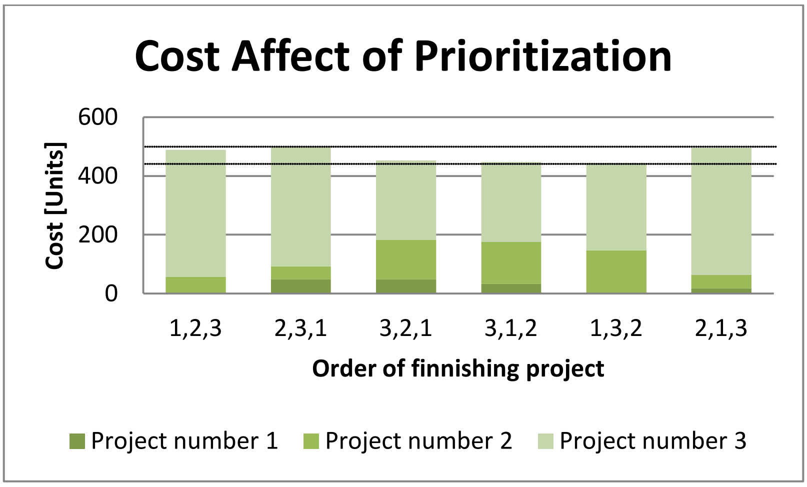

Figure 11 Example of the impact on cost due to implementation order

According to both the graph in Figure 11 and the fraction guide in Table 2, the most optimal project implementation order is project 1-3-2. In this certain example the cost would have been reduced by 10 % if the design engineer uses the weighted fraction instead of following the project number, i.e. order: 1-2-3.

To be able to do this kind of prioritization the knowledge of COD for each project is essential. Therefore, it is of importance for the design engineers to get an enhanced understanding for COD of different projects they are involved in.

3.2.5 Cadence and Synchronization

Cadence initiates the pulse to the process. When it is present in the process, activities occur at a regular basis and it is possible to foresee and plan when certain activities are going to be executed (Reinerstein, 2009). *Synchronization* is more about integration. In a synchronized process activities are planned cross functionally and different departments gets a common milestone (Reinerstein, 2009). It is possible to have a cadence in the absence of synchronization, for instance if each department has its own cadence and plan the projects independent of other departments. It is also possible to have synchronization without cadence; product launches can for instance be executed continuously, but without a predicted frequency. Since the time between two launch dates might vary cadence is not present.

Cadence is one of four concepts that the management of Toyota product development rely on (Ward, 2007). It is crucial to level the workload in the process as well as secure that internal deliveries in a project not are delayed. Cadence also makes it possible to plan the project more efficient since the supporting activities of a process are predictable. Milestones can be used to sustain the cadence and the number of milestones is crucial for the efficiency of the process. Too few gateways will cause waste in the process, due to large batches of information and waiting time (Reinerstein, 2009). If large batches of information are delivered to the process all at once, the feedback will be delayed. As a consequence, iteration loops and rework will be time consuming. Therefore are several short meetings is a better approach than a few long meetings to create an efficient process. Cadence can be initiated to the process in several ways with different targets, see Table 3 (Reinerstein, 2009).

Table 3 Different kinds of cadence adapted from Reinerstein (2009).

Type of Cadence	Description	Result
Product Introducing Cadence	New projects are launched at a regular basis.	Projects cascading into each other can be eliminated and create a leveled work load.
Prototyping Cycles	The deadline for submitting items to a test is fixed and testing occur at a regular basis	Create leveled work load for the testing department as well as minimize the number of tests since projects can be coordinated regarding the test cycle.
New Product Portfolio Screening	The product portfolio is updated regularly, for instance daily or weekly	When a the portfolio is updated regularly it is possible to ensure that all involved parties have the same version of an item
Design reviews	Reviewing design at a regular frequency, do not wait until the drawing is ready	Information delivered in small batches make it easier for more rapid feedback and find problems proactively

Ward (2007) proposes a project oriented cadence. The demand time and product launches are the crucial parts for finding the correct rhythm. The synchronization or milestones can be used in combination with cadence to sustain small batches and minimize queues in the process.

3.3 Simulation Driven Product Development

Simulation Driven Product Development, SDPD, and Simulation Driven Design, SDD, has been frequently discussed in the automotive industry for the last decade. For instance Volvo Cars Corporation designed its S80 model by great support of simulations already 2001. This was the first car where the strength the spot-welding was predicted by computerized calculation instead of conventional testing (Westling, 2001).

The differences between SDPD and SDD are their implementation range. In SDD, simulation is the basis when generating the design. The design engineers make, for instance, concept choices based on simulation. In SDD, simulation still might be complementary to the physical testing which tends to be the primary way of verifying a solution. In SDPD, simulations are the basis for the entire product development process, not only decisions related to the design phase. It can for instance comprise different kinds of virtual testing, virtual factories etc. Physical testing might still be necessary to, for instance, verify legacy requirement and capture the reality in order to be able to generate accurate simulation models. However, in a SPDP environment, physical testing is a support function to virtual testing and not vice versa. By using simulation at an early phase of the product development process companies has a potential of reducing time to market, increase quality and reduce costs (Adams, 2006). However, even though the methodology has been in use for more than ten years, it is difficult to find academic publications of the topic. Most of accessible information is related to best practice articles.

This section will give a theoretical basis for possible simulation methods to use as well as highlighting some examples of documented preconditions for a successful implementation of SDPD. Finally, it also comprises economically findings of simulation driven design implementations.

3.3.1 Simulation Methods

Different simulation methods are mainly used today by manufacturing companies to support the product development process (Hirsch, 2007). Nowadays, the whole product development and production cycle can be computerized, the three most important parts are: (1) Computer-aided design, CAD; (2) Computer-aided engineering, CAE; and (3) Computer-aided Manufacturing, CAM (Hirsch, 2007). These three areas create the different phases of a virtual prototyping environment, see Figure 12.

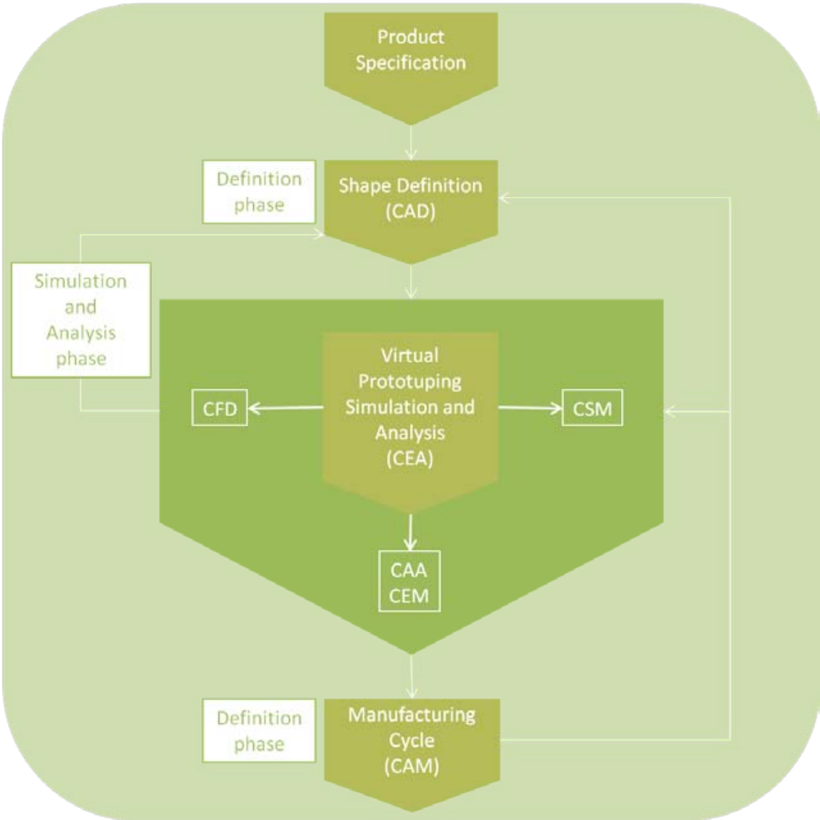

Figure 12 The virtual prototyping environment adapted from Hirsch (2007)

In order to use any CAE tools, such as FEM or CFD, a CAD model needs to be created first. That model will then be the input to the CAE simulations. The results from the CAE simulations will then be used to redesign the previous CAD model. This is repeated in an iterative simulation driven design cycle until the CAD model has the demanded functionality. When the design objectives are reached CAM software is used to simulate the manufacturing processes, such as milling parameters and tool routes (Hirsch, 2007).

Since the methods today are more specialized, engineers are either a design engineer working with Computer-Aided Design, CAD, or a calculation engineer working with Computer-Aided Engineering, CAE, i.e. Finite Element Method, FEM and Computer Fluid Dynamics, CFD (Holmdahl, 2010).. However, the role of the design engineer might change over time since different CAE tools are becoming more integrated with the CAD-programs. Many software providers believe that the next generation of design engineer does, except for specific product areas, need more insight in CAE tools (Honeywill, 2008).

CAE is mainly used in the automobile industry to decrease cost and time to market (Raphael & Smith, 2003) and some of the most common CAE tools and methods used within this industry are described further below.

3.3.1.1 The Finite Element Method

The Finite Element Method, FEM, is a methodology developed in the 1950's to analyze expected durability of a physical geometry (Adams, 2006). When analyzing durability of different geometries, partial differential equation is used to describe the geometry analytically (Hutton, 2005). However, the partial differential equations tend to be complex and very difficult to solve analytically. Therefore, numerical methods, such as FEM, are necessary; these methods generate a numerical approximated solution to the equation. FEM nodes are combined into different kind of elements, see Figure 13 (Hutton, 2005), which all are reasonable to describe analytically. By study each element, the impact on the geometry as a unit can be approximated. The practical engineering application of the mathematic methodology FEM is referred to as Finite Element Analysis, FEA.

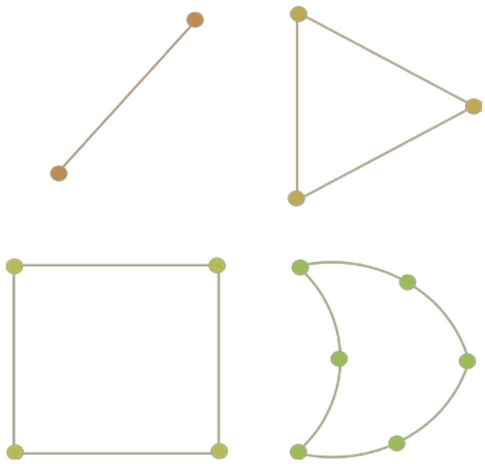

Figure 13 Different types of elements used in the finite element method; U.L. Beam element defined of two nodes, U.R. Triangular element defined of three nodes, L.L. Quadrant element defined of four nodes, L.R Triangular element defined of six nodes.

The FEA is usually performed with separate software, like ABAQUS or ANSYS, but there are also available FEM solvers on the market that are integrated with CAD software. The integrated applications are usually considerably faster to use since many of the steps, like building up the mesh-model, is made automatic. Though, the integrated application performs a simplified calculation and cannot handle as complex systems as the separate programs. In comparison, both types of solvers give a fairly similar result when it comes to where the critical areas are in the model, see Figure 14, but the separate solvers are better to determine the absolute values of the tensions (Loman Strinnholm, 2012).

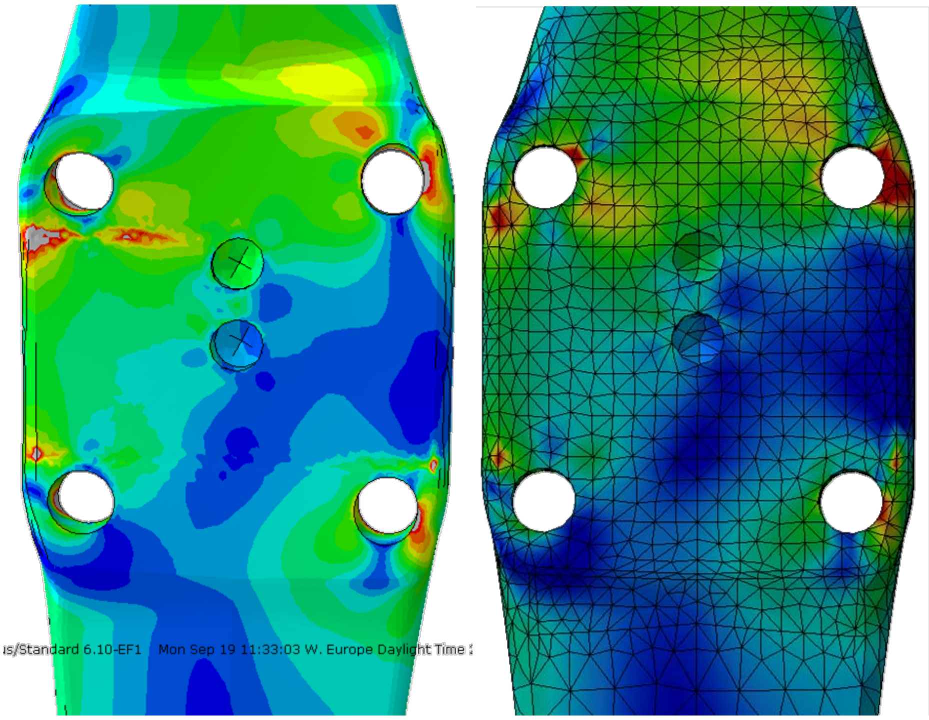

Figure 14 Comparison between calculations models where the left model comes from ABAQUS and the right from GAS in CATIA.

3.3.1.2 Crash Simulation

Computer simulation has had a large impact on crashworthiness of the design. It is possible to do many more iterations with virtual crash methods than physical tests since a crash simulation goes a lot faster and is cheaper than a physical crash test (Thomke & Fujimoto, 2000).

A crash simulation is based on a FEM simulation, but it still differs from static strength simulations regarding the calculation methods. For static loads in FEM, implicit methods are used to invert the matrix and find a reasonable solution. The crash simulations are instead calculated with explicit methods since they need to take big deformations, plasticity and hardening factors of the materials into consideration (Karlsson, 2006). The element grid has historically been coarser for crash simulation models due to limits in computer capacity, but this is not always the case today because of the evolution in computer performance over the last years.

The short period of time that is simulated affects the material properties and how fast the materials stretch needs to be considered since the hardening varies with the stretching velocity. Therefore, behaviors cannot as easily be intuitive predicted as static strength analysis or fatigue simulations. The stiffness in the components are put against each other and fairly small changes in the strength in the components can rise to completely new modes for indentations (Karlsson, 2006).

The crash simulation models also need to take the driver and passenger behaviors into consideration which other simulations usually do not need. There are standardized models of drivers and passengers today on the market and their behaviors are calculated either with FEA or rigid body dynamics (Karlsson, 2006).

Almost all the simulation programs for FEM today have the possibility to do explicit calculation, but some are more suitable and common for crash simulations like PAM-CRASH, ABAQUS and LS-DYNA. The automotive industry is leading in this type of simulations and use crash simulations to reduce the number of physical prototypes and crash tests in order to reduce both cost and time to market. One development project at BMW contained 91 iterations on the design with help of crash simulations and those iterations improved the crashworthiness by 30% for the side-impact, which would be very difficult to accomplish with only physical crash tests (Thomke & Fujimoto, 2000). The physical tests made in this project was also very time consuming and more expensive than the simulations, see Table 4

Table 4 Approximate Lead time and Cost for a Development project at BMW AG, Germany (Thomke & Fujimoto, 2000)

Problem-Solving Step	Simulation (per iteration)	Physical Prototype (per iteration)
Design	*Technical Meeting* • <0.5 days	*Planning and Piece part Design* • >2 weeks (involves many meetings)
Build	*Data Preparation and Meshing* • Small change: <0.5 days • Significant change: 1 week • Entire automobile: 6 weeks	*Design and Construction* • Using existing model: 3 months ($150,000 per prototype) • New model: >6 months ($600,000 per prototype)
Run	*Crash Simulation* • 1 day (varies with computer hardware) $250 per day	*Crash Physical Prototype* • 1 week (includes preparation of test area)
Analyze	*Post-processing and Analysis* • <0.5 days	*Data Preparation and Analysis* • 1 day (crash sensor data only) • 1-3 weeks (data, crash films and analysis of physical parts)
Total time	About 2.5 days to 6.3 weeks	About 3.8 to 7 months
Total cost	About < $5,000	About >$300,000

3.3.1.3 Computational Fluid Dynamics

Computational Fluid Dynamics, CFD, is a type of CAE simulation used to analyze fluid and thermal transport. It can for example be used to analyze the flow through the different stages of fixed and rotating blade rows in a turbine, compressor in an aircraft engine, the combustion process in diesel engines and to predict the pressure drop in an exhaust system.

The governing equations that are used in CFD are based on three fundamental physical principles: (1) conservation of mass, (2) conservation of momentum, and (3) conservation of energy (Anderson, 2009). This set of equations is known as the continuity equation, the Navier-Stokes equations, and the energy equation.

THE CFD SIMULATION IN FIVE STEPS ADAPATED FROM HIRSCH (2007)

1. *Select the mathematical model* and define the level of approximation of the reality that should be simulated.

2. *Discretization* of the space by define the grid generation and of the equations by define the numerical scheme.

3. *Analyze of the numerical scheme* and establish its properties of stability and accuracy.

4. Select an appropriate *time integration method* and a subsequent resolution method in order to obtain the solution.

5. *Post-process* the numerical data graphically so the result can be understood and interpreted easier, see Figure 15 .

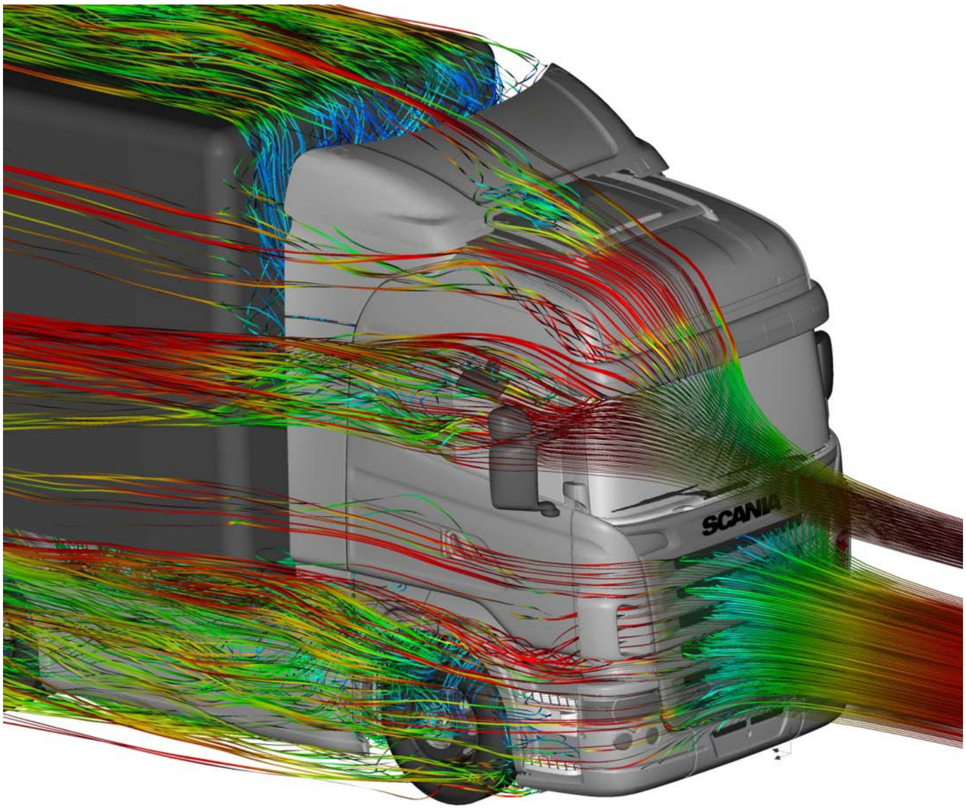

Figure 15 A CFD analysis of a truck's external flow.

CFD should be used in combination with pure theory and experiments about fluid dynamics since they complement and support each other and CFD is therefore used for both basic mechanical research and engineering design (Anderson, 2009). One example is the wind tunnel testing that has been used to make the CFD methods and simulations even more accurate and it had decreased both cost and time for especially developing new air craft designs (Anderson, 2009).

3.3.1.4 Interference Analysis

An interference analysis is performed inside a CAD program and is used to find interferences between different geometries. The interference analysis can be divided between different subsystems on the product to control where to look for interferences. It can also be regulating the distance between two geometries that will count as interference, i.e. geometries which tangent with each other, interferences for real, see Figure 16, or have a smaller gap between two surfaces than 2 mm. This type of simulation together with digital assembly differ from FEM and CFD, since they are problems of fit and not function The answer to an interference analysis is either yes or no compared to function problems, e.g. FEM, which have a more nuanced solution (Thomke & Fujimoto, 2000).

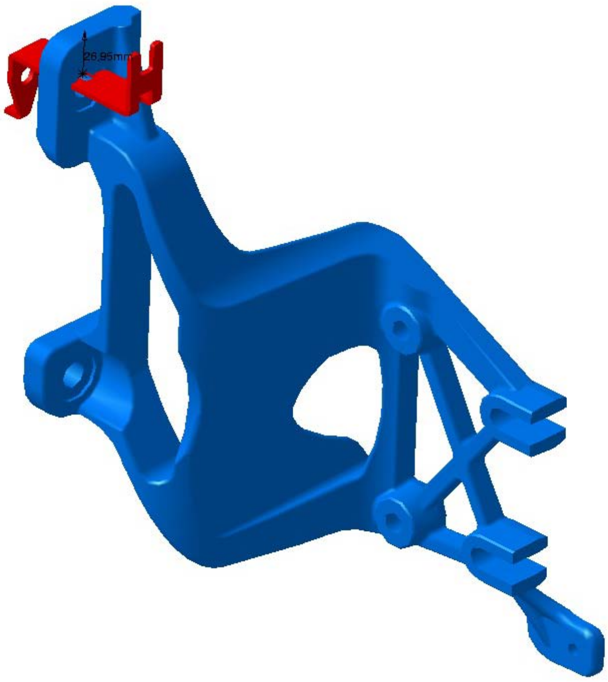

Figure 16 Interferences between two components from an interference analysis in CATIA

Boeing was one of the companies who started with interference analysis in the end of the 1990's. They build *digital mock-ups* of their 777 aircraft and used software to check for interferences during a time period when the geometrical data was locked. The design engineers were informed by interference for their components when the next design phase started which opened up for doing design changes again (Thomke & Fujimoto, 2000). The interference checks found 251 interferences that were prevented before they moved on the physical assembly tests. These interferences created a stronger interaction between different design engineers since they needed to solve the interference issues together (Thomke & Fujimoto, 2000).

3.3.1.5 Digital Assembly

Digital assembly is usually performed with applications integrated in CAD software, e.g. DELMIA in CATIA. Digital assembly tools can identify risks in the manufacturing process in an earlier phase in the development process, i.e. in the conceptual design phase (Diesel & Gas Turbine Publications , 2003). Digital assembly is mainly used in the automotive industry where the time between the design phase and start of production is critical. A digital assembly simulation can be used to decide the assembly sequences for new products and discover interferences and deviations without physical prototypes and assembly tools. If realistic manikins are used in the simulation, see Figure 17, ergonomics for the operator and assembler can also be evaluated (Dassault Systèmes, 2012).

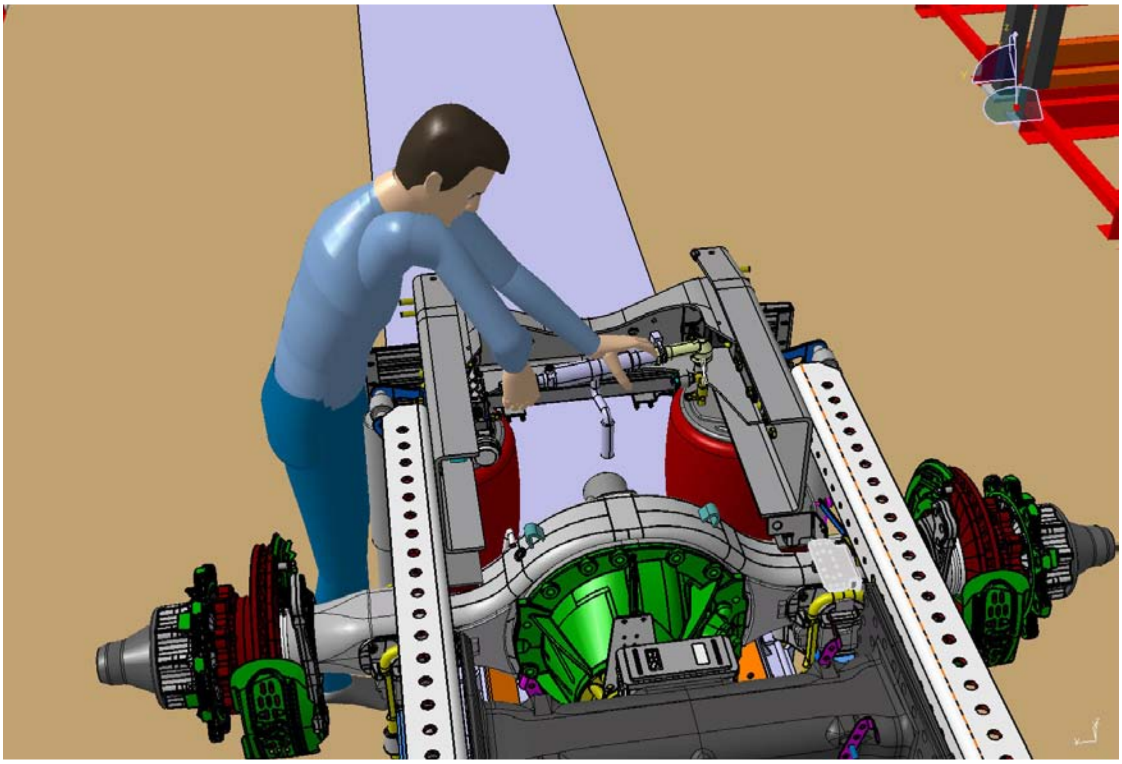

Figure 17 Digital assembly of a truck chassis with help of digital tools and a manikin.

Toyota Motor Company was one of the first users of digital assembly when it started with Visual and Virtual Communication, V-comm, in the beginning of the 21st century (Normile, 2001). Digital assembly was mainly used to be able to communicate between different factories overseas and to get feedback on the design from floor workers early in the design phase without physical prototypes. With help of the digital manufacturing program, which contained more than just digital assembly, they cut their development time from 18 to 13 months (Normile, 2001). In the annual report from Toyota in 2003 the mention digital engineering as an invaluable tool to reach a lead-time reduced by more than half and they see the V-comm system as a way to enable more digital assembly (Toyota, 2003).

3.3.2 Economic Aspects of an implementation

In order to estimate the *return of investment*, ROI, for a Simulation Driven Product Development, SDPD, project two parameters is required; (1) The cost for implementation of SDPD, both the investments cost of hardware and software as well as education and training of employees. (2) A monetary value of savings of implementing the project. One of the most obvious impacts of SDPD is the decreased number physical prototypes (Ansys Inc., 2011). If the simulations can explain the real phenomena all physical testing that is used today will not be needed in the future. However, physical testing is still necessary for validation. Though, the number of iterative physical tests is going to be reduced if a successful implementation of simulation driven design is done. According to Jackson (2007) the best in class companies in the U.S. have reduced their prototypes from 4.6 generations of prototypes to a mean of 3 generations. Ansys Inc. (2011) emphasizes that best in class companies have reduced their need of physical testing from five-six trial-and-error experiments to two validating test cycles. How large the actual monetary savings will be is related to both the type of business the focal company is active in and how large it is (Jackson, 2007).

Aberdeen Group (2006) presents a study examining the experience of SDPD at 270 American companies. Aberdeen compares how the best in class companies have implemented SDPD and what kind of consequences it will have on the cost and time to market. The companies are divided into different categories depending on product complexity, see Table 5.

Table 5 General Characteristics of Product Complexity. Source: (Aberdeen Group, 2006)

Product Complexity	Number of Parts	Length of Development	Cost to Build a Prototype
Low	Less than 50	Between a week and a year	$7 600
Moderate	Between 50 and 1000	Between a month and 5 years	$58 000
High	Between 50 and 10 000	Between 1 and 5 years	$130 000
Very High	Between 1 000 and 100 000	Between 1 and 20 years	$1 200 000

Aberdeen Group highlights a difference of 1.6 prototype generations between best in class and average companies which correspond to an average project saving of between $12 160 and $1 900 000 for each project. The annual savings is then related to how many projects a company completes during a year.

In order to estimate the ROI, Ansys Inc. (2011) has collected data from a couple of cases where virtual prototyping and SDPD has been implemented. One example is the awarded *Department of Defense HPC Modernization Program – DEW* in the U.S. Virtual prototyping has enabled initial savings of $13.8 million (IDC, 2011). The expenses for the program are $812 million and the lower and upper bound of the ROI is calculated to 678% respective 1292 % (Ansys Inc., 2011). This might be a best practice example, but Ansys emphasizes that the ROI rate is quite high overall and a ROI of 300% is reasonable for several businesses.

It is not only the costs of prototyping and physical testing that is affected by SDPD. Intangible parameters such as increased product quality, goodwill and increased brand reputation is often also affected (Ansys Inc., 2011). According to Jackson (2007) companies which have used simulation tools at all stages of the product development process have experienced less quality complaints from customers. The result at the field will not emerge momentary, but in time the warranty cost curve will decrease significantly. The savings due to reduced warranty complains tend to largely exceed the investment cost for the virtual prototyping projects.

Another parameter that is affected by the implementation of SDPD is the lead time. By reducing the number of prototypes series and replace them with virtual prototyping, time to market will be decreased. Depending of the product complexity the Aberdeen Group (2006) estimate the lead time for a physical prototype testing cycle be from 13 to 99 days, see Table 6.

Table 6 Prototype Time per Product Complexity

Product complexity	**Number of parts**	**Time to build prototypes**
Low	Less than 50	13 days
Moderate	Between 50 and 1000	24 days
High	Between 50 and 10 000	46 days
Very High	Between 1 000 and 100 000	99 days

Since best in class companies have reduced the number of prototype series they have the possibility of launching their low complexity projects 21 days before its competitors who has not implemented SDPD to the same extent. For a very high complexity product the corresponding value is 158 days (Aberdeen Group, 2006). An earlier market release will probably increase the market shares of a mature market or the profit margins if the market is immature when the conventional release were supposed to take place. The benefits of decreased lead time and shorten time to market are difficult to put into monetary value. However, it will be an advantage and should increase the ROI rate.

3.3.3 General Preconditions for an implementation

One issue with Simulations Driven Product Development, SDPD, is that the competitors have access to the same software vendors and therefore, the simulation applications themselves do not give any competitive advantage (Adams, 2006). The main difference among a best in class company and a laggard is instead related to how the tools and methodologies are implemented into the product development process of a focal company (Jackson, 2007).

One significant difference between the very successful companies and the others is in which stage of the development process simulation tools are used (Jackson, 2007). The product development process can be divided into three different phases; *Design phase/concept generating, Test Phase/Validation Phase* and *Post design release phase.* Best in class companies have front loaded their simulations more than the others, see Figure 18.

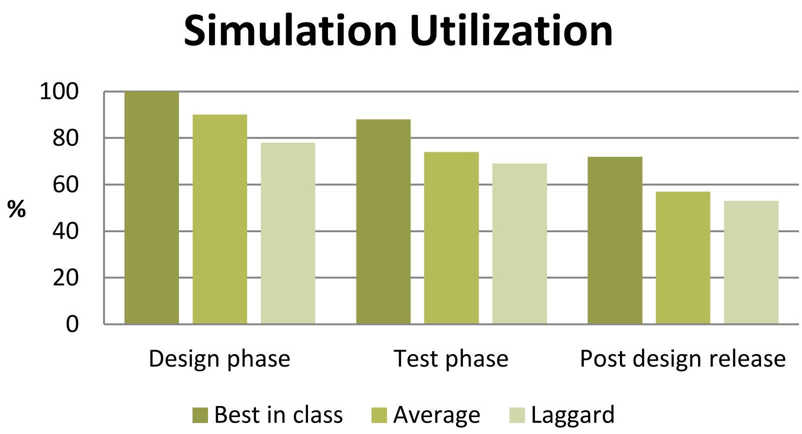

Figure 18 Comparison of simulation utilization adapted from Aberdeen Group (2006). Different companies were asked when they use simulations in the product development process. E.g. All Best in class companies uses simulations in the design phase, but less than 80 % of the laggard companies do.

All best performing companies among the 270 companies involved in the study, that Figure 18 is based on, uses simulation in the design phase (Aberdeen Group, 2006). Overall, best in class have a more frequent use of simulation in all phases. How simulation is used in the product development process will influence the performance of the company. Aberdeen Group (2006) emphasizes that CAD embedded simulation capabilities should be used in the design phase. Their main argument is that the design engineer does not need to spend time learning new software from scratch that only will be use sporadically. Best in class companies are 63% more likely than others to use the embedded simulation systems in the design phase (Aberdeen Group, 2006). The familiar layout and accessibility in embedded simulation capabilities lower the entry barrier of using simulations in the design phase.

According to Jackson (2007), the structure of the training programs for employees has an impact on the result of the implementation. Aberdeen Group (2006) emphasizes that the best methodology for education seems to be a combination of specific examples and individual performed training exercises. This is analogous to Adams (2006) who add a suggestion that the training should be mandatory in order to keep a high knowledge level among the employees. Adams also highlights the importance of choosing the right pilot projects to reach success. If the initial projects are a success it will be spread within the company. However, if it becomes a failure, a widespread program will never gain commitment. Therefore, projects that are reasonable or almost guaranteed to success with should be used as examples in an early phase (Adams, 2006). It is tempting to use the software until the limit of its full potential, but if these pilot projects fail in an early phase it is a risk that the methods not only lose their credibility of advance projects, neither will they success to gain acceptance for the more simple tasks they actually have documented power of perform efficiently.

The management has a crucial role during the implementation of a program towards SDPD. Management's commitment to a change program is fundamental to a success. However, the visionaries at a company have to be continuously questioned in order to develop robust and bullet proof analysis and this is also a task for the managers (Adams, 2006).

3.3.4 Plausible Difficulties in an implementation

There are some common challenges to overcome in order to be successful with an implementation program towards SDPD. Aberdeen Group (2006) emphasizes lack of available time among design engineers as the most common doubt in organizations. Design engineers are already choked as it is today and therefore, they do not have any extra time for doing simulations. Jackson (2007) assign this time limitation issue as a paradox; one of the main advantages of implementing SDPD is the shortened time to market. By using SDPD each project should consume less time and therefore, the time issue should not be a problem. According to Jackson, it is more a question of how to use the resources in the most optimum way. Aberdeen Group (2006) present analogous data to Jackson's statement; none of the most common actions taken among companies that have implemented SDPD are related to lack of time among design engineers. Therefore, it is likely that the anxiety related to work burden is groundless or at least the problem will be so easy solved that no specific actions are required.

Another issue is the available knowledge at the focal company. Independent if the company uses CAD embedded simulation systems or separate simulation software, experts in each field are required for success (Jackson, 2007). Several companies have a lack of this expertise when starting its implementation. Aberdeen Group (2006) emphasizes that this problem is one of the trickiest to overcome; four out of five of the most common actions to overcome the initial threshold are related to this issue.

A third difficulty to handle is the physical test correlation. When striving to go all the way with an implementing program towards SDPD it is not enough to achieve directional answers from the simulations, the output from simulation has to be accurate (Jackson, 2007). To reach accuracy in simulations, the model and method have to be frequently updated and improved continuously until they actually describe the reality (Jackson, 2007). However, measurements and data have to be gathered from physical testing. Therefore, high accuracy in physical testing is a precondition when developing simulation models for successful virtual testing.

Adams (2006) highlights the quality assurance as another obstacle. When the product development process relies on physical testing, simulations is often used as an additional assignment. Therefore, the quality of the analysis and simulation phase is not crucial; the physical testing still has an accurate quality assurance process. When eliminating assignments of the physical testing in favor of virtual testing the quality assurance has to be built into the new virtual testing process. Otherwise Adams (2006) emphasizes a risk of building in quality issues to the new process instead of reaching increased quality, which often is a target when implementing a SDPD program.

3.4 Scania Product Development

Since the primary case of the thesis study is Scania, a basic theoretical understanding for the company is required to understand the circumstances for the result of case studies, chapter 4. In this section the product development process at Scania is explained followed by the department guidelines presented in R&D factory. Finally a briefly introduction of some company specific methods such as GEO is presented.

3.4.1 The Product Development Process of Scania

The product development, PD, process comprise three different phases or sub-processes; *yellow arrow, green arrow,* and *red arrow*, see Figure 19 (Scania CV AB, 2011). Frontload

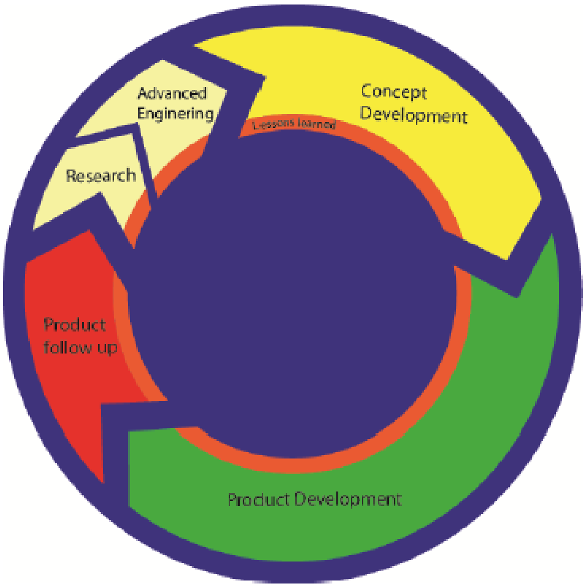

Figure 19 Illustration of the Product Development Process of Scania (Scania CV AB, 2011)

The PD process rests on some fundamental principles or statements connected to how Scania develop products:

- *Product ownership* – The line is the owner of the product. The projects can never own a product.
- *Cross-functional and parallel* – Product development is cross functional and it should influence the process from the initiation of a new project to product follow up downstream in the product flow.
- *Uncertainties* – When developing new products, uncertainties are necessary and have to be handled, iterations will be something natural.
- *Configuration* – The project plan should be performed by a cross functional team and has milestone as a basis.

3.4.1.1 Yellow Arrow – Pre Development

The pre-development sub-process comprises three different areas of responsibility; *Research, Technology development* and *Concept development*.

Scania uses *Research* to gain knowledge of the technique of tomorrow and find areas in which core competence should be developed to get a leading market position for the future (Scania CV AB, 2011). The knowledge gained by research is going to be applied in technology development.

In *Technology development,* new techniques are applied to improve the properties of the Scania's future products (Scania CV AB, 2011). The new technique is evaluated and knowledge of which technique is suitable to fulfill the customers' needs is delivered to the next yellow arrow activity *concept development*.

In *Concept development,* the concept which will be the basis for the new components is generated. All concept will be related to a demand, e.g. from a customer, legal requirement or a cost rationalization.

A concept is finalized and ready for the next step when following paragraphs are fulfilled (Scania CV AB, 2011):

1. *Performance/Property objectives are described*
2. *Profitability analysis has been conducted*
3. *The concept is planable*
4. *The concept has been modularized*
5. *The concept has been cross functionally accepted*

3.4.1.2 Green Arrow – Product Development

A project in this phase is characterized by an ability to be planned in detail. All deliveries have a high delivery precision and a project at this stage will most likely in the nearest future be available for the consumer (Scania CV AB, 2011). The main activities and resources within the green arrow are allocated to product development projects. A product development project has a predicted market launch date as well as due date for start of production. The line, which includes all delivery functions of Scania, is responsible for delivering in time. The Project office supports the project with methods and tools for project management, set milestones etc, but the line is responsible for the delivery (Scania CV AB, 2011).

At an early phase of the Green-arrow process a project configuration is performed. The project will be divided into single activities that are necessary to fulfill to reach expected benefits, application targets and demand for the project. The planning is performed by a standardized method named Scania Project Planning, SPP.

The development of the component is continuously in progress through the entire project. The target with the green arrow phase is to adapt the concept chosen in the yellow arrow to its environment. The project manager keeps the control of the project through a couple of milestones. When projects reach Start of Production, SOP, a process verification is done and some adjustments might be necessary before the project is ready for Start of Customer Order Production, SOPCOP.

Except product development projects this phase also comprises three other type of projects; Design On Line, DOL, Special Order, S-Order, and Fit For Use, FFU.

3.4.1.3 Red Arrow – Product Follow Up

In the *red arrow* phase, projects already launched in SOPCOP are treated. The projects are maintained and updated with the purpose of improve quality or decreasing costs (Scania CV AB, 2011). A component deviation that reaches the consumer will cause negative goodwill for the brand. Lack of quality at the field often causes large costs and therefore has a direct impact on the profitability of Scania.

3.4.2 Description of R&D Factory

R&D Factory is a set of guidelines used to support the decision making and create a stable and reliable product development process in order to keep the market position of the company and satisfy the customers' needs (Scania CV AB, 2010). Analogous to the guidelines for production, the concept is often described with the metaphor of a house with a ground, pillars and roof, see Figure 20. Even though it looks quite similar to Scania Production System, SPS, the R&D Factory is adapted to suit the product development instead of the manufacturing environment.

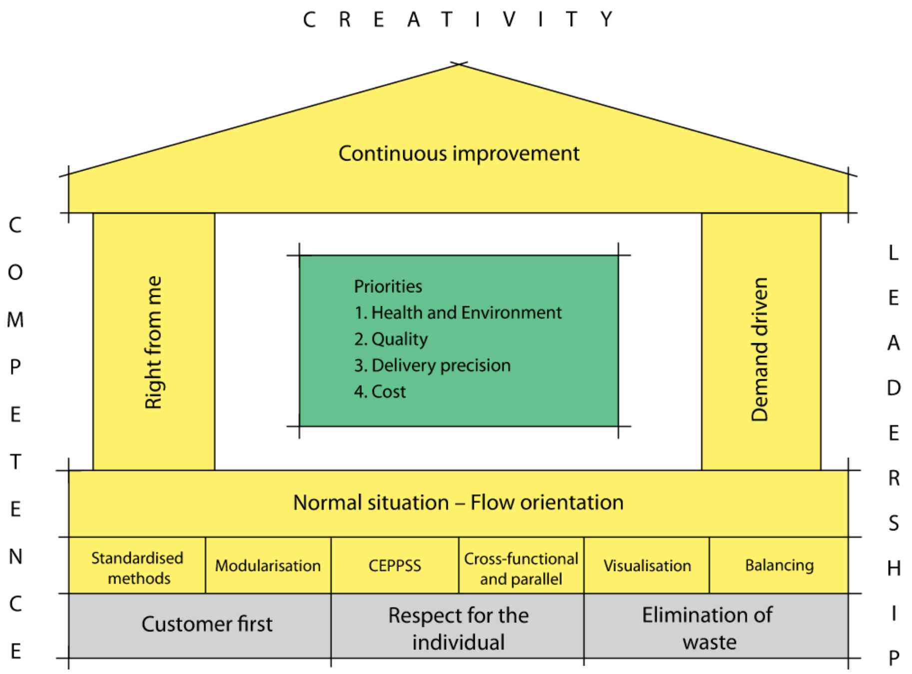

Figure 20 R&D Factory described with the house metaphor (Scania CV AB, 2010)

The house includes three different categories of boxes; *the core value*, *the principles* and *the priorities* of the product development department at Scania. It is surrounded by three important success factors for the performance of the department.

3.4.2.1 The Core Values of Scania R&D

The core values *customer first, respect for the individual* and *elimination of waste* reflect the culture of Scania and are always present together, see Figure 21 (Scania CV AB, 2010). Since all three core values are equally important for the company, it is no prioritization among them.

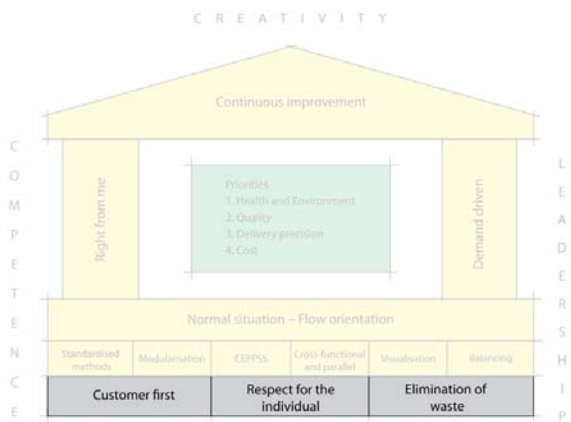

Figure 21 The Core Values of Scania R&D

Customer first refers to the importance of always having the customers in focus. The product development process has to be driven by the demand (Scania CV AB, 2010). At the R&D department it is two types of customer in focus; it can be either the end costumer or an internal customer, e.g. production. One key to create a consciousness of the customer’s need is to have a focus on that the employees are doing the right activities, i.e. activities that create value for its customer.

Respect for the individual is aiming to use the knowledge and experience that is available among all employees. It also refer to the possibility for individual development (Scania CV AB, 2010). Another example of *respect for the individual* is to fulfill promises and deliver in time.

Elimination of waste is related to eliminating disturbances in the process. Scania defines waste as anything that does not provide value or benefits for the end customer (Scania CV AB, 2010). Examples of waste at Scania R&D department are described in section 3.2.2.3. Then waste is eliminated the competitiveness of Scania can be increased by increased efficiency and reduced lead times.

3.4.2.2 The Principles of Scania R&D

The R&D factory house contains four different principles; *Normal situation, Right from me, Demand driven* and *Continuous improvement,* see Figure 22. These principles are aiming to sustain a common way of thinking in every situation (Scania CV AB, 2010).

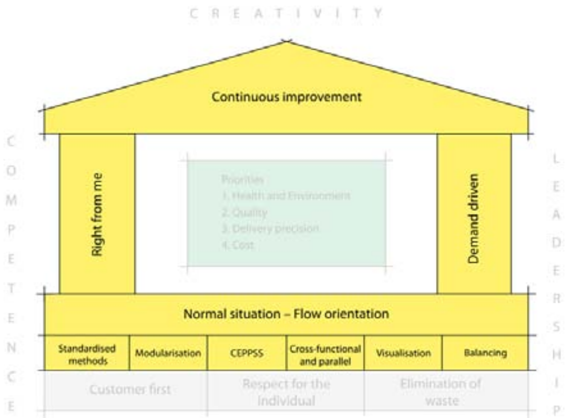

Figure 22 The principles of Scania R&D

Normal situation – flow orientation describes how activities should be performed. The *flow orientation* secure that the deliveries continuously flow through the value chain and not are stuck in queues (Scania CV AB, 2010). The R&D department has two different types of flow present; (1) The information flow which delivers information to a specific project, for instance a stress target that is fulfilled for a certain component and (2) the knowledge flow which contribute to a knowledge bank, see Figure 23

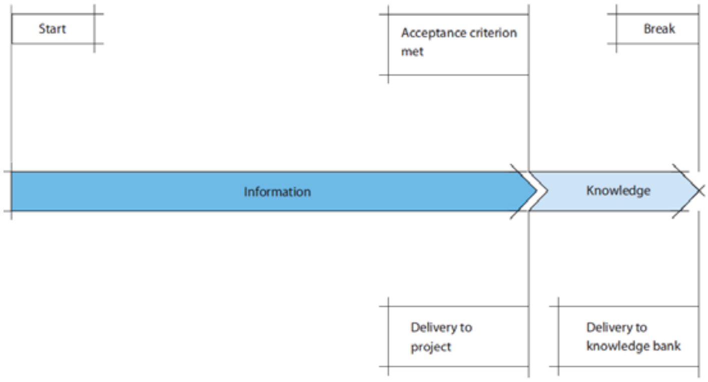

Figure 23 Illustration of the two types of flows (Scania CV AB, 2010)

If a component is tested until the acceptance criterion is met, a delivery takes place to the project. However, the test can be continued until the component breaks in order to learn how it breaks. This gains knowledge and is a delivery to the knowledge bank. The *Normal Situation* is supported by six sub processes; *Standardized methods, Modularization, CEPPSS, Cross-functional and parallel, Visualization* and *Balancing.*

Demand driven output is the second principle of Scania R&D Factory. The demand will be used to control the flow. To have a continuous feedback between different parts of the flow is crucial for this principle. The delivery shall not take place before it is needed. The core of the method is to not process more information than is needed downstream the chain (Scania CV AB, 2010). The deliveries are going to be in small batches in order to sustain the internal customer's current need. The small batches have a potential of decreasing the throughput time due to reduced waiting time and more rapid feedback. It is easier to detect a mistake earlier if only a small batch is delivered every time.

Right from me refer to that deliveries to internal customers are performed right from the beginning. There are methods, tools and instructions which facilitate this principle. If the standardized method is followed and the delivery still not is satisfying, it is a shared responsibility among all parties to improve the method (Scania CV AB, 2010). The internal customer evaluates the quality of a delivery and is responsible to give feedback to the previous step if the delivery does not fulfill the needs. A rapid feedback is important in order to minimize the effect of a mistake. The one whose delivery does not fulfill the requirements is responsible for doing the rework. If it is any uncertainties of who is responsible for the lack of quality, the parties should cooperate in order to come up with a solution (Scania CV AB, 2010).

Continuous improvement is described as the engine of R&D factory. The starting point for improvements is the *normal situation.* Disturbances and deviation from the normal state is assigned as waste and is a great opportunity for improvement. Within the *continuous improvement* principle the *normal situation* is maintained, challenged and improved. The continuous improvement is a daily work and based on that the cooperation with improvement works (Scania CV AB, 2010). It is also something every employee will participate in since everyone's competence and knowledge are going to be utilized. The *normal situation* and standardized method is not only the starting point for *continuous improvements,* it is also a requirement; if there are no common method among the workers it is no "best known procedure" to improve. The improvement work has to be based on facts, it is not sufficient to trust intuition for this kind of work.

3.4.2.3 The Priorities of Scania R&D Factory

Scania has four priorities included in the R&D factory; (1) *Health and environment ,(2) Quality, (3) Delivery precision* and *(4) Cost,* see Figure 24 (Scania CV AB, 2010).

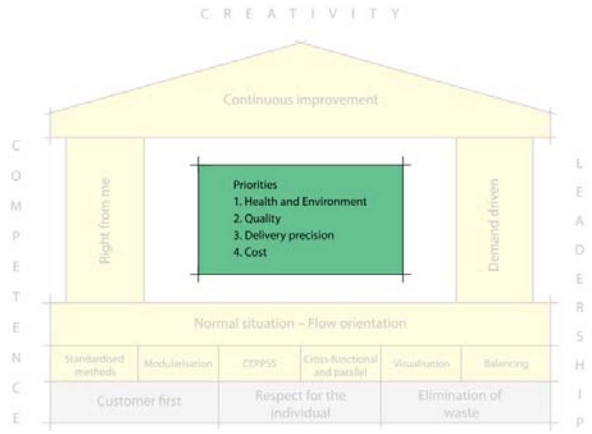

Figure 24 The priorities of Scania R&D

To measure the performance, *Key Performance Indices*, KPI:S, are generated for each one of them. The result of the KPI:S is a basis for the improvement work. In an abnormal situation, compromises among the priorities might be necessary and the order between the alternatives can help to act. However, it is only in abnormal situation the decision principles are compared and eliminated with this specific order.

3.4.2.4 Success Factors of Scania R&D

The R&D Factory house is surrounded by the three success factors of R&D; *Leadership, Competence* and *Creativity,* see Figure 25.

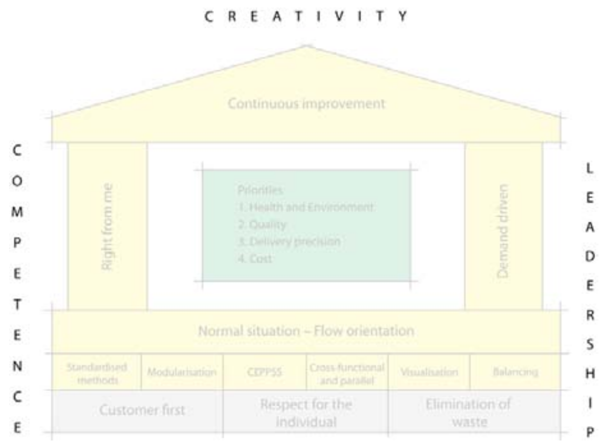

Figure 25 Success factors of R&D

Leadership will ensure a positive interaction among managers, groups and co-workers. A manager at Scania has the role as a coach; it should help the team to collaborate to outperform the individual. It is also crucial for the manager to help the co-worker to grow as an individual. The leadership at Scania has a focus on learning by doing (Scania CV AB, 2010). It is important to sustain a culture where it is allowed to make mistakes. However, when a mistake occur some kind of learning has to take place to ensure that it does not recur.

Competence is gained by both education and experience, but also by the individuals' skills to conduct its own work. The managers have to get the understanding for the future's demand of competence and ensure that Scania has core competence in strategic important areas.

Creativity is about thinking outside the box in new ways. Innovation at Scania is related to converting a creative idea into knowledge that can create value for the end customer (Scania CV AB, 2011). Therefore, creativity is a prerequisite for innovation. Creativity and innovation are not explicit for the pre-study phase; they should be present in all steps of the product development process.

3.4.3 GEO

GEO at Scania is an abbreviation for GEOmetry assurance (Brantefors & Gadman, 2007). It is a method used to ensure that each item has a feasible position to its surrounding components in each truck variant, see Figure 26. The software is explicit developed for Scania. By using GEO it is possible to explore deviations and interference issues in an early stage of the product development process (Wernsten & Hanna, 2012).

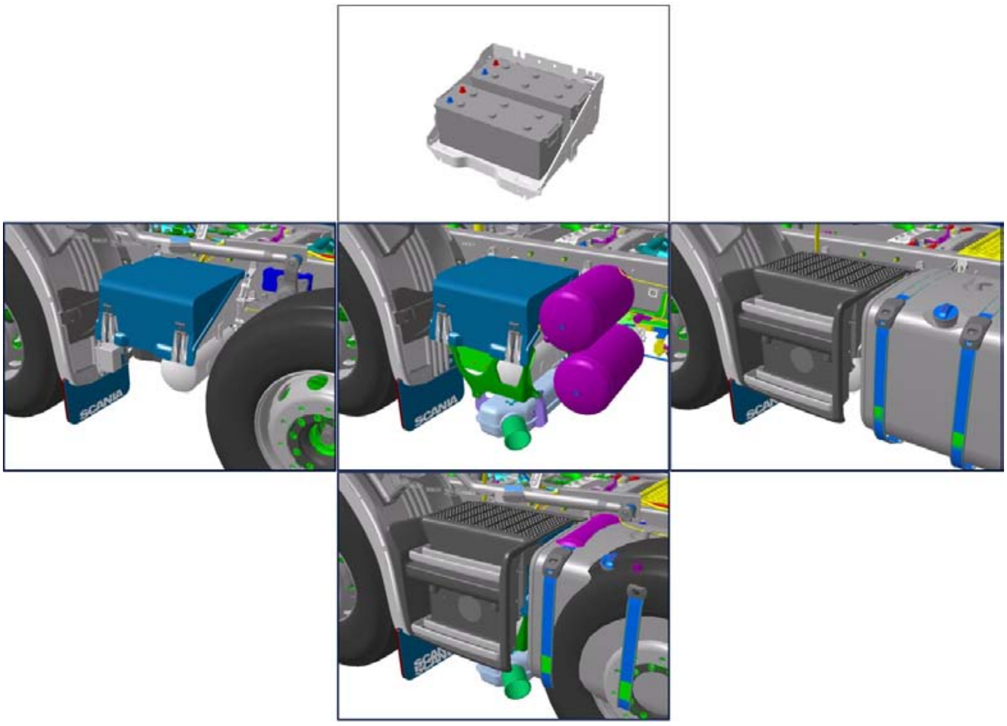

Figure 26 Examples of GEO assurance for a battery box, the upper picture show the battery box itself, the middle row pictures show three different possible surroundings of the box and the lower picture give an illustration of the box when all possible surroundings are put together.

From a more practical point of view GEO links two different systems together; CATIA V5/Enovia LCA and SPECTRA. The CAD model and its reference system, referred to as Part Axis at Scania, is collected from Enovia while the items' geometric position, GP, is collected from the system SPECTRA (Brantefors & Gadman, 2007). It is the design engineer who updates the GEO archive by connecting its 3D-model to its ID-number and GP (Wernsten & Hanna, 2012). The idea is that the design engineer should do the first GEO update quite early in the design process. It might be just a quadrant box that informs others that something is going to be in this area in the future.

GEO should be updated continuously; it should be an iterative process and should be done much more frequently than other synchronization gateways in the projects (Brantefors & Gadman, 2007). Today, there are no possibilities to see the maturity of an item in GEO. It is neither possible to see older generations of an item as long as the item number is consistent.

GEO information is shared among several different functions at Scania, see Figure 27. Since it is a lot of individuals who are using GEO in their daily work, it is of great importance that the version of the item in GEO is up to date.

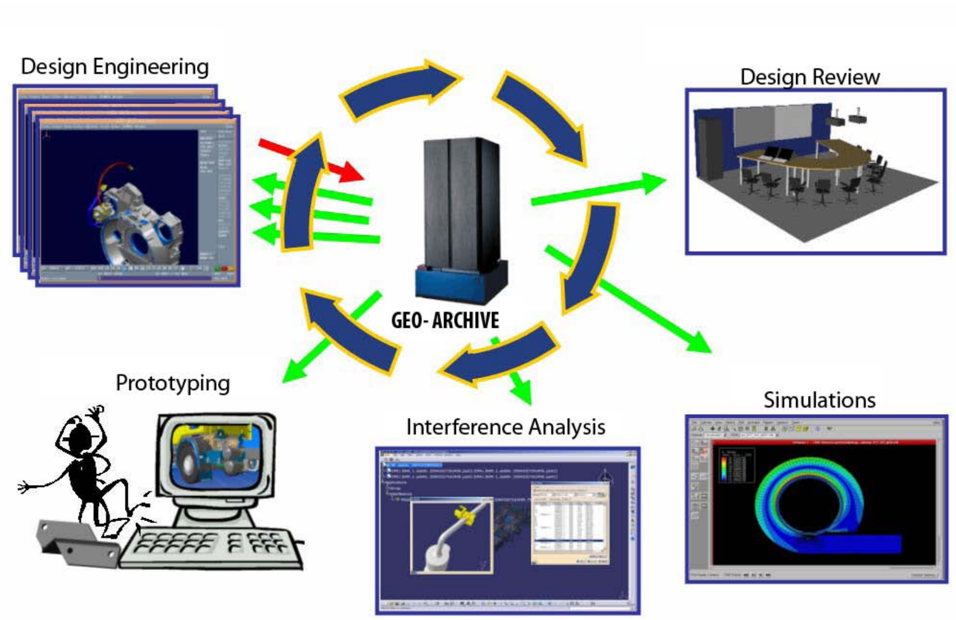

Figure 27 Information flow of the GEO archive, adapted from Brantefors and Gadman (2007)

4 RESULTS FROM CASE STUDIES

This chapter comprises the case study of this project. It has two main sections. The first one is based on qualitative interviews at Scania and aims to describe the current state of the simulation usage at the product development department. The second section of has a benchmarking focus and describes how three other companies within the automotive industry have implemented simulation driven product development in their product development processes.

4.1 Scania

Employees with different functions at Scania R&D Department have taken part in a qualitative study in order to investigate the status of using simulation tools and simulation driven design at the company. The study includes 25 Design engineers interviews, the questions is available in Appendix C and a list of the interviewees in Appendix D. Six simulation groups have taken part and the simulation questions is available in Appendix E and a list of the interviewees in Appendix F. Finally, three testing groups and 20 other individuals who by taken part in interviews contributed to the understanding of the current state, a list of the testing engineers and other individuals that has participated in the study is available in Appendix G.

4.1.1 Interaction between Simulation and Design Groups

The design engineer at Scania has the full responsibility of its components. Therefore, it is usually up to the design engineers to take a decision if simulations with help of the FEA or CFD engineers should be performed or not. The simulation departments work as a support function and can sometimes have responsibility for properties, but mostly they only give advice about strength and dynamics.

4.1.1.1 Simulation and Analysis Assignment Processes

The contact between a design engineer and the simulation department usually starts with a dialog about what should be achieved. Although, to start a simulation job, a testing request, known as PA at Scania, is written. The PA is used to keep track of all the jobs made by the simulation department. It contains information about involved components, what questions or areas to investigate, which project it belongs to etc. Except for the PA, there is no common method or process used at Scania within the simulation departments. Some departments has made their own process, some wish to have one, but do not have the resources to create one and some groups are so small that they have not had the need for it yet. At the dynamics and strength analysis group for chassis, a process has been made, see Figure 28.

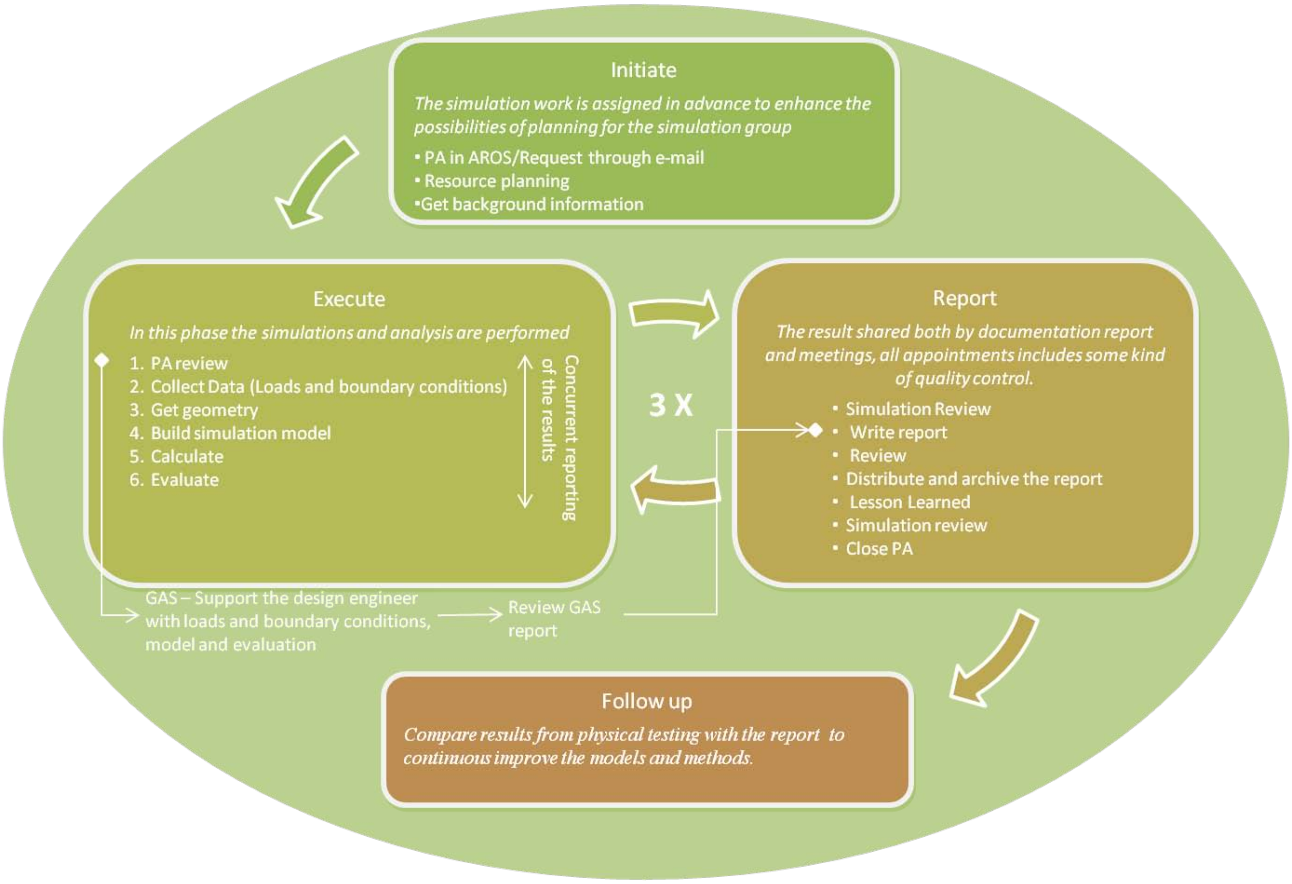

Figure 28 Work process at dynamics and strength analysis for chassis

The process described in Figure 28 comprises four different phases or sub processes; *Initiate, Execute, Report* and Follow up. Usually the simulation assignment is made by iterations between the design engineer and the simulation engineer. The iterations take place between the execution and report phase. As a rule of thumb three iterations has to be done before the design fulfills the simulation targets or requirements. Due to the iterations, one single PA can comprise more than one loop of calculations. However, if it is a long time gap between the iterations it is preferred that a new PA is used instead and the old one is closed.

When simulations are introduced in the PD-process is very individual dependent. Since it is a lack of description about simulation and analysis in the design engineer's check list, it is up to the design engineer to involve simulation in the project. Therefore, when simulations are used in a project vary from being introduced in the concept phase to not being included until just some weeks before SOP when design usually s locked for changes. Traditionally, simulation has entered the projects too late, when the components already has been broken in the physical testing or when the drawing has been locked and only small changes are allowed. In projects with a tight time schedule simulation can sometimes be made parallel with ordering physical prototypes which leads to that the simulation results cannot be used to redesign before physical testing.

A simulation assignment can vary in time from one-two weeks to several months. The average standard time for a fairly known component with a familiar simulation method takes about two weeks. This time includes the start up meeting, modeling, calculation and analysis. The computation processed by the computer can take from 20 min for a fairly easy FEA up to three days for a full vehicle simulation. This time used to be longer and has been shortened due to increased computer performance. Though, the simulation software has also become more advanced and therefore has the calculation time not decreased as much the last few years compared to the increased capacity in clusters and computers. If there is a possibility to do the calculation more detailed still within a reasonable waiting time this is usually done. Most of the engineers working with simulation and analysis prefer a more detailed calculation instead of reduced calculation time. FEA calculation has reached the magic limit were they are calculated over the night and the result is shown for the simulation engineer the next morning. As long as the result is shown the next morning, it would not matter if the calculation takes two hours or eight hours and therefore the longer alternative is often chosen in order to make the calculation more detailed.

In the end of every ordered simulation job from a design engineer a report is written. The report is always connected to the PA number, contains the result and usually the method so information from the simulation should be able to reuse. Some groups have started to write A3-reports with graphs representing, for example, temperature distribution and fluid changes. This type of report is, in comparison to a standard report, easier to overview and gives a faster understanding.

4.1.1.2 Simulations impact in the Product Development Process

The simulation result is almost always delivered before the report is written through a meeting between the simulation engineer and the design engineer verbally so the design engineer does not have to wait for the report to be written and approved to get the result. Every design engineer interviewed is located close to their responsible simulation group which makes it easy to have a regular verbal contact during the simulation assignment. The geographical position has a great impact on the communication between the design group and the simulation group according to all the interviewed engineers.

Simulation and analysis has taken a greater part in product development and has been involved earlier in the projects since the design engineers has started to rely more on the simulation results than before. Earlier, most simulations and calculations were made after the physical testing and their purpose was to explain why the components broke or had cracks from the durability tests. It was usually a very big hurry with these simulation assignments, also known as *"fire fighting"* assignments, since the components were supposed to make it through the physical testing and the time to start of production was not far away. The design groups with experience from these firefighting assignments has gained increased trust and knowledge about the work of the simulation groups and therefore started the testing for the upcoming projects with virtual testing and simulation instead for going directly to physical testing. The case study has shown that groups with a history containing many late rework projects and problems from physical testing has a bigger trust and reliability in the work and results from the simulation groups.

4.1.2 Interaction between Simulation and Physical Testing Groups

According to the interviews in the study, the main purpose of *simulation and analysis* and *physical testing* is equivalent. Both fields of expertise are striving to answer the same questions about the product and its functionality. Though, their methodologies to come up with the answer differ. At Scania, the two areas have a common history; simulation and analysis started to grow as a sub-function to the physical testing groups. Therefore, simulation and analysis used to be done in the same workgroups as the physical testing. Nowadays, the simulation and analysis groups tend to be separated both geographically and organizationally from physical testing. Simulation and analysis is treated as an own field with separate workgroups. Geographically they are often located more closely to the design engineers than the testing engineers. Several of the engineers involved in the study, both testing and simulation engineers, put attention to that they would appreciated if they were located more closely and tighter connected to each other.

The simulation and physical testing groups highlight that they are complementary functions to each other. Simulation and analysis is dependent of physical testing to validate their models. If the result from physical testing and virtual testing mismatch, the fault is often assumed to be related to the simulation model. Therefore, the results from physical testing can be used in order to do more accurate models. The simulation engineer does not initiate a physical testing by its own to develop methods and models. The design engineers tend to do both simulations and physical testing on the same components which make it possible to get feedback from physical testing anyway. However, how the information flows between the groups differ a lot. Some simulation groups have integrated generating feedback within their groups' process map and can by that ensure that they always get feedback to its models and methods. Other simulation groups do not have a clear process description and have not this opportunity. Instead they trust that the design engineers give them access to feedback from the tests. Due to the common history of the two areas, it is a lot of personal contacts between the groups which often is used to get feedback; the simulation engineer calls the testing engineer in order to get feedback from the tests.

When the design engineer sends a concept to simulation it only gets the information that is asked for. The output from the simulation is dependent on the questions the analysis and simulation engineer wants to get answer to. The testing gives an impression of the entire picture since more loads are present. Test engineers involved in the study highlights that testing should be called measuring, since it is all about measurements. To measure a load or a stress, the sensors have to be placed at right positions and the tests will actually only give feedback of what the customer asks for. If the component breaks it will of course be detected without a sensor, but as long it does not break it is impossible to get full control of what happens within the entire component. Physical testing is dependent on simulation and analysis to be able to reach an accurate position of the sensors. Both test and simulation engineers have recognized a trend of a lot of complex designs for basic components such as brackets. The complex design makes it difficult to both do simulations and testing in an accurate way and the complex geometry for the brackets probably depends on increased modularization according to the testing engineers.

Sometimes is virtual and physical testing present in a project simultaneously and in parallel. It may cause problem to get use from the result of simulations before the next generation of physical testing appear, see Figure 29.

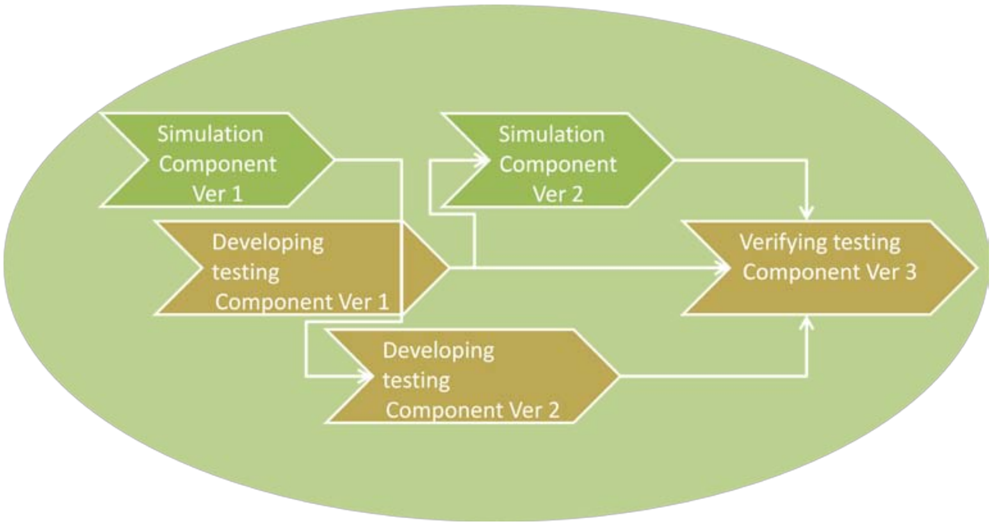

Figure 29 Example of simulation and testing simultaneously

Since the prototypes for the first run of physical testing is ordered before the result from first simulation run is available, the knowledge gained from the simulation is not used in the first physical test, see Figure 29. Interviewed testing engineers emphasize that they have several examples there the result from physical test 1 is not available before the second run take place. This is a scenario the groups would like to eliminate. In this case knowledge from the first simulation run is used for a second simulation run. The final verifying test never occur in parallel with any other testing, neither virtual nor physical testing.

4.1.3 The Role of the Design Engineer

The design engineer at Scania has several different kind of work tasks included in its daily work. A lot of tasks are of course design related, but it also comprises administrative activities and to some extent a role of a coordinator. The broad responsibilities and spectra of activities included in the role of the design engineer sometimes make it difficult understand what the design engineer actually are supposed to do in their profession.

4.1.3.1 The Daily Work of the Design Engineer

The work tasks and time share between them are quite individual. It depends on both the role in a project the design engineer has and how it wants to work. Some design engineers are interested in simulation and analysis and tries to do as much as possible by themselves while others feel inconvenient when getting in touch with analysis and simulation tools. Some design engineers do all CAD work by themselves, while some design groups have consultants who handle the work in CATIA. However, almost all design engineers involved in the study mention their component responsibility first when they are asked about work tasks. Most of the design engineer has responsibility for one or several items. Explicit what kind of activities and tasks involved in the component responsibility depends on how mature the component is. Some design engineers are involved in projects with new concept generation and tries to come up with new concept to solve problems while other engineers responsible for mature components conduct and fine tune the current component.

The cross functional work, as contact and interaction with other people involved in the project, is another recurring task for the design engineer. The majority of the design engineers spend a lot of time in meetings or in discussions with, for instance, production, purchasing or subcontractors. Some of the interviewed engineers highlights that they spend a lot of time distributing and searching for information regarding their specific component. This type of activity has often the same purpose as the meeting, i.e. gather and distribute information. Help other engineers or asking for help are other frequent activities mentioned as a part of the daily work.

The documentation is included in the daily work for a design engineer. Almost all engineers mentioned the tasks connected to create and maintain Engineering Change Orders, ECO:s, related to their component as a significant part of their daily work. The attitude to documentation diverge; some engineers emphasizes it as something good and a part of their learning process while other engineers describe it as time consuming administrative tasks and doubt the value of it.

Some design engineers also mention the continuous improvement work and enhancement of methods as a part of their expected daily work. Although, they say that they should do it, no one has actually put attention to it as a frequent part of the daily work.

4.1.3.2 Design related Time

As a quantitative part of the qualitative study each design engineer was asked to estimate what share of their time was related to design tasks. Design tasks are not only related to CAD. The participants in the study were asked to bring all activities related to add value to its component into consideration when doing the assumption. The result gives a mean value of 35 % and a median of 30 % time spent on design related tasks. The entire distribution is visible in Figure 30.

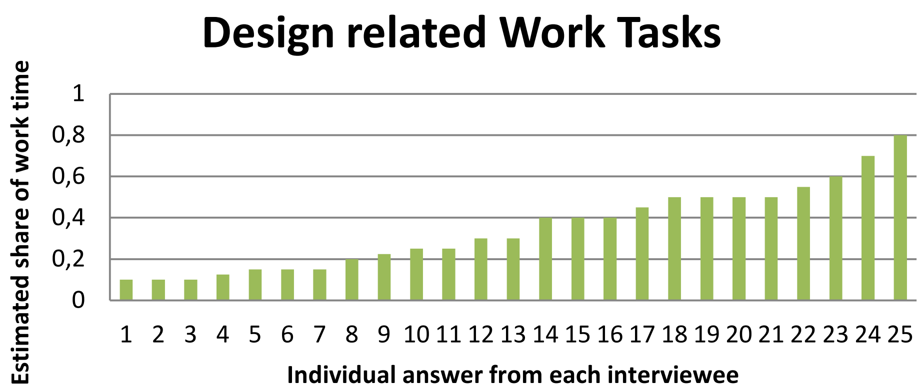

Figure 30 Design tasks' share of total time at office

Several of the design engineers emphasize that the share of design related work tasks tend to decrease proportionally to the employment time at the company. This hypothesis is supported by the result in the study, where senior engineers have other complementary areas of responsibility and also tend to get interrupted more frequently by questions than an engineer in an early phase of its profession.

4.1.3.3 Knowledge Developing Activities

What kind of activities enhancing the knowledge of the design engineers seems to be quite individual, see Table 7. Some design engineers increase its knowledge when they can work in CATIA undisturbed for a longer period. Others gain knowledge by cross functional discussions and feels that working in CATIA is more of a repetitive kind of work task.

Table 7 Knowledge developing activities mentioned by design engineers, all engineers were allowed to emphasize unlimited number of activities. Therefore, the sum of the sample share is more than 100 %

Knowledge developing activities	Share of sample
Feedback from testing and simulation	32%
Cross functional discussions	32%
Working in CAD by my own	32%
Own simulation and analysis	20%
Discussions with colleagues	20%
Collecting information/Reading reports	12%
Benchmarking	8%
Commitment to the work task	4%
Everything that is a part of my work (Including administration)	4%

According to the discussions with design engineers and the statistics presented in Table 7 what knowledge developing activities are seems to depend on two factors. The first one is what kind of work task the certain design engineer has and what kind of obstacles it faces in its daily work. The second is how it defines knowledge developing. The definition of knowledge was dependent upon the answering design engineer which may have influenced the deviation in answers.

4.1.3.4 Secure "Right from me"

Right from me is one out of four principle of R&D Factory at Scania, see section 3.4.2.2. The purpose of the principle is to ensure that an activity is executed and delivered to next internal customer in the right way at the first time. The design engineer uses different methods to fulfill the right from me principle. The most trivial one is to follow the designers' checklist which includes several steps and activities that should be taken into consideration in the different design phases. However, several design engineers find the level of detail of the checklist to be unleveled. Some steps are described in detail while others are widely opened for individual interpretation. One example is the step *"brainstorming"* which can be done in unlimited different kind of ways. On component level, design engineers uses designer guidelines which is a document including learning from previous work done regarding the component. The guidelines are used more frequently among recently employed engineers in comparison to senior engineers. When an engineer has looked at the guideline a couple of times it keeps the most important in mind. Another tool to deliver *right from me* is to follow standards such as PA when sending a request to physical testing or simulation and analysis.

When mention right for me, the majority of the design engineers relate to production and how the quality of the component they are responsible for is secured before it is launched to market. Physical testing is the primary way of secure the quality of the component before a delivery. Several, but not as many as uses testing, also uses simulation and analysis to ensure that the component fulfills the targets. Some of the engineers that uses GAS to do some FEM simulation and analysis by themselves emphasize that GAS give them an understanding for the properties of their component and by using

GAS in collaboration with a simulation and analysis engineer they can secure that they deliver *right from me.*

Approximately 15-20 % of the design engineers that have taken part in the study highlights that they do not follow any standard or method to secure *right from me*. Some base their concepts on intuition and experience while others emphasize that they actually do not know that they deliver *right from me,* instead they try to do as good guess as possible.

4.1.3.5 A Design Engineers Consciousness of Economics

The parameter almost all of the asked design engineers start to think about when talking cost is the manufacturing cost for their component. The design engineer tries to make a smart construction and avoid expensive and unnecessary tools in the manufacturing process and find as cheap raw material as possible. However, some of the engineers involved in the study emphasize that the engineers should put more attention to weight optimization when designing; the truck weight influence both fuel economy and load capability for the customer, i.e. it affect the customer value. The weight also affects the need of raw material and therefore the component cost at the market.

When focus on development process cost for the components, the awareness is much lower. During the interviews, the development process cost has been defined as the costs for developing the component. It involves factors such as expenses for prototypes, physical testing and internal resource consumption, when for instance order a simulation work from another person. The majority of the design engineers tend to ensure that the right number of prototypes are ordered, but less than ten percent emphasize they actively tries to avoid, for instance, unnecessary physical testing due to a believe that physical testing is expensive. One of the design engineers says that it believes the way of reducing cost is to do as much as possible by itself, for instance to do FEM calculations in CATIA. According to this engineer the cost heavily increases as soon as a hand over to another person takes place.

The cost for prototypes is displayed to some design engineers, but no one involved in the study can connect the cost of prototypes to the total project cost. Several design engineers says that they have a lack of feeling for cost; a prototype might cost 100 000 SEK, but they cannot estimate if it is a small or large share of the project budget. The majority of engineers answering the question come up with the conclusion that they do not have any connection to cost and therefore a lack of consciousness. Another statement among the answers is the lack of incentives for reducing development process cost.

No one could give an accurate number for the cost of delay of a project to start of production. They tried to think of consequences, but could not give a monetary term. However, some tried to guess a value, but they clarified that they did not actually had a clue.

4.1.4 Simulation and Analysis executed by the Design Engineer

Of the interviewed design engineers almost everyone has been in contact with the Finite Element Analysis, FEA, application GAS in CATIA. Most of them got familiar with it recently and has still not used it as much in their daily work. Some design engineers believe that how frequent GAS is used depends on the background of their group manager; if the group manager has a background as a simulation engineer, GAS is encouraged and used more frequently.

4.1.4.1 The Experiences of Simulations executed by the Design Engineer

Many design engineers find it difficult to get started with the GAS application. They experience that the entry level is pretty high, especially if you have little experience from FEA software and solid mechanics from earlier. Therefore, they need help and support from their simulation group, especially in the beginning regarding loads, boundary conditions and how to build a FE-model. They also feel a need for help to evaluate the results and decisions how to proceed. During the evaluation of the GAS calculation, the simulation engineers can also take the decision if they need to do a more detailed simulation in their group or if the GAS-simulation is good enough to continue to the next step, i.e. physical testing. Design groups that do not get support from their simulation group regarding GAS, does not use GAS as frequent as design groups that have a supporting simulation group who can help them.

The design and simulation groups are currently often located next to each other, which almost every design engineer mentioned as helpful. It is easier for the design engineer to have a dialog with the simulation group when they are familiar with each other. They can have the discussion about the results from either the GAS simulation or a regular simulation at someone's screen instantly instead of waiting for a meeting setup or until the report is finished to get feedback.

The GAS work made today is not as well documented as regular simulation jobs. Some design engineers do some print screens and others automatically generate a report inside CATIA and GAS. Though, the automatically generated report does not contain any valuable information according to the interviewed simulation engineers and design engineers with more GAS experience. Most of them also mentioned that if GAS becomes more common and is used as decision making support a report is needed for every GAS work made.

4.1.4.2 The Potential of Simulations executed by a Design Engineer

Both the design engineers and the simulation engineers that have experience from working with GAS, emphasize that the GAS application should be used to see differences in strength when comparing two designs and not to find any absolute values. Therefore, it can especially be used for components that have field quality problems today and needs to be more robust, but without increasing weight.

According to the interviews GAS is very helpful when it comes to design new or improve already existing brackets. Brackets have not been seen as components that need to be simulated compared to the silencer, fuel tanks or electronics that the brackets usually hold. Therefore, the feedback for the design has not arrived until after the physical testing. GAS has therefore been useful to design the brackets without guessing when it comes to ordering prototypes for physical testing. GAS can also function as an effective interface between the design engineers and the FEA engineers, according design engineers taking part in the study. Since the design engineers get more familiar with analyzing FEA color grids and red spots in their calculation model, they also feel like they understand the discussions better regarding more complex FEA work made by the simulation engineers. The simulation groups do also experience more quality in the design when taking over a model that has been calculated in GAS. They do not need to do as much iteration compared to if GAS has not been used.

GAS is more popular among design engineer with little or none experience and younger employees. Since a GAS simulation goes a lot faster than a regular FEA software simulation the design engineer can get a feeling about the strength and robustness through more iteration many weeks earlier than by doing a regular simulation. By using GAS, the quality of the components get enhanced very quickly since the design engineer knows more about the design and its strengths and weaknesses than it did without using GAS. Many of the design engineers said that they often had no clue how good and robust a design actually was and they often draw new geometries based on guesses combined with earlier versions and reports from the field. They did not really get a feedback on their design until they started the physical testing. If they had bad luck and their guess did not make it, the rework was usually very expensive, time demanding and stressful since rework is not a part of the project plan. Another issue has been to gain knowledge from simulations.

Often the simulation department delivers the results from the simulations as a yes or no. By using GAS in the early design phase, the design engineer can both reduce the workload of the simulation groups and gain more knowledge about how different design parameters affect the robustness.

4.1.5 Synchronization and Geometry Assurance at Scania R&D

Today, most simulations are made on components or smaller sub-systems. The interviewed engineers mention that full vehicle simulations are rare since they do not have any virtual prototype vehicles to simulate and analyze. The current Product Data Management, PDM, system containing the CAD models and their GEO-position does only comprise the latest updated model and therefore they cannot go back and use an older model to build a virtual vehicle. It is also difficult for the simulation engineer to know if the model in the GEO archive is the current valid model right now or if the design engineer is working on a new model that has not been updated. The simulation engineers that were interviewed feel a need for some type of synchronization for virtual geometries so they knew when they could go in the GEO archive and pick out the models. Both the design engineers and the simulation groups feel a lack of expressing maturity levels in the models so other users could see if the model in the concept phase, under development or locked due to tool order.

4.2 Benchmarking of Simulation Driven Product Development

To get an enhanced understanding for SDPD in the automotive industry in general a benchmarking study at three other companies are made. The first company that is studied is former SAAB Automotive AB. Due to the bankruptcy in December 2011 the case is based on a story from former employees. The case describes Saab's journey of reducing the amount of prototyping heavily in favor of simulations. Next case is about Jaguar Land Rover, JLR, a classic British car brand, nowadays a part of Tata Motors. According to the simulation software provider Dassault Systems JLR is in the cutting edge of using simulations in its product development process. The third and final case is about AB Volvo with focus on how its four truck brands use simulations in a common global development process. Volvo is analogues to Scania providing heavy duty trucks and has Sweden as base for its headquarter. Therefore, a benchmark study of how Volvo uses SDPD is of interest for the study.

4.2.1 Cost Rationalization by using Simulations at Saab Automobile AB

Saab Automobile was under hard pressure from General Motors, GM, to reduce cost by reducing the number of physical prototypes and testing. Therefore, virtual development without physical prototypes was implemented. Both the Saab 9-5 MY10 and the new phoenix platform for Saab 9-3 were developed without usage of classic physical prototypes. However, the mule vehicles were used to test new combinations with existing components from the platform shared between several GM brands, for instance the Saab 9-5 and Opel Insignia, and one production validation series were made with components adapted for mass production. Regarding the new 9-3, the validating production series never took place since Saab Automobile went bankrupted in December 2011. Saab Automobile used a platform strategy together with the rest of the GM Group which helped them with the virtual development since many of the parts used in the 9-5 had already been tested physically for other vehicles. The strategy was to remove the alpha-, beta- and gamma-prototype series, integration series where the prototypes are made from scratch, and replace them with virtual testing, see Figure 31.

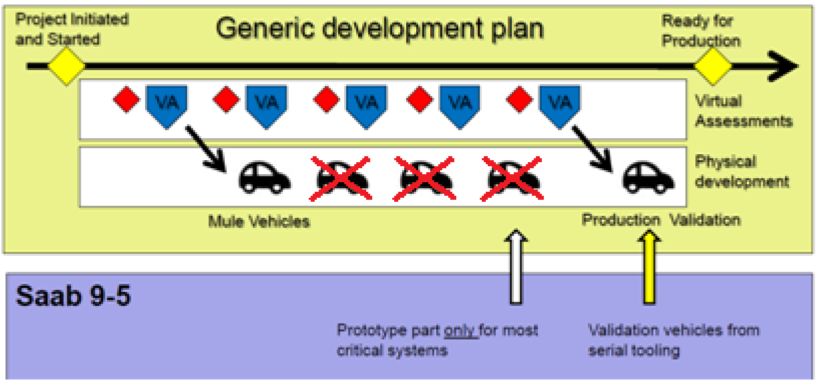

Figure 31 New test plan for the development of the new Saab 9-5.

The reactions were strong, especially among employees within the physical testing and with property responsibility. According to them, it was impossible to replace all the physical testing since it was a too big risk and it would lower the quality. Therefore, every property responsible had to go over their tests and prototypes to replace the physical testing with virtual methods. Every property responsible still had to have physical prototypes, but since the Saab management was under hard pressure from GM to reduce cost and lead time they did not accept any prototypes they had to develop new methods. The physical tests were either replaced with a simulation method or with a test result from the platform. Every test that did not have a virtual test method got a *Road to Lab to Math*, RLM, project. These projects were supposed to find a way to move the physical road tests in to the lab, still with physical prototypes. Once the lab tests were verified, the next step was to remove the physical prototypes and replace the lab test with a virtual test. Sometimes it was even possible to go directly from road testing to a simulation method. In several areas, a simulation tool was missing, so Saab had to involve their software providers in order to develop new applications.

The big challenges with the RLM projects were to translate different complex feelings, for example the feeling of closing a car door to measurable parameters from the simulation. In order to be able to translate the attributes based on feelings and driving performance you need to have experienced employees with knowledge about what to looking for while testing prototype cars (Sjödin, 2010). Therefore, the biggest challenge area with virtual development was vehicle dynamics, since it is hard to translate the feelings from driving a vehicle in to measurable numbers. It was important to break down big goals to measurable parameters, for example five stars in EURO-NCAP had to be translated to acceleration levels for different components and *"a comfortable sound level"* has to be broken down to Eigen mode frequencies (Sjödin, 2010).

Moving over from physical to virtual testing also required an organizational change since they needed more simulation engineers and less lab test engineers. Many lab engineers were a big help in the RLM projects and continued working with the tools they helped to develop. Saab also needed a more centralized CAE group. Their earlier organization had the CAE- engineers spread out in the different areas which gave problems with non-synced CAD geometries and simulations were made on a model at the same time another group made changes on the same model. Saab kept the CAE engineers decentralized, see Figure 32, but they reported to a centralized CAE group which took care of the models so everyone could be aware of any changes that was made.

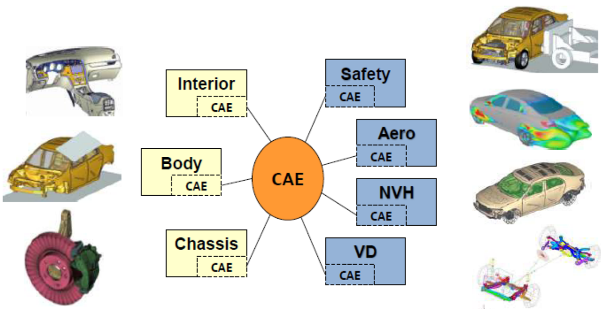

Figure 32 New CAE organization (Sjödin, 2010)

The physical tests, mule-, alpha-, beta-, gamma- and the validation test series, had become the spine in the product development process at Saab automobile. All the other work, like simulation and analysis, were just added to the test series process. The big problem with the physical test series was that the results and changes from the alpha series were not tested in the beta series since the prototypes for the beta series had to be ordered long before the alpha series was finished. Many problems therefore remained through the beta series even though they were already known and discovered in the alpha series. Since a prototype series takes six months it is very time demanding to go through the testing without being able to include the change made from the earlier series. It is also very expensive to test prototypes one more time that already have been tested and where the problems already are discovered.

When moving over to virtual testing the series testing phase were minimized to 6-8 weeks instead of 6 months. To be sure that the tests always were made with the latest version of geometry, they used synchronization time points there the CAD models geometry were frozen. This way, one simulation group, for example noise and vibrations, were sure it was the right model they were using since no other group, for example safety, were able to make any changes in the geometry. When the simulation was done, they held a vehicle assessment meeting during 1-2 days where all the problems and issues were brought up. After the meeting the simulation engineer worked together with the design engineer to solve the problems until the next sync time point, see Figure 33.

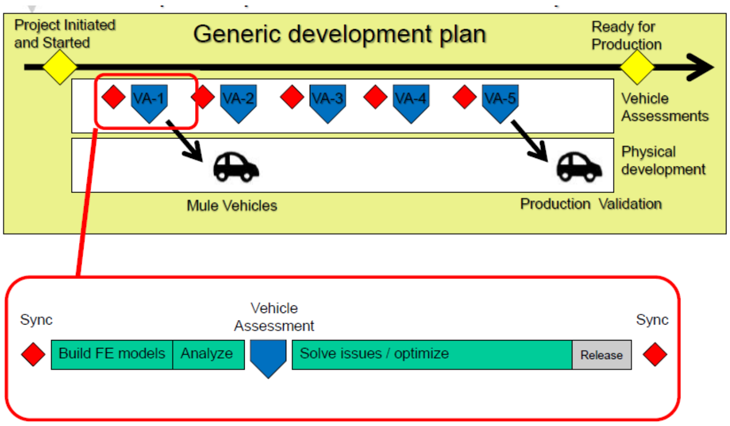

Figure 33 Time plan between sync points (Sjödin, 2010)

This new strategy made the synchronization points and the vehicle assessments to the new spine in the product development process. With less hardware prototypes resulted in less administrational work and the design engineers therefore had more time to spend on the design instead of fill out paper work for ordering prototypes.

Their next step with SDPD was to shorten the time between the sync points and Vehicle Assessment meetings with help of a more automatic process for the mesh modeling, CAD assemblies and the evaluation of the results, see Figure 34.

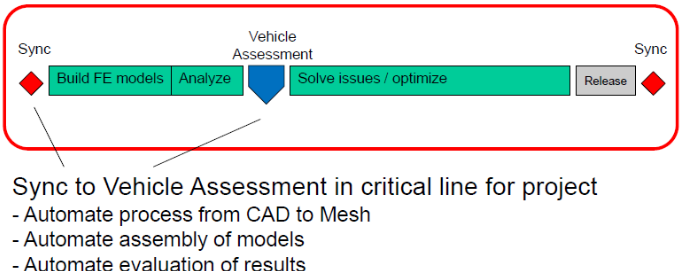

Figure 34 A more automatic process between sync points and vehicle assessment (Sjödin, 2010)

Another area that they wanted to look further into was to use optimization tools in the phase after every vehicle assessment to shorten the development time even more.

The big advantages were the reduced overall cost for the development process, the shortened time-to-market and the enhanced quality on the product. The Saab 9-5 received five stars in the EURO-NCAP safety test and it was development with less than 50 % of the physicals tests compared to the previous 9-3 model. At the same time the number of requirements and workloads were increased. There were also less late issues to solve in the project during the validation series compared to earlier projects. According to Sjödin, the most important factor for moving over to virtual driven development is the have the right methods, an organization with skilled and brave employees and to have a supporting process integrated with the simulation tools.

4.2.2 Towards Zero Prototyping at Jaguar Land Rover

Jaguar Land Rover, JLR, has had clear business goals due to increased market competition. Except for just delivering premium vehicles with reduced CO^2 emissions, they always want to deliver a robust design for all world markets with a reduced dependency on physical prototypes and a shorter product development time (Boon, 2009). In order to reduce physical prototypes, JLR will use more Computer Aided Engineering, CAE, and increase the confidence for CAE. In the mean time, their increased CAE usage is supposed to generate fast design iterations which will lead to shorter product development time. More detailed CAE is also supposed to help them get a more robust design (Boon, 2009).

Jaguar Land Rover, previously owned separately by Ford, is now going through an offensive system platform exchange called “End to end product development with a single architecture”. Jaguar and Land Rover were acquired by Tata Motors in 2008, they required JLR “Clone and Go” which meant that all the data had to be copied over to their own systems and JLR was not allowed to work at the same system platform as Ford anymore. The applications and systems used by Ford were both in-house made and delivered from many different suppliers. This made it very expensive for JLR to just maintain support for their old system platform and the applications from Ford. It was also far from an ideal platform for JLR since they had very different sales volumes compared to Ford; 250 000 vehicles/year versus millions of vehicles/year.

JLR divided their system platform problem in to four pillars.

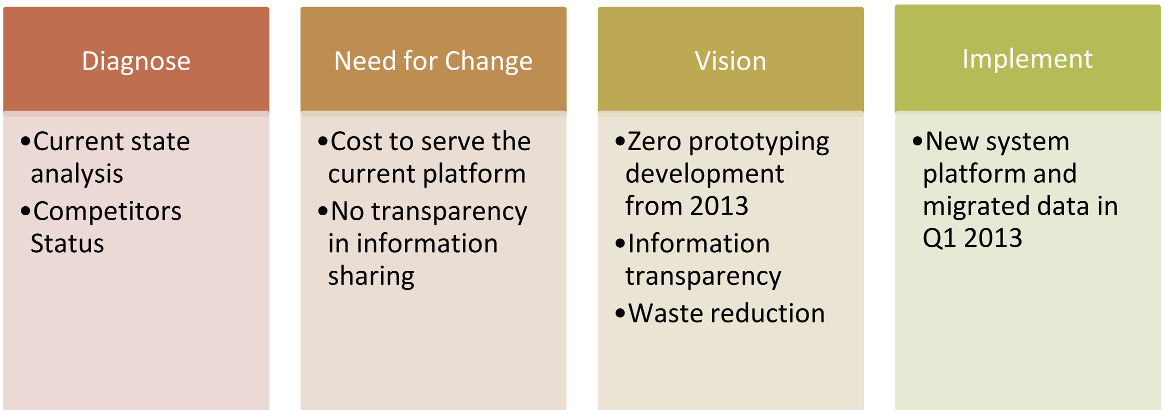

Figure 35 Four pillar of the ”End to end product development with a single architecture”

The competitors status in the diagnose pillar, see Figure 35, was made as a benchmarking matrix where different areas as digital manufacturing, PLM, visualization etc. were on the horizontal plane and knowledge level on a scale from one to five on the vertical plane. The goal for JLR was to be as good as the best company in every area.

Together with this project, they created a 50-30-10 strategy where their goals are to have 50 % more products, reduce time to market with 30 % and decrease the tool changes due to late design changes with 10 %. Combining this strategy with the goal of being the best in all the different simulation areas shows that they are clearly choosing a SDPD.

Sustainability has also been a driving force behind a simulation driven process. When developing the new Jaguar XJ virtual testing performed 7000 crash tests and over a million miles of virtual driving which gave them far more data and information then what physical testing would have (CIMA, 2009). It also reduced emissions and cost within their product development process. Then introducing more virtual methods instead of hardware prototypes JLR has had the sustainable benefits in focus as well as the economical. It did reduce the cost for their prototype manufacturing with 50 % between 2002 and 2003 and a recent modular project used 93 % less hardware prototypes compared to the previous one (Jaguar, 2012).

4.2.3 Simulation Development Loops at AB Volvo

This section is based on an interview at Volvo Group Trucks Technology. Volvo Group Trucks Technology is a subsidiary of AB Volvo and supports the four AB Volvo truck brands Volvo Trucks, Renault Trucks, Mack and UD with product development, planning and purchasing services.

AB Volvo used to have difficulties to perform simulations of the entire truck due to lack of synchronization in product development projects. Everyone worked as fast as possible, but it did not create any synchronization. Due to this, it was almost impossible to get sufficient data to perform simulations with the entire truck as boundary boarder. The solution to the problem has become development loops. It was launched in 2007, but since the time horizon to develop a new truck generation is fairly long the development loop process has only been completed once.

One development loop comprises three different phases; (1) Definition, (2) Implementation and (3) analysis, see Figure 36. The *definition* phase includes both definitions of what to evaluate during the loop as well as evaluation of the results from the previous loop, this phase last for 4 weeks.

The *implementation* phase is the most time consuming, it takes approximately 20-25 weeks, and it is in this phase the majority of the development takes place, each time this phase is performed for a component its maturity will increase and a lot of simulations at component level are performed within the implementation phase. In the *analysis* phase simulation on the full vehicle level takes place, it is a gateway for the design engineers and all components have to fulfill a predefined level of maturity. The *analysis* phase takes place in parallel of the *definition* phase of the next loop. A project consists of several steps. The last project using the development loop process at Volvo had seven loops, each one of them with a predefined purpose. The development loop project is performed by eleven cross commodity groups with shared responsibilities, four groups focus on the cab and seven on the chassis development. The simulations, that have the entire vehicle as system for the analysis, are performed by simulation engineers with ordinary location at chassis simulation.

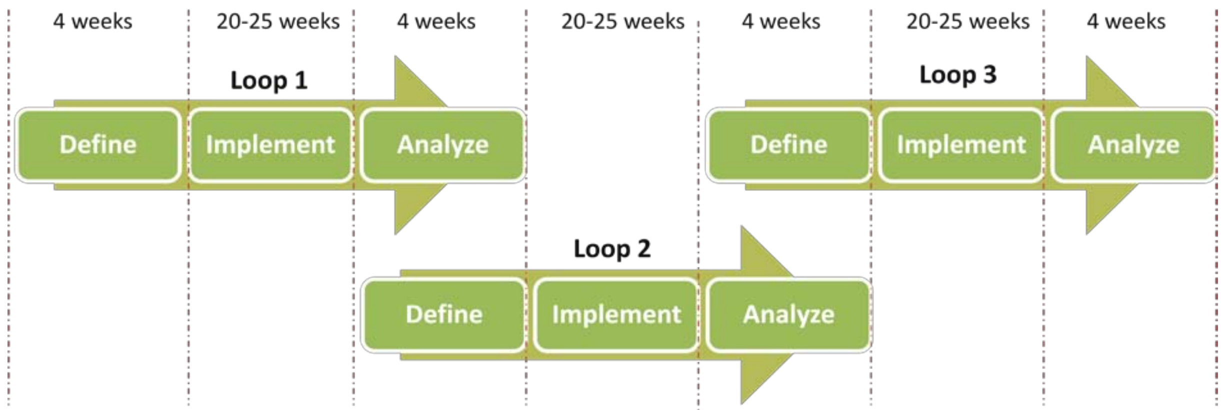

Figure 36 Illustration of Development Loops at AB Volvo

4.2.3.1 A Way of handling Maturity of Components

Volvo categorize its components that are included in a project into three different categories; (1) *Prioritized Critical Areas* comprises development of new components or technology with large importance for the success of the entire truck. (2) *Critical Areas* comprises development of new component with less importance or complexity in comparison to the prioritized ones and the category (3) *ALL* comprises all other components included in the project, where are often a lot of "carry over" components from previous generation. All components are classified into these categories by a cross functional network. Within each category the components have three levels of maturity, LOM, which are defined as E, F and G, see Figure 37. These three steps are defined for all CAD-modules. A CAD-module can for instance be the exhaust pipe from the engine to the muffler including brackets and fasteners. Next module might be the mufflers itself inclusive brackets and then can the tail pipe of the exhaust system be a third module.

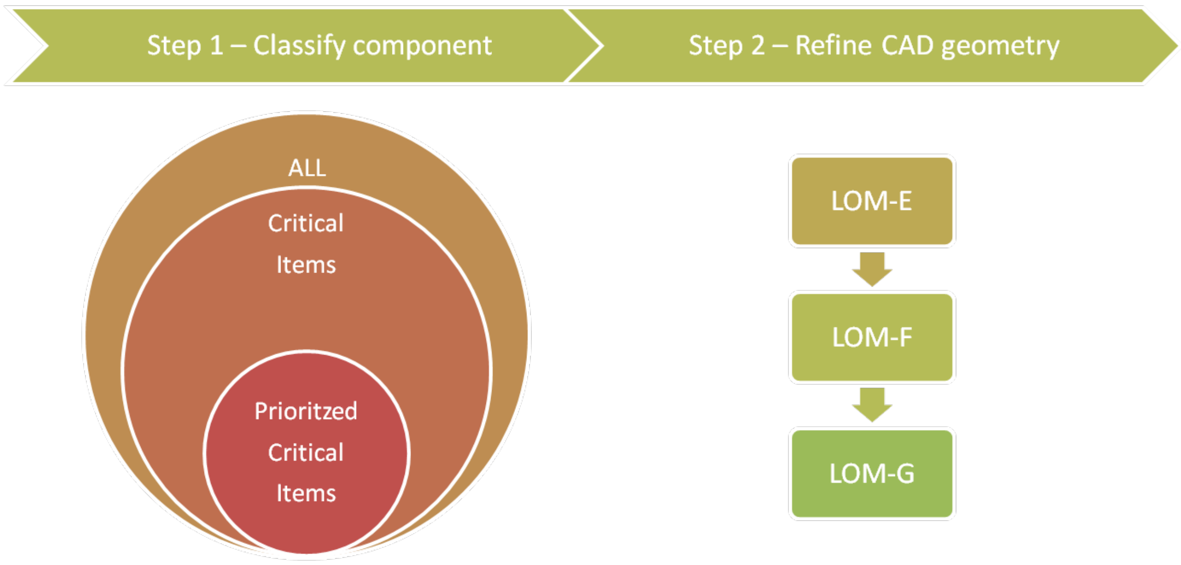

Figure 37 Illustration of CAD-geometry's level of maturity

A LOM-E gives the basis for geometry envelopes for each module to claim the space for new design modules. It is usually a compromise between different modules to perform as good designs as possible; almost all design engineers want to use more space than what is available. A module with LOM-F has locked it outer interfaces and at this level some simulations regarding the complete vehicle or sub-systems can be made. However, it is first when the modules have reached LOM-G status the simulations regarding strength and dynamics can be made on whole vehicles. The prioritized critical areas of the truck reach a higher level of maturity before the other categories. One feasible focus of the first development loop might for instance be that all prioritized critical areas fulfill LOM-E.

4.2.3.2 Physical versus Virtual Testing at AB Volvo

As mentioned earlier in the thesis, simulation and analysis is virtual testing often with a common objective as physical testing. At Volvo the view of testing has changed. Nowadays, almost all developing testing is made in a virtual reality. Simulation and analysis is performed on an item until it fulfills all targets theoretically and then the physical tests are only used as validating tests to secure that the simulation model was accurate. It is no time for surprises in the physical tests, though it happens sometimes, it does not appear often enough to be a disturbing problem for Volvo. However, it is the design engineer who is responsible for the quality of its component and if it feels secure that the component fulfills the targets by previous experience it actually does not have to do any simulations. In case of insecurity of the strength of the design, simulations are the way of evaluating it. It is important with a tight collaboration between physical testing and virtual testing, measures from the physical testing track are used to update simulation models and verify its accuracy. The virtual tests and the validating physical test are usually consistent.

Volvo has a vision of zero prototyping, but today still it is only a vision. The focus is to find the shortest route to the answer. Sometimes it would take ten times longer time to simulate a result than ask the mechanical workshop for help with a simple prototype. In this case the physical prototype should be favored. It is mainly in two areas the virtual tests do not reach sufficient accuracy in sufficient time; how the wire harness behave when the cab is tilted and routing of wire harness. These two areas still have a need of physical testing. On a larger perspective Volvo has a potential of implementing simulation tools to a larger extent in the pre-production. A lot of assembly preparation operations are still performed physically even though it is virtual tools available.

The work with development loops has had a great impact on the product development lead time. When the project that has had this loops and simulation on the full vehicle level is compared to the classic global development process the lead time has been decrease by 20-30 %. The development loops is the new standard procedure at Volvo and it is actually founded on the basic principles from the middle of the 20th century to front-load product development projects as much as possible.

5 ANALYSIS AND DISCUSSION

In this chapter, the findings from the theoretical framework and results from case studies are analyzed and discussed. The analysis has to some extent a Scania perspective, but will be applicable generally as well.

5.1 Feasibility of combining Lean and Simulation Driven Product Development

To investigate to what extent Simulations Driven Product Development, SDPD, can be integrated in Lean product development an analysis have to be made in several levels. The Lean philosophy and SDPD methodology has to be compared in several different layers. On an upper level the different principles of Lean product development might be affected by SDPD. On a lower level it is more a matter of how Lean methods, such as SBCE, are affected by an implementation.

5.1.1 The impact on the Lean Product Development Principles.

The impact on the thirteen principles of Lean product development introduced in section 3.2 Lean Product Development will be analyzed from the perspective of the three categories *process*, *people* and *tools and technology*.

An implementation of SDPD might affect *principle 2: Front-load the product development process while it is maximum design space to explore alternative solutions thoroughly.* In comparison to testing, simulation and analysis can be performed on an earlier stage since it does not demand physical prototypes. This should facilitate the front-load principle. However, it is very dependent on how simulation tools are used in the process. In order to support front-loaded product development processes, simulation tools should enable to base decisions on facts. It can for instance be used in the pre-development phase when concepts are going to be evaluated. Sometimes simulations is used for firefighting and backtrack an unexpected failure of a component, this is not related to front-loading at all. As long as simulation tools is used proactively to drive the product development forward it will have a positive contribution to the second Lean principle introduced by Morgan and Liker (2006).

An implementation of SDPD might affect two of the principles connected to the area *people*. The first is *Principle 7: Develop towering technical competence in all engineers.* In cases there the SDPD comprises simulations performed by the design engineer it might be seen as the design engineer starts to broaden its competence by starting using simulation tools instead of increase competences in CAD. To some extent simulations performed by design engineers might be a contradiction to principle number seven. However, it is all a matter of what kind of competence the design engineer role conduct. If the design engineer is supposed to have skills in strength and durability for its component simple simulation might be useful to gain this knowledge and can be classified as a towering instead of a broadening activity. Since strength properties often is an important target regarding the design, it should be reasonable to combine principle 7 and simulation performed by the design engineer. Other kinds of simulations does not have an impact on this principle, but if a simulation driven approach is chosen it will be necessary to have engineers who are experts and towering within the field.

SDPD might also affect *Principle 9: Build in learning and continuous improvement.* In the case where the design engineer performs simulations, learning connected to strength theory is going to be built in the system. In order to support continuous learning simulation results have to be well documented. Once again the impact of an SDPD implementation is a matter of how the implementation is done rather than if it is implemented or not.

When studying the principles associated to tools and technology it is more related to how to implement SDPD in a Lean environment rather than a matter of if Lean production and SDPD support each other or not. To be supported by these principles, implementation of new simulation tools has to be performed in alignment with the people and process. It is important that simulation tools are used to support the process and people and not vice versa. Therefore, it should be reasonable to be a little bit conservative when implementing new technology and tools in order to assure that the people and process always are in focus.

5.1.2 The impact on Waste in the Product Development Process

In the theoretical framework waste has been defined in several different ways, see 3.2.2 Definitions of Waste. The categories introduced by Ward (2007) is developed for the product development environment explicit in contrast to categories introduced by Morgan and Liker (2006) that is more an adaptation of well known waste categorizations from Lean production. Scania R&D has its own categorization of waste even though it is quite similar to the categories defined by Morgan and Liker.

5.1.2.1 Scatter, Hand-Off and Wishful Thinking

An implementation of SDPD will probably affect the amount of scatter waste in the product development process. However, the impact is ambiguous; it is a potential of decreasing the amount of waste, but it is also o risk that a SDPD implementation actually increasing the amount of waste in the process. If design engineers starts to use for instance simple FEA tools to do some simulations by themselves it is likely that their understanding for the simulation engineers environment and preconditions will increase. Another positive aspect is that to be successful with simulations the design engineers probably need to perform its simulation with support by a simulation engineer; therefore, the frequency of the daily contact between the different workgroups should increase. These two aspects correspond to decrease the part of scatter waste related to communication barriers.

When implementing SDPD the available research suggests a kind of method standardization. The result should be analogues and independent on the individual who perform a task. This approach initiates a risk of forcing engineers to use tools that is not sufficient for its certain situation; the kind of scatter Ward (2007) define as waste caused by poor tools. It is only engineers who get usage for the result of the simulation that should use SDPD and therefore it has to be done some examination of which circumstances the method should be used or not. If a too detailed SDPD methodology is implemented all over the department it will probably cause this kind of waste.

Waste caused by *Hand-off* will probably be affected by a SDPD approach. The first root cause of Hand-off Ward derives is useless information, i.e. generated information that does not add value. If a design engineer executes simulations by itself it will get only the answers it asks for and it can be seen as a method to secure that useless information is avoided. However, it is a risk that the accuracy of the calculation or simulation performed by the design engineer is low and actually does not add any value to the quality of the design. In this case SDPD actually increase the amount of waste in the process. A trend during interviews with simulation engineers was that they prefer to come up with a result that is as close to the reality as possible. However, sometimes it is not a need of high accuracy of the computation or simulation. In cases were a simulation is more accurate than needed waste has actually been added to the process due to that the simulations have used more resources, both man hours and hardware, than actually was needed for the computation.

Ward classifies waiting as the second root cause of *Hand-off* waste. The waiting is twofold; it is related to a work-in-progress project have to wait between value-adding activities as well as individuals hand over its responsibility to another division and waiting for input to continue their work in the project. The possibility of decreased communication barriers between simulation and design engineers due to enhanced understanding for simulation among design engineers will probably reduce the waste of individuals waiting. It will increase the cross functional work which Ward suggest as a solution to the waiting issue. For the other part of waiting simple simulations made by the design engineer reduce the number of transfers between different individuals. As soon as an order is placed to a simulation group the object has to queue for a free simulation slot. Since the number of iterations between departments likely decrease SDPD has a possibility of decreasing the waste caused by waiting.

The final category of waste according to Ward (2007), *wishful thinking,* is probably not as affected of an SDPD approach as the other categories. For instance the behavior of testing to specification is independent of if the test is executed virtually or physically. However, it is essential to put attention to the importance of deliver more knowledge than just a binary answer if the design fulfill the targets or not. Ward suggests an approach where tests should provide the design engineers with knowledge and possible solutions. It is a statement to keep in mind when implementing SDPD and developing methods and processes in order to gain knowledge. The second root cause of wishful thinking is related to how the knowledge gained during tests is sustained. If results from simulation is not documented and reused when a comparable simulation takes place next time it will drive waste related to discarded knowledge. Therefore the development process should include demand of sufficient documentation and to sustain the knowledge from a development cycle or an individual to another.

During the introduction of the thesis *rework* is assumed to be one of the most common wastes at Scania's R&D department. Even though rework is not stated as an example of waste by Scania (2010) it is mentioned during interviews with employees as a common waste. However, rework in itself is not obvious to assign as pure waste since it at the current state sometimes seems to be necessary in order to deliver demanded quality. Therefore, rework in itself is maybe not waste, but rework is a clear sign of other wastes present in the product development process. Therefore an implementation of SDPD should reduce the number of rework cycles.

Changes towards SDPD, from a more traditional development procedure, will probably have an impact on all Ward's waste categories. However, if the effect is going to be positive or negative is probably closely related to how SDPD is implemented to the product development process.

5.1.2.2 R&D Factory's Definition of Waste

In comparison to the categories Ward prefer for classifying waste, the examples of waste described by Scania (2010), see 3.2.2.3 Scania R&D Factory's Definition of Waste, is not affected by a SDPD to the same extent, although, it might have an impact on some of the categories. *Doing more than necessary* might be increased in the same way as it might cause waste caused by hand-off in the previous section. However, if some simulations and calculations are suitable to be performed by a design engineer instead of a simulation engineer it is also a possibility of avoiding more accurate simulations than actually needed. This is also related to the example *Not using everyone's competence.* When a simulation engineer perform simulation that actually is suitable to be performed in an integrated simulation module to the CAD software by the design engineer it should be waste of the simulation engineers competence, due to overqualified skills. Instead the simulation engineer could have spent its time on more complex tasks, which for the moment is idling in a queue. However, the phenomenon described in this section is more a matter of how simulation is used in the PD process and of who actually performs the simulation than if the product development process is simulation driven or not.

5.1.3 Flow and Cadence

As mentioned in the theory framework chapter the flow is in focus in a Lean enterprise. The target is to generate a seamless flow where the amount of waiting and other waste is minimized in contradiction to the traditional approach where focus is on maximize resource utilization. To sustain the flow the presence of an obvious cadence and synchronization will be necessary. From a SDPD perspective several individuals independently emphasize the need of cadence and synchronization to be able to do simulations that comprises several different sub-systems that affect each other. Therefore, SDPD should be more easily implemented at a company that already has implemented Lean production and has initiated some kind of flow in its product development process than in a company that has not. Still it seems to be common that it is either the start of production or planned physical tests that steering the product development process. The projects are planned with these deadlines in mind and it is dependent on available time to what extent other activities, such as simulations, are included to the plan or not.

In a SDPD approach simulations should be a key to both create the flow and identify the cadence and therefore, simulations probably has to get a more central role than it has at a company that currently has physical testing as primary gateways during the process. Several important simulations in a SDPD environment will take place on a lower level, for a component or subsystem, than the large gateways in a flow driven by physical tests or start of production. Therefore a cadence on project level which Ward (2007) argue for should be suitable for a SDPD approach. A project individual cadence would level the work load on different functions since all activities do not occur simultaneously. However, simulation with large system boarders such as full vehicle simulations probably has to occur synchronized and with a common cadence for the entire department.

5.1.4 Set-Based Concurrent Engineering

Set-Based Concurrent Engineering, SBCE, introduced in section 3.2.3, is on a more detailed level than the philosophy and basic principles discussed in previous sections of this chapter. From a holistic view the core of SBCE is two principles; base decisions on facts and eliminating concepts stepwise. One common opposition to SBCE has during interviews been that it is to resource consuming to work with several concepts too long into the project. If each decision has to be based on fact all concepts has to be evaluated to some extent. In a physical test oriented environment it will be very costly and time consuming to do prototypes and actually test concepts to eliminate them.

With a SDPD approach it is actually possible to do calculations and simulation at an early stage of a concept and therefore base concept elimination on fact instead of intuition. If the early decisions in the product development process are based on fact instead of intuition or best guess it is likely that the number of rework cycles due to insufficient design will decrease. In cases, such as the Saab case described in section 4.2.1, where SDPD is implemented to an extent that makes it possible to eliminate all physical tests except verifying tests parallel concepts can be used all the way. Therefore, SDPD and SBCE is consistent, actually if SBCE are going to be used in an environment as complex as the automotive industry, SDPD seems like a precondition to be successful.

5.1.5 The impact on Knowledge Creation

Even though the Lean philosophy commonly focuses more on how to eliminate waste, it is of interest to think about how the value adding share of the activities at an R&D department would be affected by an SDPD approach. What a value adding activity is depends on the specific company, but Ward (2007) analogous to Scania (2010) emphasizes knowledge creation as one of the value streams in the product development process.

The three types of knowledge learning described by Ward in section 3.2.1, *Integration learning*, *Innovation learning* and *Feasibility learning* can all be enhanced with help of simulations in different ways. Simulations performed by design engineers will create a stronger integration between design groups and simulation groups and therefore contribute to *Integration learning.* These types of simulations do also enhance the *Innovation learning* for the design engineer since the case study showed that the biggest advantage for a design engineer using GAS in CATIA was they gained knowledge about different concepts and solutions. Simulations in general are a helpful tool for *Feasibility learning* since it is a good way to get decision support about different functionalities.

One crucial part when striving to enhance the level of knowledge in a field is feedback. Simulations often have the advantage of provide shorter lead time from question to answer in comparison to physical testing. Decreased lead time for each learning loop will probably shorten the learning time for each individual. However, the result itself will not gain the knowledge. It is a significant difference between transferring data and generating knowledge. Knowledge is about understanding and be able to do accurate analysis from given data. Therefore cross functional teams and experts in different fields are needed as a support when transferring data into knowledge.

Ward (2007) highlights that "*trade-off curves*" as a sufficient information carrier when transferring knowledge between individuals. When using simulations it is rather easy to change one parameter and get an illustration of how another parameter is affected. The use of simulations should therefore facilitate the creation of trade-off curves. However, it will likely be an initial inertia when starting to increase the number of simulations in the product development process. It is a knowledge threshold that each individual that getting in touch with simulations have to overcome in order to be able to enhance its knowledge. Otherwise the result of the simulations will continue to be confusing data and SDPD cannot contribute to the knowledge creation.

5.2 Preconditions for Simulation Driven Product Development at Scania

Based on the theory and results from case studies there are some different preconditions to reach a successful implementation of SDPD at Scania. Even though some of the statements and discussion are quite company specific it should be possible to generalize findings to a level that is accurate for a company in the automotive industry that currently use a lot of physical testing within its development process. Areas such as knowledge and experience, cross functional interaction, and integration in the product development process are all preconditions that likely are present at more companies than Scania.

5.2.1 Knowledge and Experience

As mentioned both in the theory framework and results from case studies knowledge and experience are crucial to be successful with a SDPD implementation. Knowledge within simulation and analysis will be necessary in order to create accurate models for simulation and justify if the result seems to be accurate. However, to be able to do accurate simulation models the knowledge within physical testing is crucial and therefore knowledge and experience are important factors for a SDPD implementation in most of the different functions in the product development process.

5.2.1.1 Competence within Simulation and Analysis

According to both theory and benchmarking cases, a key success factor with SDPD is to have a deep core competence about simulation methods and use it to improve and support the simulation processes. Experts in simulations should not necessarily do the simulations themselves. Scania has today many engineers already working with simulation and analysis. They have also been involved with calculations as FEM and CFD many years back and therefore Scania has a fairly long history when it comes to simulation and analysis. The existing competence is therefore a valuable resource if a SDPD approach will be implemented. However, the simulation groups at Scania are already choked and it is a frequent queue of simulation tasks idling for each group. Some groups therefore do not have sufficient time to develop its simulation models or create a work process for the simulation tasks which would probably be needed to fulfill an implementation of SDPD.

One way to manage the choked simulation groups and get available time for method and model development is to try to eliminate the tasks that the simulation engineers are over classified to spend their time on. Some of the simulations might be executed by the design engineer itself. However, if more employees, e.g. the design engineers, than only the specialists are going to perform the simulations, enhanced simulation competence is needed at the design groups. The close collaboration between a design and a simulation engineer is mentioned by both parties as a precondition when design engineers try to do simple simulation by their own. To facilitate this knowledge it could for instance be reasonable to have a simulation engineer geographically located at each design group or at least a specific engineer responsible for each design group.

One issue with decentralization of simulation engineers is that the individual separated from the simulation group will lose its depth in competence. One way to solve this, analogous to the Lean approach, is to arrange some kind of rotation there the simulation engineer is located at a design group just for limited time period and when it has come to its end it will be replaced by a colleague. To handle the paradox of increasing core competence and broad the knowledge simultaneously Saab Automobile used a mixture of a decentralized and centralized simulation groups, by locate the CAE decentralized, but they were tight connected to a centralized group which was responsible to develop the models and spread knowledge to each individual. In Lean, general work rotation is a tool used to gain knowledge.

5.2.1.2 Knowledge and Experience about Physical Testing

To be able to simulate more areas in product development, new methods and tools usually needs to be developed. In order to create new reliable simulation methods, knowledge from physical testing labs are used. When Saab Automobile implemented SDPD they used Road-to-Lab-to-Math, RLM, projects and they had to start to transfer signals from road testing to physical testing in labs. Since Scania is leading within dynamic strength tests and has a long history with physical lab testing, it has already done half the journey of RLM project by going from road testing to lab testing. Therefore, Scania has the possibility to take advantage of their knowledge in the physical testing labs to create mathematical simulation models, the other half of the RLM-projects. When introducing SDPD physical testing is not going to be eliminated, it will be necessary to advantage of benefits physical testing has, e.g. discover unexpected cracks, measure loads in specific areas and use it to get a more accurate simulation model. Physical testing is also needed to evaluate the new simulation methods and therefore it will still be a need of engineers within the area of physical testing, even though the tests might change a little bit compared to the current situation; test engineers might be used to develop new simulation methods and are needed to do validating tests to verify the simulation models.

5.2.2 Concurrent Engineering

A positive side effect that comes with SDPD is the faster and more frequent interactions between different departments within the company, e.g. the interference analysis at Boeing, see 3.3.1.4 Interference Analysis. The communication barriers will and has to be reduced in order for SDPD to work properly. This section will describe and analyze the importance of interaction between different groups to make SDPD function better.

5.2.2.1 Interaction between Design and Simulation

Since the roles within product development usually consist of a design engineer who does the design and 3D geometry and different types of simulation engineers who perform the different types of simulations a stronger interaction is required between them. The first reason is that the transfer of geometry and information often needs some type of communication since it is based on both the demands required to perform the simulation, but also the existing data the design engineer already has. Depending on the PDM/PLM-system, the design engineer also need to inform the simulation engineer which model should be used and which one that is most up to date. If there would be a possibility to express maturity levels of the models and if the product development projects had clear synchronization points, this communication demand would probably vanish.

The other reason is the transfer of the result of a simulation. To just deliver a “pass or fail” answer will not help the design engineer to improve the design or learn anything about its functionality. Therefore more simulation jobs usually increase the communication between design groups and simulation groups since they need to interact more with each other. In order to lower the communication barriers and to enhance knowledge in each other’s areas, the groups should preferably be geographically located close to each other as the most groups are at Scania today or as mention earlier, see 5.2.1.2 Knowledge and Experience about Physical Testing, integrate a simulation engineer within a design group.

The interaction between the simulation groups and design groups will and need to enhance when some simulations are performed by a design engineer. Since the design engineer has to learn more about the method of the simulation and how to analyze the results, it will also gain a better understanding for simulations in general and is able to have a more deepen discussion with the simulation engineer about more advanced simulations.

5.2.2.2 Interaction between Simulation and Physical Testing

As mention earlier regarding the RLM projects performed at Saab, enhanced or new simulation methods usually arise from methods and measurement from physical testing. Therefore a strong connection between simulation groups and physical testing groups is necessary to improve and extend current simulation methods and tools. Scania has today no clear connection here either geographically or through the organization. If simulations will increase and the employees at physical testing will slowly decrease without any clear interaction between the areas, the knowledge about physical testing might vanish instead of being integrated with the simulation models.

A common process for virtual and physical testing with an obvious and clear connection between the tests regarding model, calculations and result is needed to enhance the quality of the simulations and not lose the knowledge Scania has within physical testing.

5.2.3 Simulations in the Product Development Process

Today, there is no clear documentation or instructions about where and how simulations are used in the product development projects. Though, there is clear documentation about physical testing and consideration when to include physical testing in the project plans. Since physical test vehicles require a lot of administrational work and planning, these can sometimes control the time plan for the rest of the project and is a clear and obvious milestone compared to virtual testing which today usually does not even have a milestone in the projects at Scania.

When prioritizes are needed due to time pressure, design engineers tend to focus on ordering prototypes to physical testing earlier instead of complete a simulation job. This is probably done since the physical test vehicles have clear deadlines and simulation results can sometimes not even be required. Here can a cadence with simulation loops and synchronization points in the project give a greater support for simulations in the product development process. It would also affect the design engineer to prioritize uploading accurate models more frequently. A maturity choice available in GEO would simplify continuous uploading for the design engineer.

Going through available documentation and materials about the product development process for design engineers the demands regarding simulation and calculations in an early stage are absent. If a simulation job is ordered or not for a design is usually more dependent on the interest for simulations within each and every design engineer and if the design group leader has a background within simulation and analysis or not rather than the actual need for a simulation on that specific design.

5.2.3.1 Simulations performed by Design Engineers

Today at Scania, design engineer can do some FEM simulation by themselves in CATIA using GAS. This is a helpful tool to increase the amount of simulations without necessarily increase the number of simulation engineers. The simulation engineer can instead of doing the simulations themselves act more of a support helping the design engineers perform accurate simulations. The GAS application is not used by all the design engineers, but only by them who have found it interesting and therefore it is mainly used by younger employees with little experience as a design engineer. The reason why this group is overrepresented among GAS users is probably because they have a stronger demand for learning about the robustness in different designs as fast as possible and will not have time to wait for feedback from an ordered simulation job or, even longer, a physical test.

5.2.3.2 Front-Loaded Projects

It is crucial when in the product development process simulations are performed. It should be an activity that is scheduled and planed very early in the projects, before any physical testing. According to lean product development and set based concurrent engineering, it is desirable to use simulation results to evaluate concepts and letting the analysis from the simulations be essential when taking important decisions about which concept should proceed and not. Since virtual testing has a very short lead time compared to physical, it is very smooth to use early in the projects. It will not push the activities closer to SOP as physical testing would. It also makes it possible to do more iterations per concept or idea, i.e. more work, compared to physical testing, which means that using a SDPD by performing many simulations early in the projects will front-load the projects.

5.2.4 Incentives for an Implementation

Incentives can be a driving factor to make a bigger change, e.g. a SDPD implementation, within a larger organization. This section aims to investigate the plausible incentives for an implementation of SDPD both at Scania and within the automotive industry in general.

5.2.4.1 Incentives to reduce Lead Time for Product Development

The research and development department at Scania has newly started the challenge *"Double Output – Half time"* which should reduce waste at R&D in order to either reduce lead time, double the outcome or both. The goal is not clear and can be interpreted in many ways, but the main purpose is to develop new products faster. This challenge is therefore a good reason and incentive to use a SDPD. Instead of letting the time demanding physical tests and generation prototype trucks be the base of the time plan, simulation loops can be the backbone of the process. Since a simulation loop takes a lot less time and resources it will shorten the overall project time and physical testing should only be used in the end of the projects to verify the simulation models. The lead time reduction is also the main cause of the SDPD approach at AB Volvo. Since the two companies are present within the same business segment demanded lead time reduction is a feasible incentive to start a SDPD journey at Scania.

5.2.4.2 Economic Aspects of a Simulation Driven Product Development Implementation

As described in the theoretical framework, see 3.3.2 *Economic* Aspects of implementing Simulation Driven , as well as the results from case studies, see 4.2.1 *Cost Rationalization by using Simulations at Saab Automobile AB*, cost reduction is a common documented outcome of a SDPD implementation. For Saab, it was the driving force for the SDPD implementation. For a company that currently uses a lot of physical testing in its product development process, it is possible savings in an implementation of SDPD and it can therefore be a good incentive for usage of SDPD.

An estimation in of how large the amount of savings a SDPD implementation should generate is rather complex due to that a lot of individuals, departments and resources are connected to physical testing in one way or another. Some interviewees taking part in the case study at Scania emphasize for instance that a purchaser spend 50-70 % of its time on sourcing prototypes. Even though the time share is not confirmed a lot of time at the purchasing department will be related to prototypes. Testing engineer is another role tightly related to physical testing and the costs to sustain the test facilities is also due to physical testing. Therefore it is very difficult to come up with an overall potential saving. At the same time an SDPD implementation does not necessarily mean reduced employees within physical testing. As mention in section 5.2.1.2 knowledge and experience about physical testing should be used for the implementation and to develop the simulation methods. However, as a simplification and quite conservative calculation the cost for prototypes can be used.

Volvo emphasizes that the design engineers are supposed to choose the most time and cost efficient alternative when evaluating the design of a new product. In the normal state of the development phase, virtual testing is more rational to use in comparison to physical testing. However, it is still areas then physical testing outperform virtual testing, see 4.2.3 Simulation Development Loops at AB Volvo, and in this cases physical testing should still be used even though it is a target of zero prototyping. To be able to make such decisions the design engineer has to have a high cost consciousness of what kind of expenses each test method correspond to. This is also connected to the Lean theory regarding cost consciousness in section 3.2.4 If it is a lack of this cost consciousness, it is likely that the cost rationalization is not being realized. Instead the category of waste referred to as hand-off, see section 3.2.2.2 will increase in the product development process. Therefore, it is of great importance to put attention to and sustain cost consciousness among design engineers to be able to use economical factors as an incentive for a SDPD implementation.

5.2.4.3 Environmental Consciousness

The reduction of prototypes in a SDPD in comparison to a traditional approach will not only affect the cost. It also has an impact on the environmental image and footprint of the company. Therefore environmental consciousness and sustainable development should be possible incentives for a change towards SDPD.

Jaguar Land Rover has used the environmental aspect as one of the main reasons to have the target *Zero Prototyping*. As the automobile industry has a bigger pressure today to be profiled as environmental friendly, not only the CO^2-emissions, but also the environmental foot print from the product development and production can also affect the association between the automobile brand and environmental awareness.

However, this incentive is unsupported by the theory as well as the other company cases. Though, the environmental consciousness has increased a lot during the last years and the articles the theoretical framework is based on are a couple of years old. Several companies within the automotive industry has the environment as a core value, e.g. AB Volvo and Scania, and that is another reason why environmental consciousness should be a possible incentive for a change towards SDPD.

5.2.5 Trust to Simulation Results

A common factor for both AB Volvo and Saab automobile is the reliability they have to simulations and how they interpretive the results regarding accuracy. When the simulation results are not consistent with the results from physical testing, the measuring methods are questioned before they doubt the simulation models. A former employee at Saab automobile mentions that simulations are used in the very beginning of a project to convince other about a concept or idea. The trust to simulations is widely spread throughout the organization and therefore the simulation results have a big importance when taking decisions.

Since Scania has a long history and experience of physical testing, its employees tend to rely and draw conclusions on the results from physical testing more often than simulations and then the results differ, the simulation methods are usually questioned over physical testing. If the simulation results are not given the attention it should and is never used ahead of results from physical testing, there is now reason to perform the simulations. At the same way the suspicion for simulations and virtual testing will prevent SDPD. The over confidence for physical testing is dangerous for the quality of the products. One broken component in a physical dynamic strength test will not guarantee that all components will break and vice versa due to the distribution in a physical population of components. Therefore, a single physical test should not have a greater importance than a simulation result with several iterations behind it. They should instead support each other trying to explain the whole scenario, e.g. predict where cracks can occur and explain why and how likely it will be.

The trust is probably a success factor for the implementation and therefore a broaden trust to simulation results needs to be established if SDPD are going to be implemented. Without trust each project needs to overtake inertia of doubt and unnecessary physical testing will still be performed in order to secure the result. According to the theory chapter trust can be gained by success stories. Therefore the pilot project for the SDPD implementation is crucial for creating trust to simulations. The initial project should be simpler than the tools have potential for in order to minimize the risk of failure. A failure at an early stage will probably decrease the trust to simulations and therefore increase the threshold for starting a journey towards SDPD.

6 CONCLUSIONS

This chapter comprises the output to the research questions introduced in chapter 1 as well as Scania specific recommendations. The chapter is divided into two sections; the first concluding the result of RQ1, RQ2, RQ3 while the second section conclude the recommendations.

6.1 Result of the Research Questions

The applicability of implementing SDPD in a Lean Enterprise is investigated in the analysis of the thesis and is according to it rather high. The effects of a SDPD implementation in a Lean environment will primarily affect three different main categories which is the output of RQ1 and are presented in the box below.

APPLICABILITY OF COMBINING SIMULATION DRIVEN PRODUCT DEVELOPMENT AND LEAN PRODUCT DEVELOPMENT

- *It is a consistency between SDPD and the Lean Principles:* SDPD support or have a positive impact on several of the 13 principles describing Lean Product Development. In several cases it can be a tool to sustain the principles. However, SDPD in itself will not create a *Lean* product development process; it is closely connected to how the implementation is done and in what way SDPD is used.

- *SDPD reduces waste:* SDPD implemented in perspicacious manner will reduce the amount of waste in the development process in several ways. The waste reduction potential is specially clear in the categories *Scatter* and *Hand-Off*, but it will most likely reduce all different types of waste more or less. Although, it is a risk that SDPD will cause waste; primarily related to “doing more than necessary” if it is implemented in the wrong way.

- *SDPD is a precondition for using Set-Based Concurrent Engineering:* The literature related to Lean Product Development consistent highlights the importance of basing decisions on facts and working with several concepts in parallel. SDPD is a precondition to be able to follow this method in resource efficient and feasible way. Without SDPD, set-based concurrent engineer would be very costly, time consuming and therefore an insufficient methodology to use in a Lean environment

The preconditions for SDPD can be found in the analysis chapter and are divided in six areas described further in the box below. Even though the analysis had a focus on preconditions for Scania, these result be can applicable in a more general perspective within the mechanical engineering business.

PRECONDITIONS FOR SIMULATION DRIVEN PRODUCT DEVELOPMENT

- *Incentives from Management:* Incentives are needed to create a more clear understanding of the importance of the simulations to achieve an increased usage of simulations among the research and development organization. Therefore, simulation driven product development should be supported by economical, environmental and lead time reducing incentives.
- *Knowledge and Experience within physical testing and simulation*: Simulation Driven Product Development requires a high level of knowledge and experience within both virtual and physical testing in order to develop new advanced methods that can be used to evaluate complex technical functions on the product. The new methods for virtual testing should grow out of experience and knowledge of physical testing. Physical testing is also used to validate virtual testing and simulation methods.
- *Interaction between design, physical testing and simulation:* Simulation driven product development require frequent interaction between design and simulation groups in order to always have accurate virtual models for the simulation and continuously aware the design engineer about simulation results. It also require a clear interaction in the process between simulation groups and physical testing so they can have the use of each other's results and experience as described in the paragraph above.
- *Clear and front-loaded development process:* If a product development process should be simulation driven, it needs to be clear when and how virtual models should be created, distributed and simulated. Analogous to Lean principles, the process should be front-loaded and simulations will have bigger effect on quality, lead time and cost if they are performed earlier in the product development process.
- *Synchronization and maturity levels:* Simulation driven product development will require full-vehicle virtual prototypes and these can be more easily achieved with a PDM/PLM-system containing maturity levels for the geometry models. Synchronization points in the project plan for full-vehicle models will also ease the possibility to perform full-vehicle simulations efficiently.
- *Courage and trust to simulations:* Simulation driven product development requires a brave organization willing to trust and daring to believe simulation results. This courage is required both in management, but also widely spread among engineers in different areas.

The efficiency of a simulation driven product development process can be increased when it is combined with simulations performed by design engineer. The box below presents the five most important impacts design engineer simulations have on a product development process.

IMPACTS OF USING DESIGN ENGINEER SIMULATIONS

- *Enhanced understanding for physical properties of the component:* By using simulations, the design engineer achieves the opportunity to understand the strength and limitations of the design more easily than when it receives an answer from someone else. The enhanced understanding creates an opportunity to achieve more optimum solutions.
- *Enable a larger number of simulation iterations:* Since the time required for each simulation loop is reduced from approximately two weeks to a couple of hours it is possible to do more simulations and therefore reach a more optimum design than if simulations are performed by a simulation group.
- *Increased integration between design and simulation groups:* To be successful with the simulations the design engineer needs support from simulation engineers. This collaboration will increase the understanding for each other's circumstances. It will probably also reduce the communication barriers and enhance the knowledge transfer between the groups.
- *Increased possibility of front-loading projects:* Simulations performed by design engineers can be involved at an earlier stage in the development phase than regular simulations. The design engineer can for instance do simulations during the concept phase to investigate some general ideas with a very low maturity of the CAD geometry.
- *Decreased product development lead-time and increased resource efficiency:* For each simulation a design engineer performs by itself instead of hand-over to another person idle time and waiting are reduced as well as start up times for the individual who otherwise are going to perform the simulation.

6.2 Recommendations to Scania

With support from the analysis and the conclusions some specific recommendations to Scania are formulated regarding simulation driven product development. These recommendations are not as generable as the result since they depend on the current state at the company.

SCANIA SPECIFIC RECOMMENDATIONS REGARDING SIMUALTION DRIVEN PRODUCT DEVELOPMENT

- *Establish targets for reducing prototyping:* Today, there is no clear incentive regarding reducing prototypes. A vision or goal would help employees to understand the importance of the amount of prototypes used and the engineers can more easily prioritize simulations. A reasonable target in a short time horizon might be the 35 % reduction mentioned earlier in the thesis. In order to be consistent regarding incentives it is important to connect other established incentives, such as Double Output – Half time, with simulation driven product development.
- *More clear product development process regarding simulation and analysis:* Today, there is no documentation when or how simulation and analysis should be used in the product development process. This should be established, especially from the perspective of the design engineer. Here the feedback process between physical testing and simulation, mentioned in the paragraph below, should also be included.
- *Secure a more clear feedback process between physical testing and simulation*: Without a clear demand for feedback between the physical testing groups and the simulation groups in the product development the connection between the groups will not vanish. How the feedback should be performed needs to be defined since it is crucial for the interaction between the two areas and the validation of the simulation methods.
- *Invest in research regarding new simulation methods for dynamic strength:* The biggest gap between physical testing and simulations for Scania is in the area dynamic strength and durability. Since it is one of the most important factors for Scania and its products the main research focus for simulations in the nearest future should be within this area.
- *Systematic simulation method development to fulfill the testing demands:* Scania will continuously need simulation method development projects where the testing demands are moved from Road to Lab to Math (RLM-projects). This should be made to be able to reduce physical prototypes.
- *A general support structure within the organization regarding simulations performed by design engineers:* Simulations for design engineers should be supported with help of simulation engineers. There should be a support function outspreaded in the organization closely located to the design engineers.
- *Require geometries and models more frequently:* A demand for getting accurate models earlier in the projects is a presumption to be able to perform sub-system or full-vehicle simulations. This requires a possibility to express maturity and to have a tact with synchronization gates in the product development projects.

7 FURTHER STUDIES

During the study some areas there further research would be appreciated has been detected. The areas presented in this chapter is beyond the limitations for the study and would be of interest to investigate further in order to be able to do a successful implementation of simulation driven product development.

Measure the amount of rework: Unnecessary rework is referred to as a substantial kind of waste. Since rework is required when other kind of wastes, e.g. wishful thinking, is present it might be a good KPI to measure quality during the product development process. Therefore, it would be of interest to consider how rework can be clearly measured and defined.

Examine how to arrange a Road-to-Lab-to-Math journey: In order to achieve a high accuracy in simulations they have to reflect the reality. In order to success with it, RLM-projects will be necessary. Therefore the RLM arrangement has to be investigated in order to be able to implement simulation driven product development.

Increase the cross functionality of the scope: Simulation tools are used in several other departments as well. This study have a focus on research and development, but it would be of interest to get a more holistic view and have the entire organization including marketing, production and purchasing in order to develop a common platform for simulation driven product development.

Investigate the possibility to handle maturity levels of items and cadence in the IT-systems: Best practice companies within simulation driven product development have implemented IT-systems that can handle levels of CAD geometry maturity and has a cadence in its process. It would be of interest to study how this arrangement could look like at Scania CV AB.

Perform a more detailed economic calculation: The economic impact of a simulation driven product development implementation has to be investigated more in detail. This study only comprises an example of reduction of prototypes. Other possible savings should also be investigated. It is also of interest to investigate the required cost for investment in both hardware and software as well as competence development in order to manage a change towards simulation driven product development.

Investigate the effects on lead time: The positive effect on lead times by implementing simulation driven product development is well documented, but it would be of interest to study how much the lead time can be decreased and what effects it would generate.

Available information from subcontractor: A topic that will affect the complicity of an implementation is what kind of information the subcontractors offer. The available CAD geometries and simulations should be investigated. It is also interesting to study the requirements on subcontractors. It is maybe possible to force the subcontractors to offer results from simulations as a complementary to protocols from physical testing.

Investigate sufficient share between simulations performed by design engineer and experts: In order to keep the accuracy good enough on the simulations the allocation of simulations should be studied. Some kinds of simulations are suitable for the design engineer to perform while others have to be performed by experts. It is therefore a need of developing some kind of guideline for in what way simulations should be executed.

Investigate the maturity and accuracy of different simulation models: As a subpart or a first step of a RLM journey the accuracy of current simulation models should be investigated in order to find areas there it is a need of enhanced model development to be successful with a future RLM journey.

Development of detailed implementation guidelines: The result of this study only comprises some general recommendations of actions in order to take some steps towards a simulation driven product development. Therefore it is a need of develop a more detailed framework for an implementation of simulation driven product development

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APPENDIX A - NOMENCLATURE

ABACUS	*A suite of software from the software provider Dassualt Systèmes. For instance used to perform finite element analysis.*
CAD	*Computer-Aided Design*
CAE	*Computer-Aided Engineering*
CATIA	*Computer Aided Threedimensional Interactive Application - A CAD software from the software provider Dassault Systèmes*
CFD	*Computer Fuild Dynamics*
Chalmers	*Chalmers University of Technology*
COD	*Cost of Delay*
DELMIA	*Digital Enterprise Lean Manufacturing Interactive Application – A software from Dassualt Systèms used for digital manufacturing*
ECO	*Engineering Change Order*
EURO-NCAP	*The European New Car Assessment Program - a European car safety performance assessment program*
FEA	*Finite Element Analysis*
FEM	*Finite Element Method*
GAS	*Generative Assembly Structural Analysis – an integrated tool that allows designer engineers to analyze assemblies as well as individual parts in CATIA V5*
GEO	*Abbreviation for geometry assurance and a system used at Scania to share CAD geometries*
GP	*Geometric Position*
GM	*General Motors*
JLR	*Jaguar Land Rover*
KTH	*KTH Royal Institute of Technology*
LOM	*Level of Maturity*
PA	*Scania abbreviation for Testing Request*
PD	*Product Development*
PDM	*Product Data Management*
PLM	*Product Lifecycle Management*
R&D	*Research and Development*

R&D Factory	*Adaptation of Scania Production System for the Research and Development environment*
RLM	*Road-to-Lab-to-Math* – Going from physical to virtual testing
ROI	*Return of investment*
RQ	*Research Question*
Saab	*Saab Automobile AB*
SBCE	*Set-Based Concurrent Engineering*
Scania	*Scania CV AB*
SDPD	*Simulation Driven Product Development*
SDD	*Simulation Driven Design*
SPS	*Scania Production System*
Volvo	*AB Volvo*

APPENDIX B – SBCE FRAMEWORK

This appendix comprises a framework for Set-Based Concurrent Engineering developed by Sobek, Ward and Liker 1999 and has its origin in the article *Toyota's Principles of Set-Based Concurrent Engineering.*

SBCE FRAMEWORK ADAPTED FROM SOBEK ET AL. (1999)

Principle 1: Map the design: Aiming to support the team to come up with different possibilities to fulfill a need of a function. Adapt

- *Define feasible regions*: This is a cross functional activity where each single department involved independently and in parallel tries to come up with constraints to the new design in its own environment. Each department check in designers' checklist in order to keep the knowledge from previous projects. The checklists at Toyota is not a long list, instead it contains holistic guidelines of how to perform more in general than in detail.
- *Explore trade-offs by designing multiple alternatives:* The key of this implementation principle is to investigate trade-offs with the possible multiply subsystems for solutions. Since the decisions should be based on fact prototypes, simulations and analysis should be used for investigation. Best guess is not good enough.
- *Communicate sets of possibilities:* In this session the sets of possible concepts is communicated. Standard design matrices are used both to communicate the solutions and to give feedback.

Principle 2: Integrate by intersection: In this phase, design teams starts to integrate different subsystems in order to identify solutions that is workable for everyone in the cross functional team.

- *Look for Intersections of Feasible sets:* The team is looking for intersections in interfaces between different possible subsystems to be able to combine them. It is important to have the overall system performance in mind and not just the subsystem that is in focus for the moment.
- *Impose Minimum Constraint:* Toyota's approach is minimum constraints needed at the time. Flexibility in a late stage in the development process makes it possible to be agile to the customers need. Often, the need is unclear when the project is launched, but will be more and clearer when the market launch comes closer.
- *Seek Conceptual robustness:* Strive to create concepts that are as robust to their environment as possible. It includes wear, weather and other external impacts as the surrounding layout and interaction with other concepts.

Principle 3: Establish Feasibility before Commitment: It is of great importance to understand the overall system before the team is getting too committed to the final solution.

- *Narrow sets gradually when increasing detail:* The solutions should gradually be eliminated due to the limitations in each solution. The narrowing has to happen sometimes and should be based on knowledge and concept failure, i.e. the concept that seems to be the best one should not be chosen, the least appropriate one should be eliminated until it is only one left. The responsibility to eliminate a solution and narrow should be a decision of the project manager.
- *Stay with Sets Once Committed:* It is important that the team stays within the narrowing funnel so all participants can be sure that they do not have to take other possible changes into consideration.
- *Control by Managing Uncertainty at Process Gates:* Toyota uses a set of both written and implied rules to handle uncertainty. One example is that if only one concept is left when it comes to the point of calculating cost, the narrowing process has been to rapid and more possible solutions or concepts has to be evaluated.

APPENDIX C – DESIGN ENGINEER QUESTIONS

This appendix comprises the questions used during the qualitative study with design engineers. Since the interviews were semi-structured, follow up questions might take place during an interview.

- *How does the daily work as a design engineer look like? What are your actual work tasks?*
- *Do you follow any process when you perform your work? How does it affect your work?*
- *How do you do when designing new components? Do you use any simulation tool such as GAS by your own? Do you develop several concepts in parallel?*
- *How do you use simulations and analysis in your work? How do you order simulation tasks? When in the process do you do it? Do you perform simulations on one or several concepts?*
- *What are the main differences between virtual and physical testing?*
- *What share of you time at work do you perform pure design tasks? What does the rest time comprise?*
- *What kind of activities in your daily work would you enhance your knowledge as a design engineer? What share of your work time do you spend on these activities?*
- *How do you secure "right-from-me" when doing a hand-over to someone else or finish a project?*
- *Do you have any possibility to affect the expenses for the methods you use when developing a new component?*
- *How much would you estimate the cost to be if your delivery to a project is 30 days late?*

APPENDIX D – LIST OF DESIGN ENGINEERS

This appendix comprises information about the participants in the case study regarding design engineers at Scania and has answered been respondents to the questions in Appendix A.

	Role at Scania	Area	Years at Scania
1	Design Engineer	Basic Chassis Development	2
2	Design Engineer	Bus Frames and Installation	8
3	Design Engineer	Cab Body and Suspension	4
4	Design Engineer	Axle Design	1
5	Senior Design Engineer	Bus Powertrain Components	10
6	Design Engineer	Engine Valve System	4
7	Design Engineer	Engine Valve System	4,5
8	Design Engineer	Cab Instrument Panel and Driver Unit Control	1
9	Object Manager	Basic Chassis Development	8
10	Consultant (Design Engineer)	Bus Powertrain Components	1
11	Design Engineer	Engine Intake Components	5
12	Design Engineer	Chassis Components	1
13	Design Engineer	Chassis Components	2
14	Senior Design Engineer	Engine Composition	6
15	Design Engineer	Bus Frames and Installation	4
16	Design Engineer	Bus Frames and Installation	3
17	Design Engineer	Bus Frames and Installation	10
18	Design Engineer	Cab Instrument Panel and Driver control unit	4
19	Design Engineer	Air and Fuel System Layout	2
20	Design Engineer	Manual Gearbox	4
21	Consultant (Design Engineer)	Chassis Components	15
22	Design Engineer	Bus Steering and Suspension	4
23	Consultant (Design Engineer)	Bus Brakes and Auxiliary system	2
24	Consultant (Design Engineer)	Chassis Components	1
25	Design Engineer	Chassis Components	6

APPENDIX E – SIMULATION ENGINEER QUESTIONS

This appendix comprises the questions used during the qualitative study with simulation engineers. Since the interviews were semi-structured follow up questions might take place during an interview.

- *Do you follow any method or work process when performing a simulation for a design engineer? How do those function?*
- *When does simulation and analysis get involved in a development project? E.g. when a new bracket is going to be developed.*
- *How long time does a computation take?*
- *How do you do to assure that the simulations are good enough i.e. not deliver more accuracy than is actually needed?*
- *Do you have a queue of incoming simulations? What is your available simulation capacity? What is the bottleneck (employees, HW resources or licenses)?*
- *How does the work load looks like over time? Is it leveled?*
- *What are the most common design mistake from your perspective?*
- *Which of these might the design engineer find out by themselves in software such as GAS?*
- *How large share of your time is spent on these kind of issues?*
- *Do the mistakes a design engineer does differ dependent on their experience?*
- *Does the design engineer demand simulations on several concepts in parallel?*
- *Do you get feedback from physical testing? How is this feedback arranged?*
- *How large amount of your time is spend on "firefighting" simulations?*
- *Do you do simulations before, after or in parallel with physical testing?*

APPENDIX F – LIST OF SIMULATION ENGINEERS

This appendix comprises information about the participants in the case study regarding simulations engineering at Scania and is respondents to the questions in Appendix C.

	Role	Area
1	Head of Dynamics and Acoustics	Engine Dynamics and Acoustics
2	Technical Manager	Axle Technical Simulation
3	Head of Strength Analysis	Engine Strength Analysis
4	Calculation Engineer	Engine Strength Analysis
5	Development Engineer	Bus Dynamics and Strength Analysis
6	Head of Strength and Crash Analysis	Cab Strength and Crash Analysis
7	Head of Fluid Mechanics	Fluid Mechanics
8	Technical Manager	Fluid Mechanics
9	Head of Dynamics and Strength Analysis	Truck Chassis Dynamics and Strength Analysis

APPENDIX G – LIST OF INTERVIEW PARTICIPANTS

This appendix comprises information about the participants of the unstructured interviewed used to gather an enhanced understanding as well as information in specific areas when developing the case framework.

	Role	Area
1	Head of Load Analysis	Truck Chassis Load Analysis
2	Head of Dynamics and Strength Analysis	Bus Dynamics and Strength Analysis
3	Head of Frames and Installations	Bus Frames and Installations
4	Head of Steering and Suspension	Bus Steering and Suspension
5	Method responsible	Geometry Assurance
6	Project Coordinator	Truck Chassis Business Development
7	Senior Technical Manager	Strength Testing
8	Head of Acoustics	Truck Chassis Acoustics
9	Head of Crossfunctional Product Information	Crossfunctional Product Information
10	Method Developer	Project Office
11	Technical Manager	Geometry Assurance
12	Head of Geometry Assurance and Testing	Geometry Assurance and Testing
13	Consultant	Geometry Assurance
14	Controller	Truck Chassis Business Development
15	Object Manager	After Treatment system
16	Development Engineer	Turbocharger
17	Senior Engineer	Truck Chassis Durability Testing
18	Senior Engineer	Truck Chassis Durability Testing
19	Project Manager	Superior Quality
20	Business developer	R&D Factory Office
21	Project Coordinator	Project Office
22	Head of Business Development and IT Infrastructure	Business Development and IT Infrastructure
23	Method Developer	Simulation Driven Design
24	Head of Product Modelling Methods	Product Modelling Methods

	Role/Area	Company
1	Deparment Manager for CAE	Saab Automobile AB
2	Head of Geometry Assurance and DMU	AB Volvo
3	Client Executive	Dassault Systémes
4	Technical Manager	Dassault Systémes
5	Director of Business Development	EDR & Medeso AB