TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

JARNO VIDENOJA

IMPLEMENTATION OF VIRTUAL PROTOTYPING IN THE CONTEXT OF PRODUCT UPDATE PROJECTS AND LOW VOLUME PRODUCTION

Master of Science Thesis

Associate Professor Minna Lanz has been appointed as the examiner at the Council Meeting of the Department of Mechanical Engineering and Industrial Systems on March 9th, 2016.

ABSTRACT

JARNO VIDENOJA: Implementation of virtual prototyping in the context of product update projects and low volume production
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The aim of this master’s thesis was to discover whether virtual prototyping could be utilized in a forest machine company’s product update projects to support the cooperation between design and production departments. The goal was to develop and evaluate an implementation method for virtual prototyping during design phases, which would make the current development process more efficient by reducing the amount of resources spent in physical prototyping in future product update projects. This thesis is part of a jointly funded research project.

In the theoretical part of the thesis a literature review considering product development, concurrent engineering, prototyping, and virtual reality technology was undertaken. In addition virtual prototyping, its previous applications, and its impact and requirements on organizational and individual level were researched, providing the theoretical framework for the thesis.

The practical part of the research included an analysis of the case company based on the literature review, materials produced during the jointly funded project, and qualitative interviews with 10 employees of the case company. The aim was to become acquainted with the case company’s product development process, current design reviews and communication between design and production departments. As a result, an implementation method for virtual prototyping was developed, which concentrated on the evaluation of assembly properties in collaborative design reviews.

The implementation method was tested in one product update project by organizing a collaborative design review and by demonstrating the benefits of virtual prototyping at a virtual reality test facility. An inquiry along with observation and open discussion were utilized to collect feedback about the performance of the implementation method and virtual prototyping in evaluation of assembly properties. The results indicate that the company saw potential in virtual prototyping utilizing collaborative design reviews. As a result, these design reviews will be partly applied in future product upgrade projects. Evaluation of assembly properties was seen as a successful implementation target. The main shortcomings for comprehensive application of virtual prototyping were the need for optimization of 3D models and the product data management’s current status in the case company, which currently does not support the implementation method as well as it could. To gain results from the practical benefits of virtual prototyping, it should be further implemented during future product update projects as a whole.

TIIVISTELMÄ

JARNO VIDENOJA: Virtuaaliprototypoinnin implementointi matalan tuotantovolyymin tuotepäivitysprojekteissa
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Tämän diplomityön tavoitteena oli selvittää, kuinka virtuaaliprototypointia voitaisiin hyödyntää metsäkoneyrityksen tuotepäivitysprojekteissa suunnittelun ja tuotannon yhteistyön tukena. Tavoitteena oli kehittää esisuunnittelu- ja suunnitteluvaiheeseen keskittyvä virtuaaliprototypoinnin implementointimetodi, jonka avulla nykyistä tuotekehitystä kyettäisiin tehostamaan, kun fyysiseen prototypointiin kuluvia resursseja kyettäisiin supistamaan tulevissa tuotepäivitysprojekteissa. Työ tehtiin osana yhteisrajoitteista tutkimusprojektia.

Työn teoriaosassa käsiteltiin tuotekehitysprosessia rinnakkaissuunnittelun sekä prototypoinnin kannalta perustuen kirjallisuudesta löytyviin aineistoihin. Lisäksi työssä tehtiin kirjallisuusselvitys koskien virtuaalitodellisuutta, virtuaaliympäristöjä sekä virtuaaliprototypointia, perehtyen tarkemmin virtuaaliprototypoinnin hyödyntämiseen tuotekehityksessä. Tämän lisäksi työn teoriaosassa käsiteltiin virtuaaliprototypoinnin vaikutusta sekä edellytyksiä niin yrityksen kuin yksilöiden tasolla.

Tutkimusten käytännön osuudessa perehdyttiin yrityksen tuotekehitysprosessiin, nykyisiin tuotekatselmuksiin sekä suunnittelun ja tuotannon väliseen kommunikointiin haastattelemalla 10:tä yrityksen työntekijää sekä tutustumalla projektin aikana syntyneisiin materiaaleihin. Kerättyjen aineistojen pohjalta tehdyn analyysin tuloksena kehitettiin yritykselle virtuaaliprototypoinnin implementointimenetelmä, joka pohjautuu yrityksen nykyiseen tuotekehitysprosessiin sekä keskittyy asennettavuuden arvioimiseen suunnittelun sekä tuotannon asentajien yhteisissä tuotekatselmuksissa.

Implementointimenetelmää testattiin yhdessä yrityksen tuotepäivitysprojektissa järjestämällä yksi yhteinen tuotekatselmus sekä demonstroimalla virtuaaliprototypoinnin hyötyjä virtuaalilaboratoriossa. Implementointimenetelmän sekä virtuaaliprototypoinnin suoriutumisen arvioinnissa hyödynnettiin tarkkailun sekä avoimen keskustelun lisäksi kyselytutkimusta. Tulosten perusteella yritys näki potentiaalia virtuaaliprototypointia hyödyntävissä suunnittelun ja tuotannon välisissä tuotekatselmuksissa, ja niitä tullaan osittain soveltamaan tulevissa tuotepäivitysprojekteissa. Asennettavuustarkastelu nähtiin onnistuneena sovelluskohteena. Suurimmiksi ongelmiksi virtuaaliprototypoinnin kokonaisvaltaiselle soveltamiselle osoittautuivat 3D-mallien optimointitarve sekä tuotetiedon hallinnan nykyinen tila, joka ei toistaiseksi tue virtuaaliprototypoinnin hyödyntämistä implementointimenetelmän edellyttämällä tavalla. Käytännön hyötyjen saamiseksi virtuaaliprototypointia tulisikin hyödyntää kokonaisten tuotepäivitysprojektien apuna tulevissa tutkimuksissa.

PREFACE

This Master’s thesis was carried out at Technical Research Centre of Finland (VTT) in Tampere between September 2015 and March 2016, and it was written for the Department of Mechanical Engineering and Industrial Systems at Tampere University of Technology (TUT).

Firstly, I would like to thank VTT, the case company, and TUT for providing me the opportunity to write my thesis considering such an interesting topic. I want to express my gratitude to Ismo Ruohomäki for guiding and assisting me and my research during the whole process. I would also like to thank my colleagues at VTT for their assistance and feedback, which helped me to achieve the goals that were set down for this research. I also wish to thank Minna Lanz for guidance and support along the research.

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In Tampere, Finland, on March 24th, 2016

Jarno Videnoja

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

2D	Two-Dimensional
3D	Three-Dimensional
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CD	Clash Detection
CE	Concurrent Engineering
CMM	Configuration Management Model
DFMA	Design for Manufacturing and Assembly
DMU	Digital Mock-Up
ECR	Engineering Change Request
Ed.	Edition or editor
E.g.	Latin exempli gratia, for example
Et al.	Latin et alii or alieae, and others
I.e.	Latin id est, in other words
PDM	Product Data Management
PLM	Product Lifecycle Management
PMU	Physical Mock-Up
QFD	Quality Function Deployment
R&D	Research & Development
SID	Spatially Immersive Device
TUT	Tampere University of Technology
URL	Uniform Resource Locator
VA	Virtual Assembly
VE	Virtual Environment
VP	Virtual Prototyping
VR	Virtual Reality
VM	Virtual Manufacturing

R	degree of readiness
t	time

1. INTRODUCTION

Market evolution has led to the need of shorter time-to-market and faster ramp-up phase. This is mainly caused by shorter product lifecycles and the need for faster product development processes (Bernard 2005; Kamrani & Nasr 2010). As a result, uncertainty and equivocality considering product development process and other organizational functions are increased (Koufteros et al. 2001). In low volume production, where products are expensive business-to-business investment commodities, the efficiency and output quality are even more important, since massive products require significant amount of resources during their development. Therefore, companies have to develop their business strategies and determine the resources, for example the selection of technology, personnel and their interaction, which support these strategies most effectively (Kamrani & Nasr 2010). Furthermore, constant learning from every product development project and applying it to subsequent projects is also crucial in maintaining and developing a competitive edge (Goffin & Koners 2011).

1.1 Research problem

New features and functions are being created and implemented during product development process, whether it is the case of a new product or a product update project. These design features are tested and analysed during the product development process to ensure their functionality as a part of the whole assembly. Both analytical and physical prototypes, known as mock-ups of the upcoming product, are used to test the design and tackle possible design errors before the ramp-up phase of the upcoming product. The overall goal of prototypes is to optimize the design regarding both external and internal requirements, so that the amount of possible design errors and inconsistencies regarding different features of the product is reduced to its bare minimum before the product development process proceeds to the ramp-up or other subsequent phases. This is justified, since the cost of changes increases and the flexibility to implement changes decreases as the design and the overall product development process nears completion (IEC 61160 2005).

Comprehensive physical prototypes are indispensable, since they are needed to achieve 100 % verification of the functions, geometry and processes related to the final product and its fabrication (Gomes De Sá & Zachmann 1999). In addition to the functional performance of the product and other aspects defined by external product requirements, prototypes are fabricated to evaluate their internal requirements, for example manufacturability and assembly properties. The latter includes for example assembly order, clearance, and ergonomics as well as collision inspection and part alignment. In practice, products should fit the current manufacturing system cost-effectively without creating bottlenecks and overloading the manufacturing system. If some of the requirements are not fulfilled during testing & refinement phase, the product design must be changed, which means that it has to be re-designed and re-documented before the current physical prototype can be updated or a completely new one can be manufactured. The changes might also extend to the production system and other supportive systems and processes along the product lifecycle. This iteration wastes a significant amount of company's resources, especially if a product is redesigned multiple times.

Analytical prototypes, for example three-dimensional (3D) assembly models created by computer-aided design (CAD) software, can be used to evaluate the design before manufacturing the first physical prototype. Since major part of today's design activities is done by CAD software, these 3D models are instantly available to be used as analytical prototypes and thus, are significantly cheaper compared to physical prototypes, allowing iterative exploration of different ideas and alternatives.

Unfortunately, when 3D CAD models are used to evaluate internal requirements such as manufacturability and assembly properties, some of the problems considering the design still do not come up until the product is manufactured the first time in the ramp-up phase of the product development process. Significant reasons to this are the decreased visual information compared to physical prototypes and lack of intuitive interaction with the prototype. In addition, expert and tacit knowledge of production workers is harder to utilize, since these workers are usually involved not until the first physical prototype is fabricated. Unnoticed design errors lead to redundant iteration, which further leads to decreasing productivity and competitiveness of the company. In the ideal situation all the possible design errors and functionality problems along with manufacturability and assembly properties are already eliminated before the physical prototyping phase.

One possible solution for improving the efficiency of design engineering, products, manufacturability, and other related activities is argued to be virtual engineering technologies (Aromaa et al. 2014; Moore et al. 2003). Like 3D CAD models, virtual prototypes are analytical prototypes, which can be used to test and evaluate the current product design during early phases of product development. However, their visual information is enhanced compared to 3D CAD model prototypes, because they can express the product three-dimensionally and in full-scale. This allows better design evaluation, especially for users not familiar with 3D CAD software.

Virtual prototyping (VP) is being widely utilized in the industry for analysing behaviour, response, appearance, and geometry of a target system (Cecil &

Kanchanapiboon 2007). VP technologies can also be utilized for creating, defining, and evaluating different possible ideas, and they help to find possible problems during the product development phase (Cecil & Kanchanapiboon 2007). Technological development, increasing computing power, and falling prices of the hardware and software components involved in VP make its implementation even more interesting. However, there are still some challenges to overcome. One of the main obstacles of gaining the full potential from utilizing VP technology is the lack of knowledge of how to utilize it effectively (Aromaa et al. 2014), and how it should be implemented in the product development process. VP should not be understood as a tool, but as a resource that has a complex synergy with both organizational and technical resources (Leino 2015).

1.2 Goals and scope of the research

The aim of the thesis is to research how VP could be utilized to enhance the product development process of product update projects in low volume production. The research goal is to find out whether the co-operation between product development and production department could be made better-off by improving the communication interface by suitable VP implementation method during the early product development phases. An international forest machine company is chosen as the case company. Virtual reality (VR) system is examined as a communication platform between cross-functional stakeholders. The goal is to find out whether VP would have potential to reduce the overall product development costs by replacing some of the iteration made by physical prototyping with VP.

The focus of this thesis is in product update projects, especially in their internal requirements, e.g. manufacturability and assembly properties. Even though product development projects usually involve external stakeholders, for example subcontractors during early product development phases, these are not considered in this research. In addition, VP as a creative platform will not be considered in this thesis. The main characteristics for the suitable VP system are defined in this thesis. However, no specific VR software or computer hardware to run the software is defined in this research. Quantitative benefits of VP implementation are left out of the scope of the research, since the schedule of the research does not allow them to be measured at a reliable level. Instead, the research aims to discover possible qualitative benefits the case company could obtain by VP implementation.

1.3 Research Methods

A literature review considering product development, concurrent engineering, prototyping, and VR technologies and their impact and requirements will be done. It will provide the theoretical framework for the thesis and for the implementation method development. The current state analysis of the case company is done based on qualitative interviews with cross-functional internal stakeholders of product development. Based on the literature review and current state analysis, a suitable VP implementation method is developed. The VP implementation method is then tested in a case study. The successfulness of the implementation method will be evaluated during the case study by observing and by collecting oral feedback from the case company. In addition, an inquiry will also be used for results evaluation. Finally, the results are analysed and compared to previous industrial applications, which also gives the opportunity to evaluate the successfulness of the implementation method as well as the implementation target.

1.4 Structure of the thesis

In Chapter 2, the research environment and methodology is presented, along with description of the research execution. Chapter 3 contains the literature review and theoretical basis of the research, which includes reviews from generic product development project, virtual reality and virtual prototyping, and the impact and requirements of virtual prototyping. Based on the literature review and the qualitative interviews, the most suitable target for VP implementation is chosen in Chapter 4. Chapter 5 concentrates on the development of the implementation method, which is based on the literature review and current state analysis of the case company. The case study, during which the implementation method is partially tested, is also included in Chapter 5. Results and observations based on the case study are presented and analysed in Chapter 6. The results are also compared to results based on other industrial applications.

2. RESEARCH ENVIRONMENT AND METHODOLOGY

This Master of Science thesis is part of jointly funded research project. The aim of the project is to research the possibilities of digitalization to create the fastest possible time-to-profit delivery environment for customers by focusing on the early development phases of product development and production ramp-up, and by enabling supplier network participation already during those early phases. This chapter presents the case company and its goals regarding the project. In addition, the research methodology used in this thesis is presented in this chapter.

2.1 Introduction of the case company

The case company is one of the world’s leading forest machine companies, which manufactures customized machines according to customer’s needs. In addition, the case company is specialized in the production, sales, and maintenance of forest machines and services related to these activities. The case company of this research is participating in the jointly funded research project. Even though the case company is a truly international company, it has centralized its main product development and production activities in one location.

From the point of view of this research, the case company’s main objective is to improve the manufacturability and assembly properties of upcoming products by developing involvement of the production department in the design process. Assembly properties, weldability, machinability, and different aiding tools in production, such as jigs and clamps, are important factors for the case company which should be better considered during the design process to ensure cost and time efficient production process. Furthermore, the case company is interested in researching the possibilities of VP in the context of communication enhancement. The case company is interested whether the VP utilization would be beneficial in their product development projects. The company is also interested to find out what actions the utilization of VP would require from them. However, the first leap towards VP exploiting product development process should be well planned and not too massive, since big changes take significantly longer time to execute, even if the resistance towards new practices and methods is not taken into account.

2.2 Research methodology

This chapter introduces the research methodology used in this thesis. The research process can be divided into 3 stages, which are (1) literature review, (2) current state analysis of the case company, and (3) a case study based on the developed VP implementation method. The research methods are elaborated in the following chapters.

Literature review

Before analysing the current state of the case company, modern product development process and its characteristics are discussed in the literature review. Concurrent engineering, prototyping, design reviews, and their interrelations will be examined in detail. This is done to understand the iterative nature of product development process better, and to discover important factors which should be noted when analysing the current state of the case company. Modern product development process is reviewed in order to understand the important associated functions and operation models before developing a VP implementation method.

VR technologies along with VP and its applications, impact, and requirements are also reviewed to gain better understanding before analysing the case company and developing the implementation method for VP. Previous applications of VP are also researched in order to discover possible implementation targets which could be beneficial also for the case company. Impact and requirements of VP are also researched in the literature review to understand what successful implementation of the technology would require from the case company.

Current state analysis by qualitative interviews

VP represents new and quite unknown technology for the case company. Thus, it is important to understand the processes and process flow inside the company before implementation of VP. By recognizing the fundamental features of the current product development process the readiness for VP implementation can be evaluated. To find the best possible practice to implement VP in product development process' forepart, the case company's activities and methods considering product development, concurrent engineering, and design reviews should be analysed.

In order to establish the current communication and cooperation between design engineers and manufacturing department most efficiently, qualitative interviews are arranged to research employees' views and conception about the collaborative work and communication between design engineers and manufacturing department. In general, interviews aim at goal-oriented information collecting (Hirsjärvi & Hurme 2008). Qualitative interview was chosen as the central research data collection method, since it is a flexible and suitable research method for multiple intentions and starting points (Hirsjärvi & Hurme 2008). The most simple way to define an interview is to describe it as a conversation, which has a specific, predetermined purpose (Hirsjärvi & Hurme 2008).

More specifically, a half-structured qualitative interview approach, also known as the general interview approach, was chosen as the interviewing method, since the aim was to tackle a specific research problem, as there already was an overall theme and topics which should be discussed. The benefit of this type of approach is that there is room for open discussion; basic themes and questions form the basis of the interviews, but the questions can be presented in different orders and some of the questions can be further expanded during the interviews. (Hirsjärvi & Hurme 2008)

The overall theme of the interviews is formal and informal communication between design engineers, manufacturing method design engineers, and production workers. Furthermore, the aim is to clarify the case company’s strengths and weaknesses considering their product development, concurrent engineering, and design reviews. The interviews help to find a suitable VP implementation target for the case company. An interview framework is conducted based on literature review and materials produced during the research project to guide the conversation to make sure that all the important topics are discussed. The interviews are recorded to make sure that important statements are not lost. In addition, the interviews are conducted individually in order to prevent biased answers. The interview framework is shown in Appendix 1.

The current state analysis is based on the literature review conducted in Chapter 3, materials created during the jointly funded research project, observations made during case company visits, and qualitative interviews with the case company’s employees. Based on the analysis, an appropriate implementation target and method is proposed. The aim is to find the most suitable target in terms of cost and efficiency. The current practices are taken into account to find the most suitable implementation method, which would utilize human resources, tacit and expert knowledge, collaboration, and other key resources as efficiently as possible.

Case study

Based on the current state analysis of the case company, a VP implementation method is developed, which is further tested in a case study in order to introduce VP and its implementation methodology to the company’s key stakeholders regarding the implementation target, evaluate the benefits of the technology and its implementation method, and compare the results to earlier applications. Since VP is a great possibility in the future and the change towards utilizing it has not yet been implemented, it is important to enhance positive prior outlook and feelings and expectations towards it. A case study introducing the technology and possible benefits it could offer is a great opportunity for this.

Participants should understand why the change is needed and researched. Depending on the attitude of the user, the change is either accepted and welcomed or rejected and resisted. Hence, the case study is not only a possibility to show the possible benefits of the technology’s implementation, but also a chance for the employees to reveal their concerns, requirements, and needs more accurately towards the technology than during the interviews performed earlier. By involving the participants in planning and implementation of the technology, concern among participants and also the whole work community can be decreased.

Since VP is rather novel technology among Finnish industry leaders, this case study allows the case company to acquire valuable knowledge about all its features and abilities and consider these factors from their own point of view. The goal is to demonstrate the technology and its implementation method by answering the questions regarding how it could be utilized during the case company’s product development process to support communication and earlier observation of the needs of production department, pursuing to achieve more efficient product development process.

The user experience regarding the developed implementation method is analysed by collecting feedback from the case company’s employees, who participate on the case study. The feedback is collected during the case study by observing the participants and after it by open discussions. In addition, an inquiry is used to collect further feedback from the participants. The inquiry is shown in Finnish in Appendix 2. The inquiry includes 15 statements which can be answered by the following alternatives:

0. I cannot say
1. I totally disagree;
2. I somewhat disagree;
3. I do not agree or disagree;
4. I somewhat agree;
5. I totally agree.

Every answer alternative is indexed by a number ranging from 0 to 5 as shown earlier. For comparison of results the mean value of participants’ answers is calculated by adding up the answer indexes of all individual answers and then dividing the sum by the amount of answers per that specific question, as follows:

$$participants' rating\ (Mean) = \frac{sum\ of\ different\ answers'\ indexes}{total\ amount\ of\ answers}. \qquad (1)$$

As the participants can answer ‘I cannot say’ if they do not have any opinion, the amount of those answers is subtracted from the total amount of answers. This means that the ‘I cannot say’ -answers are excluded from the mean calculation. The inquiry also includes four open questions, which allow the participants to describe their VP experience in detail. These inquiries, interviews, and observations act as the base for the demonstration analysis, which aims to clarify the successfulness of the implementation method, implementation target, and the acceptance of the implementation method among the case company's inquiry participants. The results are further compared to the previous applications' results presented in Chapter 3.2.5.

3. LITERATURE REVIEW AND THEORETICAL BASIS OF THE RESEARCH

Product development process has become a crucial phase during the product lifecycle due to higher demand for innovative products with low production costs caused by global competition and market-driven needs (Cecil & Kanchanapiboon 2007). In addition, high-quality products with short lifecycles and good customizability options are one of the main characteristics of the global demand (Kamrani & Nasr 2010; Moore et al. 2003; Swink 1998). The market evolution creates challenges for the manufacturing industries, especially in Finland, where most of the products are business-to-business -investment commodities and related services (Leino 2015). Thus, companies have to make significant efforts to stay competitive and maintain their competitive advantage (Annacchino 2003).

The meaning of product development process efficiency and company's productivity are emphasized in low volume production, where the output is usually under 1000 products per year and the products are expensive investment commodities with high customization possibilities and long development times. Hence, if the consumption of resources spent in product development could be reduced, the savings would be relatively significant.

According to Leino (2015) people and their knowledge are the main core competences in companies. Therefore, the product development is one of the main competitive advantages of companies because of the people with knowledge involved in it. Although the importance of the product development process is understood, it is often underemphasized as a function of the company, because product development is often considered to be a cost-creating support function rather than value-creating main function (Leino 2015).

This chapter is a review of the modern product development process. Furthermore, VR technologies and VP are researched and discussed from product development point of view. Earlier VP applications are also introduced, and will be used as benchmarking targets later during the research. Finally, the impact and requirements of VP implementation will be discussed.

3.1 Product development

In order to a product idea to become a designed, optimized and manufactured physical product that could be sold to customers, it has to go through a product development process (Kamrani & Nasr 2010). Including several phases, the product development process refines the original product concept into specific drawings, bill of materials, manufacturing and assembly plans, and service and maintenance activities. The process also includes all the management and investment decisions as well as strategic planning considering the product (Kamrani & Nasr 2010).

Product development process has evolved in the course of time from being step by step -progressive process to concurrent and cross-functional cycle with significant amount of stakeholders with different expertise. Despite this, the main characteristics of product development process have remained the same. According to Bernard (2005) the success of the product development process depends on four objectives, which are development speed, production cost, product performance and development programme expense. The goal is to find a balance between these objectives according to the desired outcome of the product development process, since these are interconnected; for example increasing the development speed usually leads to decreasing product performance, if levels of the other two variables are kept constant (Bernard 2005). If the product development time is made shorter without giving substitutive resources to product development, fewer defects are detected in the development process which will eventually decrease the overall product performance. Hence, the product development process is more or less a compromise between the 4 objectives.

3.1.1 Product development process

Unger & Eppinger (2011) define product development process as the method and procedure that companies use to design new products and bring them to market. There exists a variety of different product development processes which are utilized by companies depending on multiple factors, including the complexity of products, company’s risk profile and the history of ideological decisions. In order to convert good ideas into successful products, the product development process must be designed to support the needs of the company. (Unger & Eppinger 2011)

Product development processes are normally company-specific and vary among industries, but their fundamental phases are usually identifiable. Ulrich & Eppinger (2008) introduced the main phases of generic product development process. The main phases recur in other literature with slightly differing names and definitions (Kamrani & Nasr 2010; Sorli & Stokic 2009; Unger & Eppinger 2011). Regardless of the differing names and definitions, 4 to 6 fundamental phases can be recognized from product development processes introduced in the literature. In this thesis, the 6 product development process’ phases by Ulrich & Eppinger (2008) are introduced. These phases are shown in Figure 1.

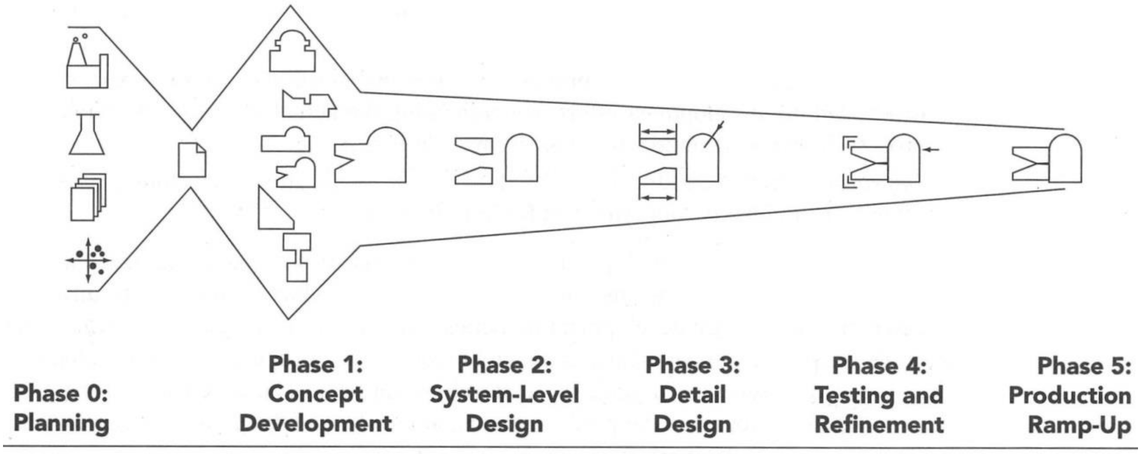

Figure 1. *Phases of generic product development process (Ulrich & Eppinger 2008).*

Figure 1 aims to describe the tasks of different phases of product development process. Bounding lines above and beneath the symbolic pictures describe the breadth of each phase; planning and concept development phases are the most broad ones. As the process proceeds, the product becomes more defined and ready, which is described by the narrowing space between the lines. Each step is introduced in detail in the following paragraphs.

Phase 0: Planning

Planning phase is called as the Phase 0, since it takes place before the approval and launch of the actual product development process. A project mission statement is created based on corporate strategy and assessment of market objectives and technology developments. The statement specifies the key aspects considering the upcoming product, including target market specification and business goals. In concept development phase, the markets are analysed in order to identify the customer needs, which are then turned into customer requirements. These requirements are attempted to fulfil by sketching possible product concepts, which are then analysed and compared to each other. The most promising concepts are developed for further testing. (Ulrich & Eppinger 2008)

As illustrated in Figure 1, the market analysis results are turned into a list of product features, presented as a single piece of paper in the figure. Broad market analysis is condensed into a clear list, which is illustrated by the rapidly narrowing space between the upper and lower lines. The content and form of the list can vary greatly between companies.

Phase 1: Concept Development

The concept development phase, also known as concept-design phase, is a crucial stage in the product development process (Kamrani & Nasr 2010). During this phase, different ideas and product concepts are brainstormed and suggested in order to discover different possible directions for the product development according to the customer requirements analysed in the planning phase (Ulrich & Eppinger 2008). No specific drawings are made during this phase; rough sketches and concept visualizations are sufficient for presenting different concept ideas and development directions for the upcoming product (Ulrich & Eppinger 2008). Many different concept designs of the product may exist, which differ greatly from each other. Eventually the outline of the project is defined and one concept suggestion is chosen based on comparisons and valuations (Ulrich & Eppinger 2008). The chosen concept will define the core product idea and main features of the product, which is passed on to the next product development phase. A concept development plan is prepared including the project schedule, necessary activities of the project, needed resources, and estimated expenses (Kamrani & Nasr 2010). Broad selection of different product concept alternatives is illustrated in Figure 1 by a great space between the bounding lines. The space narrows rapidly, as one of the concepts is chosen for further development.

Phase 2: System-Level Design

According to Ulrich & Eppinger (2008), system-level design aims to define the main features and architectures considering the concept selected in the Phase 1. The product is divided into primary subsystems and components for further development. Since the development is divided among multiple individuals, clearly defined interfaces between different entities of the product are required. The product architecture defines the interaction between these subsystems and functional units, which affects to multiple important attributes, such as modularity, standardization of components and options for future changes (Kamrani & Nasr 2010). The final assembly process is normally defined during the system-level design phase. Geometric product layout and functional specifications of the subsystems and components are also the outcomes of this phase (Ulrich & Eppinger 2008). Effective system-level design phase is the foundation for successful product development process and high-quality products (Kamrani & Nasr 2010).

Phase 3: Detail Design

Kamrani & Nasr (2010) and Ulrich & Eppinger (2008) argue that in detail design phase, specific drawings considering the geometry, materials and tolerances of all parts, subassemblies, and manufacturing methods of the product are defined and produced. The control documentation of the product is also made during this phase, which provides inclusive instructions for manufacturing the product, including tooling, machining, nesting and other possible information considering the fabrication and assembly of the product. The design phases aim to fulfil the customer requirements introduced in the Phase 1, while trying to minimize overall costs (Wang & Tsai 2011). As noted by Pahl et al. (2007), changes and corrections to the design are common during this and preceding phases for assembly and component improvement and cost reduction.

Phase 4: Testing and Refinement

In phase 4, the construction and evaluation of the product versions are performed. The preliminary design is refined by testing different alternatives considering shape, features and overall functions of the product. Next, a prototype is manufactured to test the preliminary functionality of the product and to find possible reasons for design modification (Kamrani & Nasr 2010). Prototype is either a physical or analytical mock-up of the product used to present one or more dimensions of interest to test, analyse and validate the product design (Ulrich & Eppinger 2008; Wang 2002). The size of the physical, tangible prototype depends on the task it is used; 1:1-sized functional mock-up is used to test the actual functionality, while small miniature models can be used to evaluate the appearance, feel and some minor functionalities of the product (Ulrich & Eppinger 2008). Analytical prototypes are used to present the product in a non-tangible manner which is normally visual or mathematical. In some cases, prototyping is followed by 0-series production, which is done in order to finalize the design and adapt it to fit the current production facilities. In practice this means balancing the production steps, training the workers and ordering the final production auxiliary devices to prepare for the production ramp-up phase. The role of prototype in product development is elaborated in Chapter 3.1.3.

Phase 5: Production Ramp-Up

Production ramp-up is the final phase of product development process. The production of the finalized product is started after the production workers have been trained and the production processes have been updated to meet the requirements of the production plans (Ulrich & Eppinger 2008). The production should be ramped up gradually, avoiding overloading the production system. This should also be considered during the preceding phases; even though the product could be manufactured with the current production system from the manufacturability point of view, the ramp-up of the new product should be able to be performed without any significant losses in the production of earlier products.

Sequential & simultaneous product development

According to Kamrani & Nasr (2010), product development process can be divided into four main tasks, which are (1) opportunity and demand identification, (2) creating and defining the technical product specifications, (3) manufacturing and assembly process planning, and (4) fabrication of the product. In sequential product development, all of these tasks are performed sequentially in the same order; once a current task is finalized, it is passed over to the next department, which is responsible for the next task (Kamrani

& Nasr 2010). Each department performs its task individually, apart from others. Figure 2 depicts the process diagram of sequential product development.

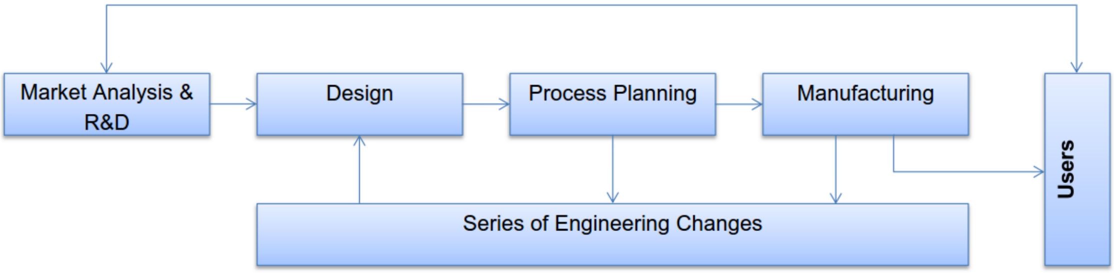

Figure 2. *Sequential product development, adapted from (Kamrani & Nasr 2010).*

The arrows in Figure 2 describe the flow direction of information and the whole process. The product will eventually find its way to the user, but customer needs are also used during the market analysis and R&D task. This is visualized with a double arrow in Figure 2 between 'market analysis & R&D' and 'users'.

Although the sequential process seems simple and straightforward, there is a major downside; according to Kamrani & Nasr (2010), the lack of communication between different departments can cause additional design changes, since some major flaws in the design might come up not until the product has reached the following tasks, or even the final customer. This causes iteration, i.e. the need for repeating working steps to approach the optimal solution until the result is satisfactory (Pahl et al. 2007). Iteration is almost always unavoidable due to the complexity of product development processes (Pahl et al. 2007). However, in sequential product development, iteration takes place not until the design stage is fully completed. Thus, there is a greater risk for unnecessary rework. This unwanted and inefficient iteration induces rework in the form of engineering change requests (ECR), pointless scrap and customer complaints.

ECRs occur when the product parameters and features do not match manufacturing capabilities or customer requirements (Koufteros et al. 2001). In addition, costs caused by design changes grow exponentially, as the process nears completion (Heydarian et al. 2015). Hence, the changes should be made earlier during the product development process. However, this turns out to be extremely difficult in sequential product development because of the lack of communication between different departments. Furthermore, Unger & Eppinger (2011) state that the staged, sequential product development process is sometimes too inflexible for companies in dynamic markets. Complex products require flexibility from the development process. Thus, sequential product development is not the best choice for a company developing such products. It is more reasonable to modify the product development process to make it more simultaneous rather than sequential to avoid wasting resources in rework.

In simultaneous product development process the design and process planning stages are replaced by concurrent product design. During this task testing, analysis, and simulation of different product features and functions are done simultaneously within engineering design activity, which helps to discover possible design flaws, functional problems and other factors causing unnecessary engineering changes (Kamrani & Nasr 2010). Before proceeding to manufacturing task, the product design is developed iteratively during the concurrent product design. The difference between system-level and detail design phases can become hard to observe, since multiple design tasks are happening simultaneously. Thus, detail design phase is regarded to be part of system-level design phase in this thesis.

The process diagram for simultaneous product development process is shown in Figure 3.

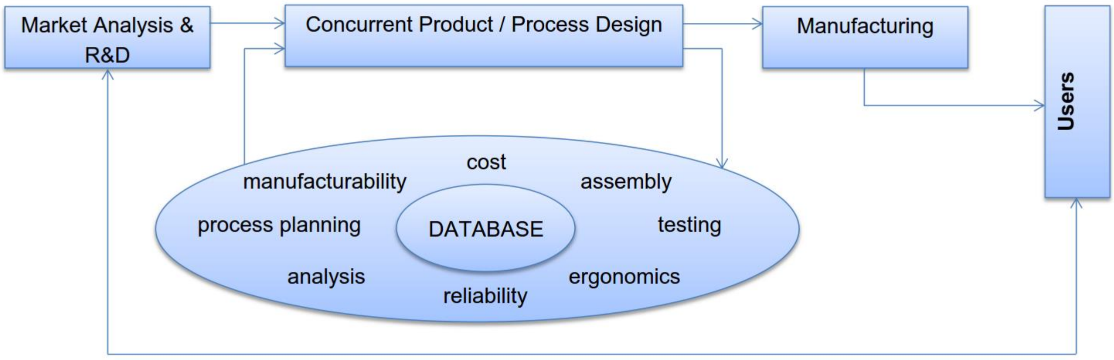

Figure 3. *Simultaneous product development process, adapted from (Kamrani & Nasr 2010).*

The arrows in Figure 3 describe the direction of process and information flows. Shyamsundar & Gadh (2002) argue that the specification of design conflicts early during product development process is important, since it reduces the manufacturing cost and development lead-time significantly. This further emphasizes the importance of having a simultaneous rather than sequential product development process.

However, simultaneous product development has also its weaknesses. Due to multiple simultaneously conducted development tasks, management of the development process becomes increasingly complex. Compared to sequential product development, more planning and management resources are needed to avoid confusion and unnecessary rework. Poor product development management in simultaneous product development can lead to great amount of iteration rework, if different stakeholders during the concurrent product design task concentrate only on their own work tasks without observing the product development process as an entity.

According to Kamrani & Nasr (2010), the successful change from sequential to simultaneous product development process can be facilitated by applying concurrent engineering philosophy. It is elaborated in the following chapter.

3.1.2 Concurrent engineering

According to Verhagen et al. (2015), concurrent engineering (CE) can be described as systematic and comprehensive approach to the concurrent and integrated design and development of complex products and other related processes. It also includes manufacturing, marketing, sales, logistics, customer support and disposal of the product. Swink (1998) describes CE as simultaneous design and development of all the information and processes needed to produce a product and all its support functions. Hence, CE aims to integrate different engineering disciplines and stakeholders during all the lifecycle phases of a product. According to Verhagen et al. (2015), higher productivity, lower costs by sorter product development time, and sorter time-to-market are the main goals of CE. All the stakeholders involved are forced to consider all the phases of a product’s life cycle in terms of cost, quality and time (Verhagen et al. 2015).

In CE, multi-functional and integrated product development teams carry out product development activities simultaneously sharing information, responsibility, and control with each other (Swink 1998). These teams can be locally or globally divided among multiple organizations (Matta et al. 2013). Koufteros et al. (2001) state that communication and teamwork are major sources for innovation in CE. Indeed, mutual understanding and continuous communication between all the stakeholders during product’s lifecycle are prerequisites for successful CE.

When trying to take into account all the possible phases during product lifecycle while developing a product concurrently and collaboratively with multiple stakeholders, the meaning of target-oriented communication cannot be emphasized enough. Along with informal communication, design reviews (see Chapter 3.1.4) and other project meetings are used to manage collaboration in product development projects (Verhagen et al. 2015). By working as a communication channel between different stakeholders, design reviews facilitate better product and process design. Hence, they participate in managing CE activities.

CE has already been utilized by many major companies since the late 20th century, for example by General Motors, Ford, ABB, SKF, BMW, Toyota, and Intel (Ottosson 2002; Swink 1998). The main benefits of utilizing CE are enhanced design quality, increased product innovation, lower costs and shorter development time (Swink 1998). In addition, uncertainty and equivocality can be reduced by applying CE into product development process, which leads to better competitive capabilities (Koufteros et al. 2001). By CE, design errors can be detected early by working on multiple phases simultaneously, thus avoiding possible rework and unnecessary iteration (Koufteros et al. 2001). In addition, CE enables more flexible processes and anticipated feedback, while also reducing cost and risk related to technical, schedule, market, and budget aspects (Leino 2015). Hence, utilization of CE is almost necessary to companies pursuing to reach satisfying profitability on global and also in local markets.

However, successful implementation of CE is not possible without proper management. CE is a continuous process, which requires commitment, tools, and resources from companies aiming to acquire the possible benefits (Verhagen et al. 2015). When implementing CE, companies must decide which of their activities should be done concurrently, and which are the most important integration points (Swink 1998). Unsuccessful targeting of CE is probably one of the most fundamental reasons why CE fails in companies, causing rework and resource wastage.

The wider the scope of a CE program is, the more stakeholders are involved in the product development process (Swink 1998). The main stakeholders in concurrent engineering are shown in Figure 4.

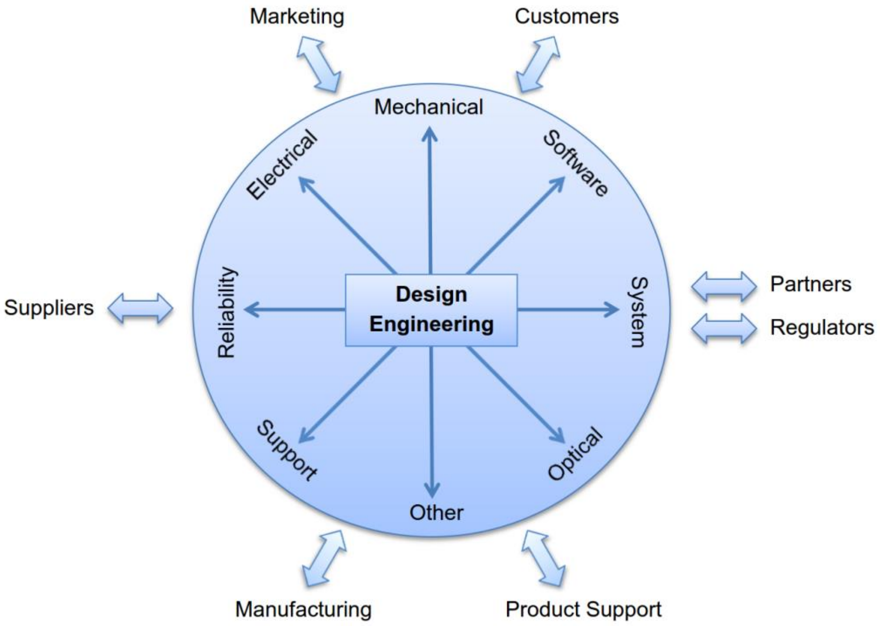

Figure 4. *Stakeholders in concurrent engineering, adapted from (Swink 1998).*

The arrows in Figure 4 describe interaction e.g. information, knowledge, and resource exchange. Interactions between design engineering and the surrounding stakeholders are bidirectional, which means that the resources move in both directions; from design engineers to other stakeholders and vice versa. Since design engineers are the leading stakeholders in product development projects, they also have the responsibility to coordinate the information and take other stakeholders’ requirements into account; otherwise the product development process will face major obstacles and raise the total expenses radically.

In product development, every stakeholder presented in Figure 4 is an important part of the entirety, and without communication between all the stakeholders the overall product development process would not perform efficiently. Due to several different stakeholders there is also a great amount of knowledge that could be communicated to different stakeholders. When a product development project is started, design engineers acquire information from marketing, customers, partners, and regulators about the market trends, customer needs, new products of competitors, and new product regulations. This information is used and iterated to find the best possible product concept for development, which fulfils and even exceeds customer expectations. During the development, design engineers communicate with suppliers, manufacturing and product support while iterating the product design to find the most profitable way to fabricate the product.

Communication with internal stakeholders can be challenging, but external stakeholders, for example suppliers, can be even harder to communicate. Differing organizational cultures, previous collaboration history, and tight schedules are only few of the many possible reasons for this. Indeed, integrating stakeholders with diverse expertise is one of the greatest challenges of CE. Even though CE among design engineers could be implemented successfully, integrating design engineers and other stakeholders shown in Figure 4 is harder to perform. Cultural differences and diverging point of views between design engineers and other stakeholders can be substantial, which further makes implementation of successful CE harder. In addition, it is vital for the company to understand what information should be communicated in different lifecycle phases of a product.

However, Bernard (2005) argues that manufacturability analysis is one of the most important aspects in product development, since it can reduce time-to-market dramatically together with plant and production line design. According to Koufteros et al. (2001), early involvement of manufacturing department in product development could help to detect potential problems and inconsistencies could be detected earlier. Thus, manufacturability and assembly properties should be considered already during the early phases of product development. Knowledge sharing between design engineers and manufacturing department should be enhanced by proper use of CE.

Production worker’s knowledge discovery is related to physical processes and know-how taking place on the factory floor, since their work is often highly physical (Riege & Zulpo 2007). It differs from the other organizational groups, such as engineers, middle managers and senior executives (Riege & Zulpo 2007). While manufacturing and assembling products, production workers obtain tacit knowledge related to different work tasks. Riege & Zulpo (2007) state that tacit knowledge can add value to companies, presuming it is utilized properly. However, it is good to notice that tacit knowledge also includes opinions, false beliefs, and disinformation, which are usually more harmful than beneficial to companies.

Edwards (2002) argues that creating an intuitive environment that makes the use of scientifically based knowledge and empirically derived beneficial tacit knowledge simultaneously is a challenging task. According to Riege & Zulpo (2007), production workers tend to share discovered knowledge primarily among each other and to production foremen. This is true, because tacit knowledge is easier to share with people who have deeper understanding of the work processes through a personal experience and with whom the point of view is shared. Furthermore, direct and informal communication (e.g. face-to-face discussion) is preferably utilized when sharing tacit knowledge.

Koufteros et al. (2001) argue that companies seeking to implement CE should concentrate on developing three sub-dimensions which form the CE construct: concurrent workflow, product development teams, and early involvement. These dimensions are shown in Figure 5.

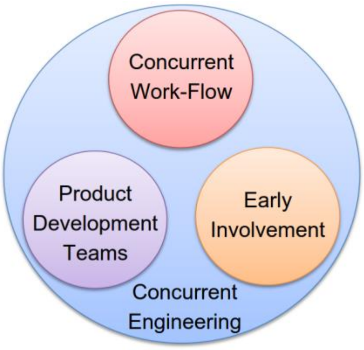

Figure 5. *Main sub-dimensions of concurrent engineering, adapted from (Koufteros et al. 2001).*

Early involvement of internal stakeholders is an essential sub-dimension. Frontloading the decision making process is done by improving the collaboration between design engineers, methods engineers, and production during early product development phases. Riege & Zulpo (2007) suggest that a communication platform should be provided to support knowledge sharing between these different stakeholders. This could be done by providing a cross-functional communication channel in order to facilitate earlier detection of design error and inconsistencies. By succeeding in this, companies could reduce time and costs of product development process, which would lead to better productivity and increased profits of the company.

Swink (1998) argues the main methods and concepts for applying CE programs. Two basic initiatives are proposed, which are claimed to be essential for CE programs to succeed: (1) improving cross-functional integration and (2) improving design analysis and decision making.

Cross-functional integration improvement

The first initiative states that cross-functional integration and communication should be improved by managers by organizing project personnel and by fashioning program procedures and policies. The premise is that different organizational units and functions are willing to co-operate. The initiative itself is divided into three management tasks, which are goal setting and analysis, controlling and directing of the integration, and communication and awareness encouragement. (Swink 1998)

According to Swink (1998), clearly defined goals enhance communication and reduce non-constructive criticism. Swink (1998) also states that cross-functional integration becomes significantly easier when goals are recognized. Setting these goals requires thorough analysis of the objectives company wants to achieve. For instance, product weight reduction by 20% would be one example of a clear goal. If the goals are quantifiable, they become more tangible to the stakeholders involved (Swink 1998). The satisfaction of customer needs is an obvious goal for companies, but internal requirements, for example regarding manufacturing and assembly properties, could also be reformed as goals. Such goals could be related to design changes that would ease production process, but also to features that are good and should not be changed.

According to Swink (1998), procedures and guidelines must be created in order to control the cross-functional integration process. Complex product development projects involving several organizational units need these guidelines and formal actions due to the complexity level of this kind of projects (Swink 1998). However, these guidelines and bureaucracies tend to make the organizational units and their collaboration more inflexible. Managers responsible for CE have the responsibility to form these guidelines and procedures to meet the needs of the company without making unnecessary sacrifices considering natural innovation processes (Swink 1998).

Communication and awareness encouragement is also essential task for CE programs, since the power of cross-functional integration lies in communication exchange. Swink (1998) argues that giving teams both responsibilities regarding deliverables and authority to acquire resources needed in the project are the essential keys for better team performance. The responsibility to achieve the goals while giving the authority to acquire the resources to achieve these goals motivates the team and keeps all the participants more concentrated in teamwork and performing (Swink 1998). However, it should be noted that while responsibility is shared with multiple individuals, avoiding the responsibility on an individual level becomes easier. Hence, it is important to assign responsibilities also inside the design team.

Recognitions, such as bonuses and incentive schemes, are also used to motivate the team members (Swink 1998). Bonuses can be both personal and shared in order to motivate individual team members even more to work towards the common goal. However, recognitions are not always the best option for encouraging communication and awareness, since they can easily become misused. Some people might try to achieve only the recognitions, while the true purpose of recognitions is dismissed.

Design analysis and decision making improvement

The perfect product satisfies both all customer needs and sales expectations, while producing profit. Therefore, it is essential to concentrate making the right decisions during the design process. According to Swink (1998), CE programs make the use of different methods and tools to improve decision-making and design analysis. These methods can be grouped under two main objectives; to find and apply the best design practices, and to simplify design generation and analysis (Swink 1998). The former objective aims to reduce the amount of rework in the design process, whereas the latter objective aims to facilitate newer and older design versions for better handing and utilization in other projects.

Rework is the inefficiency of design process, when features in the product already designed have to be re-designed due to problems that have come up later in the product development process (Swink 1998). When problems come up and they require changes to the current product design, ECRs are generated. Koufteros et al. (2001) argue that ECRs are the most cited reason for delays during product development projects. Hence, problems that are caused by design errors and inconsistencies lead to ECRs, which further lead to rework. This process describes the iterative nature of product development. This iteration is characteristic and quite often inevitable for product development process, but should be reduced to its bare minimum, since it does not bring any value to companies. This is why best design practices' application is an important part of CE.

Facilitation of newer and older design versions enables their better handing and utilization in other projects. It also strives to enhance design analysis by design review methodologies, such as failure mode and effects analysis (FMEA) and simulation (Swink 1998). These methodologies help in joint decision making and give stakeholders, such as manufacturing and support representatives, an opportunity to express their own opinions and ideas about the design (Swink 1998). The earlier manufacturability and assembly properties of a product can be simulated during design reviews, the earlier these properties can be evaluated. If significant design changes can be made earlier due to simulation, benefits would become visible in the decreasing amount of ECRs during later phases of product development process. Hence, facilitation of design versions is important for enhancing CE activities, such as simulation.

3.1.3 Prototyping in product development

Modern, simultaneous product development process includes multiple concurrent activities, which take place during several different product development phases, including design for manufacturing, prototyping, product development economics, project management and many others. Figure 6 depicts the main activities of product development process.

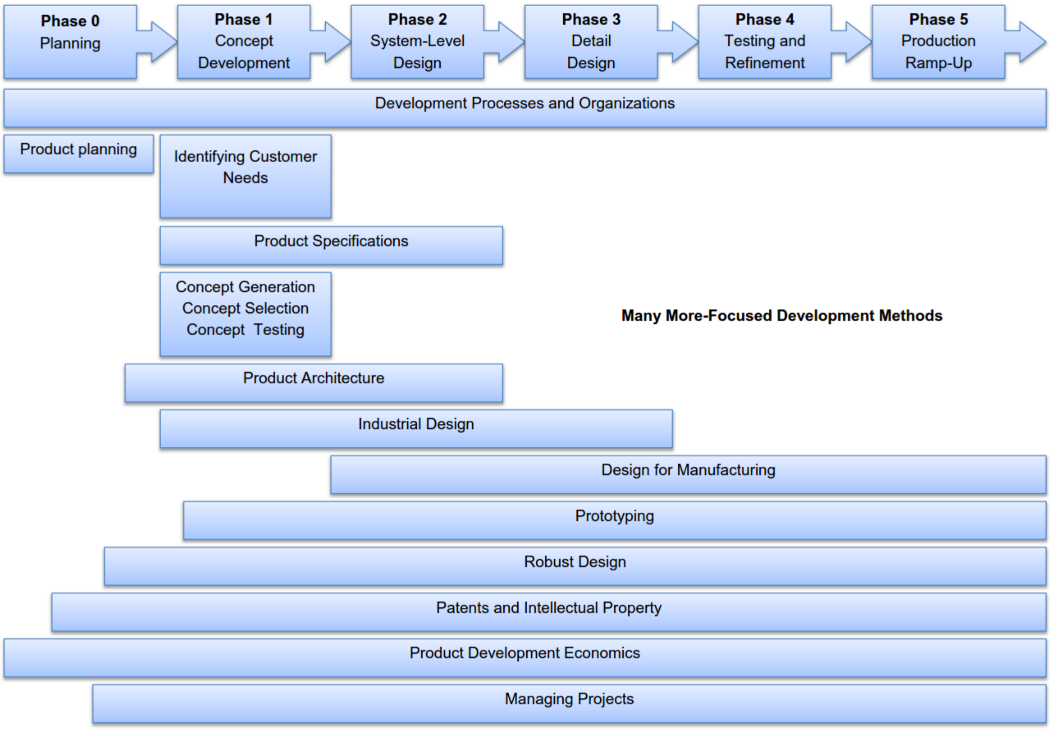

Figure 6. *Concurrent processes of product development process, adapted from (Ulrich & Eppinger 2008).*

Ulrich & Eppinger (2008) argue that prototypes are utilized to help the communication and integration of people and stakeholders. They are also used as tools for learning and as milestones during the product development process. According to Bordegoni (2011), prototypes are used to demonstrate physical and functional properties of the product allowing the exploration of different alternative solutions and performance testing. From integration point of view, prototypes force different design team members to coordinate with each other and to integrate everyone's own professional view to reach the eligible functionality (Ulrich & Eppinger 2008). Thus, prototypes have an important role on multiple levels and in various activities during product development projects.

It is a common mistake to think prototyping only as an activity that takes place during the final stages of product development process. As noted in Chapter 3.1.1, prototype is an estimation of the product that seeks to present one or more dimensions of interest (Ulrich & Eppinger 2008). According to Elverum & Welo (2014), prototyping has various roles during the product development process; during the early product development stages prototyping helps communication and information exchange among designers and other stakeholders involved in the product development process. As the process proceeds to the final phases of product development, prototyping helps to acquire information about product requirements and reveals different aspects considering possible problems in upcoming phases, including fabrication and ramp-up phases of the product (Elverum & Welo 2014). Before production ramp-up phase, a physical prototype is built to achieve 100 % verification of the functions, geometry, and processes related to the final product and its fabrication (Gomes De Sá & Zachmann 1999). Prototyping with physical prototypes is typically followed by the 0-series fabrication, which is aimed to tackle the final problems with the upcoming product before the ramp-up phase. Therefore, prototyping should not be understood only as an activity of the testing and refinement phase, as prototyping is part of the product development process starting during the concept development phase continuing until the very last phases of the whole product development process, as seen in Figure 6.

Bordegoni (2011) distinguishes thee major phases of iterative product development process. These phases, shown in Figure 7, are design, engineering, and testing.

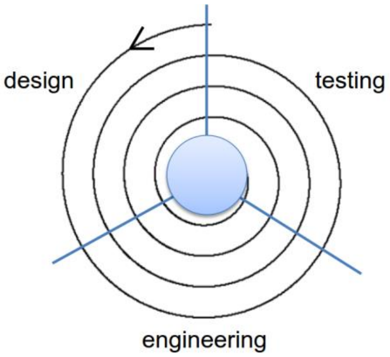

Figure 7. *Design evaluation phases, adapted from (Bordegoni 2011).*

Figure 7 describes the iterative character of product development process. The circle in the middle describes the ideal solution, which is approached gradually by designing, building a prototype, and testing the prototype. The black arrow in the figure shows the direction of propagation. Designers, engineers, and users should all be involved in the testing phase in order to achieve effective design process and result that satisfies both customer requirements and financial objectives.

Design reviews, introduced further in Chapter 3.1.4, are regular events, which utilize prototypes and participate on the design evaluation. During design reviews product prototypes are used to evaluate functionality, manufacturability, design, and other essential product aspects (Ulrich & Eppinger 2008). Based on observations, change requests, and evaluations made during design reviews, the product can be further developed to meet all its requirements. Hence, design reviews participate on the design evaluation.

The type of the prototype can be varied according to the test purpose. Ulrich & Eppinger (2008) classify prototypes into analytical and physical prototypes. Analytical prototypes present the product in nontangible, either mathematical or visual way, where as physical prototypes are tangible artefacts which are created to approximate the product. Furthermore, prototypes can be either comprehensive of focused depending on their purpose (Ulrich & Eppinger 2008). The former implements most, if not all, of the product features and attributes, being full-scale, fully functional version of the product. The latter implements one or few of these features and attributes e.g. size, shape, or performance of a single component. For example, in the beginning of system-level design phase, some modules might already be finished and ready to be prototyped as own entities. During the detail design phase, more comprehensive prototypes are needed to test the manufacturability and assembly properties of a whole product.

Bordegoni (2011) divides prototypes into four types: visual, shape, functional and full physical prototypes. A visual prototype is used for aesthetic evaluation of the design as well as to simulate colour, texture, and overall appearance of a product. Shape prototypes mimic the size and form of a product, and are used for visual and ergonomics factors' evaluation. They do not actually include the exact visual properties (e.g. texture, colour, finish) or functions of a product. Functional prototypes aim to simulate one or more of the functional and operational principles of a product. Full physical prototypes are used to simulate aesthetics, final design, materials, and functionalities of a finalized product. They can be either fully working scaled prototypes or full-scale prototypes. (Bordegoni 2011)

As mentioned earlier, the product mock-up during design reviews can be either a physical or an analytical prototype. Depending how far the design project has progressed, the presented prototype can be a concept sketch, preliminary layout picture, incomplete 3D CAD assembly, or fully finalized physical or analytical mock-up of the product. It can also be anything between those alternatives mentioned; design project progresses by small steps, and new features, items, and modules are being designed and added to the aggregate weekly or even daily. Thus, the mock-up under revision is also updated constantly.

Computer-aided engineering (CAE) software utilized by design engineers can be used present, analyse, and evaluate product design collaboratively with other direct and indirect stakeholders during design reviews. It is a valuable tool to design engineers, if these engineers share the same software, and are capable of utilizing models created by other design engineers. The screen view of the computer running CAE software for design review purposes can be shared by a projector to all design review participants.

Prototyping helps to analyse the product performance, discover possible design flaws, and enhance the overall quality of the product (Ulrich & Eppinger 2008). This is important, since design flaws eventually affect the quality of the product and, furthermore, the customer satisfaction. As stated by Heydarian et al. (2015), the cost of correcting design errors and other problems related to the product grows exponentially as the product development project progresses further from design phases to fabrication and even to product deliveries. Furthermore, Ming et al. (2005) argue that nearly 70 % of the product's cost is defined and built-in during design and development phases.

Thus, eliminating possible design errors and making cost-efficient and productisation-boosting design changes already during the early design phases has a significant impact on cost and time savings, since less iteration has to be done during the testing & refinement and ramp-up phases.

Evaluation and prototyping of the product is also an inevitable tasks of today's product development process (Seth et al. 2011). Physical prototypes are needed to test unanticipated phenomena which are completely unrelated to the original objective of the prototype, for example taking into account the laws of physics (Ulrich & Eppinger 2008). Hence, it is not beneficial to completely eliminate physical prototyping. In practice, all complex products include some features and functions that can be evaluated only by physical prototypes. Production workers in charge for the fabrication of physical prototypes along with methods engineers in charge for designing those processes are in vital position, since they are also responsible for giving feedback to the design engineers about the current design state of the product and whether it fulfils its requirements regarding manufacturability, assembly properties, and other internal processes. Field testers and key customers on the other hand are responsible for giving feedback about the physical performance of the prototype.

However, evaluation of every single feature and function with physical prototypes is not profitable, since physical prototypes are expensive and time consuming to build (Seth et al. 2011; Swink 1998). For instance, the manufacturing and ordering process of all the items and modules included in the prototype takes time and money. After the items and subassemblies have arrived, the product prototype has to be assembled. The assembly process can also take a significant amount of time, since the prototype is new to production workers and because the assembly process is not automated due to the newness and complexity of the prototype. In addition, items and entities of the product need to be designed in detail for manufacturing processes, which also takes time. Furthermore, as the prototype is being fabricated, due to CE further changes to the items, modules and assemblies of the product are being made, resulting in a situation where the physical prototype does not resemble the updated 3D CAD model of the product (Gomes De Sá & Zachmann 1999). Thus, there is no direct correlation between the physical prototype and the 3D CAD model of the product (Gomes De Sá & Zachmann 1999).

Due to the iterative nature of product development process the physical prototype is updated partially, or completely new ones are manufactured for further testing in order to reach the satisfactory level. The number of iterations affect to the total resources spent significantly, especially if only physical prototypes are used. Furthermore, the literature cited by Koufteros et al. (2001) argue that ECRs are the most cited reason for delays in product development projects. In today's product development of more complex designs, both physical and analytical prototypes are needed to make the product development process as effective as possible.

Compared to physical prototypes, analytical prototypes are generally more flexible. Changing an attribute related to an analytical prototype is easier compared to its physical counterpart. In addition, an analytical prototype usually allows greater changes to be done to it compared to a physical prototype. Due to these reasons, analytical prototypes normally precede the first physical prototype. Design alternatives can be tested and narrowed down by an analytical prototype, while the physical prototype should be used to validate or fine-tune the design before ramp-up. (Ulrich & Eppinger 2008)

However, when it comes to communication, physical prototypes perform better than analytical (Ulrich & Eppinger 2008). Visual, three-dimensional and tactile representation of a product is much easier to understand (Ulrich & Eppinger 2008), while as 3D CAD models representing the product as analytical prototypes are not capable of offering equally visual information. By 3D CAD models, product features such as physical size and shape do not come across as effectively as they do by physical prototypes (Ulrich & Eppinger 2008). Tangible nature of the physical prototype is one reason for this, but other significant reason can be the lack of true, three-dimensional (3D) representation. Although the 3D CAD model is in fact a 3D assembly, it is presented on a two-dimensional (2D) screen, which does not provide the third dimension and thus, the presentation lacks in depth. This can be a distracting factor when examining different features of the product, especially if the examiner is not familiar with 3D CAD software or has difficulties to prepare a mental image of the configuration based on a 2D image of a 3D assembly.

Production workers responsible for fabricating the prototype and series-produced products have tacit knowledge, which would be valuable for the design and methods engineers. However, such knowledge is also hard to document and utilize due to its tacit nature. Even though production workers are sometimes included during the early design phases to evaluate the product, they have difficulties on commenting the design based on the 3D CAD model. One of the reasons to this might be the analytical manner of representation, which might make it difficult to grasp the overall size, weight and volume of the prototype (Watanuki 2010). Production workers have obtained their tacit knowledge by performing different work tasks by physical prototypes, 0-series machines, and series production machines. Paralleling mental image of a physical prototype with an analytical 3D CAD model might be hard for production workers not familiar with 3D CAD software’s way of representing the product.

Due to their flexibility and significantly lower cost, analytical prototypes should be utilized more during early design phases. When done successfully, analytical prototyping helps design engineers to detect errors and inconsistencies in the product design already during the early design phases. This gives the design engineers more time to react on those inconsistencies. As a result, the readiness level of the design is increased due to increased prototyping, and less iteration has to be done with physical prototypes.

However, it is important to notice that prototypes do not bring savings, but their efficient and suitable utilization does. Poorly managed prototyping drains resources and weakens the efficiency of product development. Even though analytical prototypes are cheaper to produce compared to physical ones, they can also cause redundant costs and be harmful to product development process. Prototyping should always have a clear utilization target and objectives. Indeed, successful target and objective selection for prototyping are crucial regardless of the type of the prototype.

3.1.4 Design reviews

In order to make the upcoming product meet all the design objectives and to coordinate the activities related to product development, the design process must be controlled through all the phases of product development process. The design process control is based on the knowledge of current design situation, crucial evaluation and decision-making. This control is usually carried out in design reviews, during which the progress of the design is evaluated towards the specification requirements. (Verhagen et al. 2015)

According to International Electrotechnical Commission (IEC), design reviews are primarily used for design verification and to provide recommendations to improve the product, process, and their realization. Thus, design reviews should be considered as a procedure for design confirmation and refinement, not as a creative procedure. Properly utilized, design reviews have the possibility to enhance product quality, performance, safety, dependability, decrease costs, and shorten product delivery schedule. (IEC 61160 2005)

According to IEC 61160 (2005) the objectives of design review are:

- “assessing whether the proposed solution meets the design input requirements that include, but are not limited to: specified general performance requirements, dependability, lifecycle costs, safety, endurance, environment, electromagnetic compatibility, human factors;
- assessing whether the proposed solution is the most robust, efficient and effective solution to achieve the product requirements;
- providing recommendations as required for achieving the design input requirements;
- assessing the status of the design in terms of the completeness of the drawings and specifications;
- assessing the evidence to support the verification of the design performance;
- proposing improvements”. (IEC 61160 2005)

In companies, design reviews are arranged regularly throughout the entire product lifecycle to facilitate communication between different stakeholders (Bassanino et al. 2014). Leino (2015) states that frequent design reviews are vital part of productisation; recognizing possible problems with manufacturability, assembly and other lifecycle issues as well as evaluating the safety of work during different fabrication and service tasks of a product are crucial before manufacturing the first physical prototype.

Design reviews can vary throughout the development process, but they usually involve multiple direct and indirect stakeholders from different functional teams (e.g. design, production, maintenance, management, and sales), who form the design review board. The board evaluates the current design and technical solutions of a product or a process from each board member’s own professional perspective, thus allowing every participant to influence these aspects. The combination of stakeholders depends on the overall objective of the specific design review; for example when evaluating the manufacturability of a specific part, in addition to the design engineers responsible for the part and assembly design, methods engineers responsible for designing the production processes should also be included in the design review to integrate their views and present their possible concerns regarding the design.

It is essential to point out that proper management of design reviews is crucial for achieving its objectives (IEC 61160 2005). Without proper structure and clear objectives, design review might stray from the intended topic and problems that need resolving. The clear structuration and object definition was also highlighted in the context of CE in Chapter 3.1.2. Poorly structured design reviews and unclear objectives lead to inefficiency and frustration among design review board members, since time is wasted discussing on subjects that are irrelevant during that specific moment. In addition, design reviews should be documented thoroughly in order to recall and track decision making (Verhagen et al. 2015). Clear and thorough documentation helps to understand the reasons why specific changes or additions to the design are made; even long after the project at issue is finished.

3.2 Virtual reality and virtual prototyping

There exists multiple tools, methods and frameworks which could improve the product development process, such as product design and development methods, knowledge management, and human factors and ergonomics (Leino 2015). According to Leino (2015) and Aromaa et al. (2014), virtual reality technology, virtual environments, and virtual prototyping have also the capability to improve the efficiency and effectivity of product development process. For example, automotive and aerospace industries have developed and utilized virtual prototyping successfully in product development since 1990s (Choi & Chan 2004; Weidlich et al. 2007). Since design reviews are existing occasions for concurrent and collaborative engineering, it is justified to investigate possibilities and previous applications of virtual prototyping in this context.

The aim of this chapter is to introduce virtual reality technology in the context of virtual prototyping and product development. The subject is also considered from the point of view of CE; especially concentrating on the collaboration and communication between company’s internal stakeholders, such as design engineers, manufacturing method design engineers, and production workers. Since design reviews are a regular communication channel between design teams and departments besides other informal communication channels, virtual prototyping in design reviews is studied in detail.

Terminology related to virtual reality technologies is introduced in this chapter, which is followed by introducing virtual reality, virtual environment and finally, virtual prototyping. As this research concentrates on developing a customized virtual prototyping implementation method, earlier applications of virtual reality technologies in other industrial branches are also introduced. These applications will also perform as the benchmarking framework in Chapter 6.

3.2.1 Terminology

The terminology and concepts considering virtual prototyping and other activities related to virtual reality technologies are not uniform in the literature (Alanen et al. 2013; Wang 2002). The fairly young age of virtual reality technologies and local vocabularies formed in different industries and companies may be the main reasons for lack of standardization of terms and concepts (Alanen et al. 2013). Therefore, a definition of the terms used in this thesis is vital for understanding the big picture of virtual reality technologies.

According to Wang (2002), a virtual prototype is a digital mock-up of a physical product that can be used to display, analyse, test and validate the functions and activities of the target product during its lifecycle, e.g. design, manufacturability, assembly properties, and service digitally in a computer environment, as could be done by the physical prototype. Virtual prototyping (VP) describes the construction and testing of the virtual prototype, which can be applied throughout the product development process from early design phases to the last fabrication phases of the finished product (Cecil & Kanchanapiboon 2007). Virtual reality (VR) describes a computer simulation of a system, which allows users to perform operations and actions to the virtual prototype while at the same time providing sensorial feedback, e.g. haptic and aural feedback, to the user of the VR system (Wang 2002). Wang (2002) further continues that VR can include various input devices, which are used to control the VP activity by the user’s movement or physical input using location tracking sensors. Thus, VR represents the technologies that allow the interaction with the virtual prototype explored in VP activity.

Term virtual environment (VE) describes the ways of interacting and experiencing the model (Leino 2015). It can be understood as a synthetic and interactive environment the user experiences while utilizing VR technologies. VE facilitates an immersive understanding of the virtual prototype (Wang 2002). Virtual manufacturing (VM) and virtual assembly (VA) can be understood as manufacturing and assembly -focused VP, where the manufacturability and assembly properties of the product are displayed, tested and analysed to develop easily producible product features and geometries (Seth et al. 2011; Wang 2002). Consequently, virtual prototypes should not be understood only as CAD/CAM models, since they use VR technologies to allow immersive interaction and involvement in the VP process (Cecil & Kanchanapiboon 2007).

3.2.2 Virtual reality and virtual environment

According to Mihelj et al. (2014), VR is an interactive computer simulation, which senses the state and operation of the user and provides sensory feedback information to one or more senses based on this information. This gives the user of the VR system the sense of being immersed in the VE. In other words, VR technologies enable humans to become immersed in computer-generated environment and to interact with it by human motions (Mujber et al. 2004; Seth et al. 2011). Thus, VR system enables the user interaction and information exchange with VE, which can further include a virtual prototype. Information is exchanged through a user interface, which can track the user while giving visual, aural or haptic feedback at the same time based on the actions performed by him/her (Mihelj et al. 2014). Figure 8 depicts the interrelations between different components of VR system.

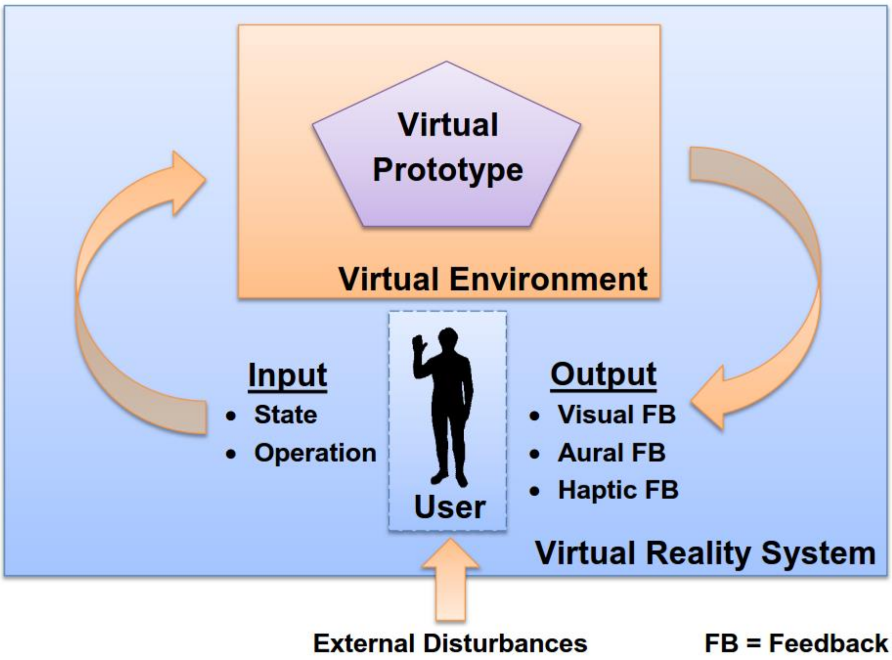

Figure 8. *The basic elements of virtual reality system.*

3D CAD geometries and environments created in 3D CAD software can be imported to the VR system to be inspected, reviewed, and validated. Depending on the system, the

3D models are converted to suitable format and optimized to support VP, or imported straight from the 3D CAD software to VR system (TechViz 2015). In the latter configuration, the VR system is constructed upon the 3D CAD software, which allows the utilization of 3D models and environments straight away without separate conversion (TechViz 2015).

The input and output of a VR system is described by arrows in Figure 8. User's inputs such as pose, state, and operations performed with different kind of controls are tracked by sensors connected to the VR system, which allow the user to affect the virtual world (Mihelj et al. 2014). The interface between VR system and VE forwards the sensor information to the VR computer cluster, which runs the VE and virtual prototype inside it. The VR system projects the VE and virtual prototype by a visual output device. The device can be for example a monitor, canvas, or head-mounted display (HMD), depending of the characteristics of the system. Utilizing the sensor information, the VR system can show VE from user's perspective, which is a basic requirement for the physical virtual presence induction (Mihelj et al. 2014).

The visual output of a VR system is a stereoscopic image, including the disparity between the right and the left eye (Watanuki 2010). The image is updated on a fast frame rate (more than 30 frames per second) to provide unobtrusive, moving, and real-time visual output (Ottosson 2002). The user visualizes the images by using either passive polarized glasses (Watanuki 2010), or active 3D shutter glasses depending on whether the VR system uses active or passive 3D technology. Thus, VR system replaces stimuli of the real world by computer-generated stimuli (Mihelj et al. 2014). Spatially immersive devices (SIDs) like CAVEs and HMDs are useful in applications where the user wants to be placed in certain location in the VE, like a building or cockpit of a machine (Claudia et al. 2013). Monitors and screens like powerwalls perform well in situations, where external viewer position is useful (Claudia et al. 2013).

The state and operations of the user work as the inputs of the system, and are tracked by sensors. Mihelj et al. (2014) divide tracking methods into three categories: Nonvisual, visual, and mechanical. Nonvisual tracking methods do not require visual input, as they utilize inertial, magnetic, or ultrasonic sensor information for determining object location (Mihelj et al. 2014). Inertia sensors included in Oculus Rift -HMDs are an example of nonvisual tracking sensors, which can detect head orientation and movements of the user. Inertial sensors are good for measuring orientation and acceleration of different objects. Magnetic sensor information can be highly responsive and accurate, but it is prone to interference, if a device near the sensor has a magnetic field. Ultrasonic information is not as responsive due to the low speed of sound.

Visual tracking methods utilize optical feedback to determine location and orientation of an object. Typically this tracking method utilizes infrared LEDs, which emit infrared light. This light is reflected from the tracked user or object to infrared sensors which track the orientation and location of the user or object. In Figure 9 a VR system with visual tracking is shown.

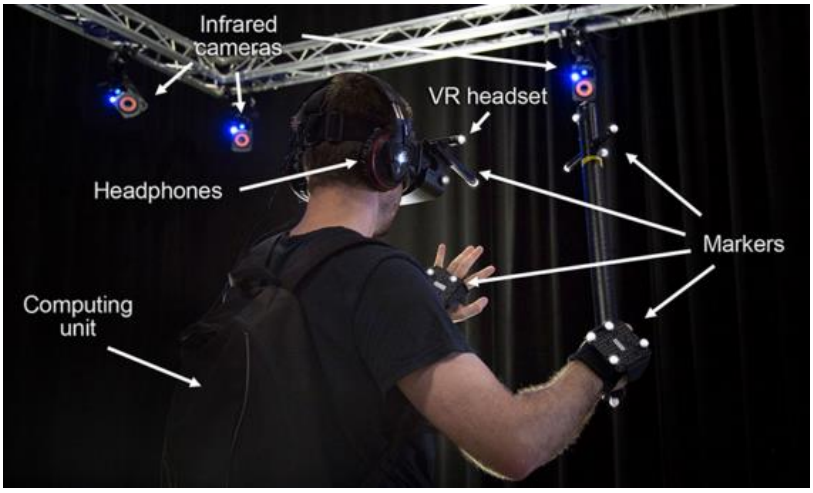

Figure 9. *Components of visual tracking system (Varias 2015).*

Visual tracking can be done by tracking markers attached to the user or different objects. In Figure 9, round white markers are used for tracking user's head and hands. Visual tracking can also be done without markers, as shown in Figure 10.

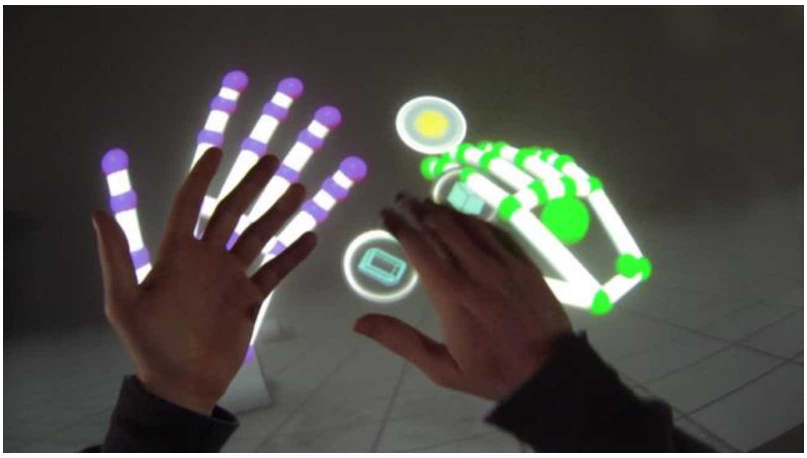

Figure 10. *Visual tracking without markers (Robertson 2016).*

Visual tracking can be highly responsive, and it is used widely in both semi- and fully immersive VR systems. However, line of sight between the infrared sensors and the tracked object should be clear; otherwise the tracking process might become interfered.

Mechanical tracking utilizes robotics or exoskeletal devices to track the orientation, location and movements of the user or object (Mihelj et al. 2014). Like visual tracking devices, mechanical tracking devices can be highly responsive. Their demerit is that they usually limit the user's or object's range of motion. Figure 11 depicts a mechanical tracking device by Haption, which is also capable of producing haptic feedback.

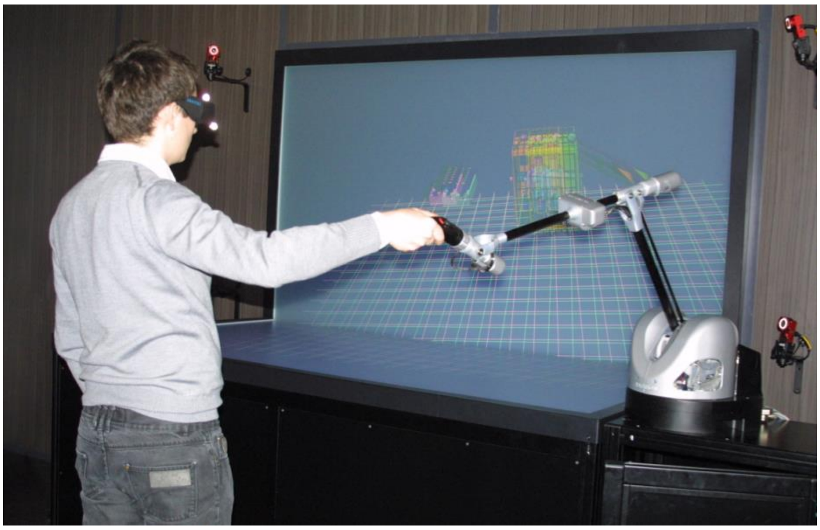

Figure 11. *Mechanical tracking device with haptic feedback (Haption 2016).*

The user inputs allow the interaction with the VE. Input and output devices allow bidirectional interaction with the VR system and the VE inside of it (Mihelj et al. 2014). There is different kind of tracking devices for different purposes; movement tracking devices, operation force devices and devices which track user's voice commands and other sounds. VE and the virtual prototype respond by changing according to the state and operations of the user based on the information captured by these tracking devices. Thus, VR system allows user's interaction in multiple levels with the VE and virtual prototype. A sensory feedback is produced as an output of the system. This feedback is often visual, but it can also include aural and haptic feedback, or only one of the feedback forms mentioned (Mihelj et al. 2014).

According to Mihelj et al. (2014) the primary tracking methods in VR are used for:

- view control;
- navigation;
- object selection and manipulation;
- tool tracking;
- user's avatar animation.

The view control tracking refers to motion tracking utilities which track user's head and its movements in VR system in order to show the VE visually from the user's perspective; as the user moves, the projected VE changes accordingly to support the new location and orientation of the user by showing the VE from realistic, changed perspective. Navigation tracking is used for user's navigation inside the VE. Object selection and manipulation tracking refers to the tracking of user's hands and hand-held objects to allow object selecting and manipulation inside the VE. Tracking a tool that user is physically holding inside the VR system to track its orientation and position to be synchronized with the virtual tools inside the VE is referred to as tool tracking.

Avatar animation refers to the user motion tracking, which is used to present the user's avatar inside the VE for realistic avatar movement. The avatar can include the whole body, or only some parts (e.g. hands and legs) can be presented in the VE. (Mihelj et al. 2014)

VR systems can be categorised in many ways, and one of them is the categorisation by the level of immersion or presence they provide to the user. The level of immersion is affected by capability of the VR system to mimic reality, which is further affected by means of modifying states of models, the capability of sensor modalities, and features of objects, models and processes (Leino 2015). There exist multiple factors that influence on the immersive experience obtained by the user. Mihelj et al. (2014) divide these factors into three groups, which are (1) virtual environment, (2) user interface, and (3) user. More detailed division of the sub-factors is shown in Figure 12.

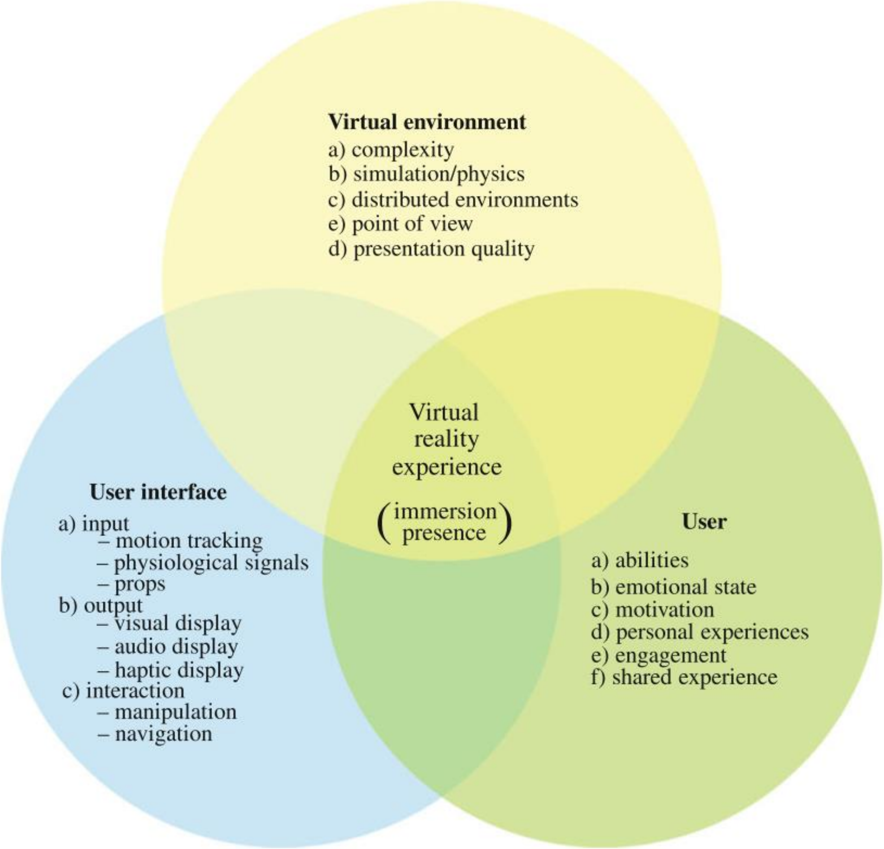

Figure 12. *Factors affecting to the immersion level of virtual reality experience (Mihelj et al. 2014).*

The first group in Figure 12, *virtual environment*, covers the complexity and level of simulation the VE provides to the user. The more detailed and realistic the VE is, the more immersive experience it provides. However, as the complexity increases and the VE becomes more detailed and realistic, more and more computational resources and working hours are needed to produce such an environment. The sufficient level of complexity depends on the application the VE is used for. *User interface* is the second group, and it refers to the hardware used in the VR system by the user, including motion tracking sensors, display, user feedback devices, and utilities used for interacting with the VE and virtual prototype. Intuitive user interface allows realistic interaction with the virtual environment, which facilitates more immersive VR experience. The last group is *user*, which refers to the actual user of the VR system; his/her mental and emotional state, motivation, abilities, personal experiences, engagement and shared experience. For example, if a person resists new technology utilization and hence has a negative attitude and a lack of motivation towards the VR system, the immersive experience will suffer from it. (Mihelj et al. 2014)

Interaction between these three groups of factors define the experience of VR (Mihelj et al. 2014), also known as the level of immersion. Despite the fact that current VR systems can be used for various simulations, they aren’t without limitations, especially when it comes to the sense of immersion (Choi & Cheung 2008). This factor along with the price of immersion make the task of choosing the appropriate VR system for its purpose even more important (Choi & Cheung 2008). The user interface and virtual environment groups in Figure 12 can be affected by increasing resources spent on the VR system. However, the user is eventually the most important part. If the user does not feel like utilizing the VR system for any particular reason, the immersive VR experience suffers from it.

Mujber et al. (2004) categorise VR systems by their level of immersion into three categories, which are non-immersive systems, semi-immersive systems and fully immersive systems. Choi & Cheung (2008) divide VR systems into semi- and full-immersive systems, where semi-immersive systems include both non-immersive and semi-immersive systems defined by Mujber et al. (2004). In this thesis, the categorization of Mujber et al. (2004) is used, since it helps to categorize different VR systems more accurately due to the additional group compared to the categorization provided by Choi & Cheung (2008). An overview of the system categorization is shown in Table 1.

***Table 1.** Categorization of virtual prototyping systems, adapted from (Mujber et al. 2004).*

VR Systems	Non-immersive VR	Semi-immersive VR	Fully immersive VR
Input Devices	Mice, keyboard, joysticks, and trackballs for VP manipulation.	Controllers, joysticks, 3D-mouses and data accessories for VP manipulation and user tracking.	Intuitive controllers, data accessories, haptic sensors, and voice commands for VP manipulation and user tracking.
Output Devices	Standard high-resolution monitor.	Large screen monitor, large screen projector system and multiple television projection systems, head mounted display (HMD), and aural feedback.	Large screen projection system, multiple television projection systems, head mounted display (HMD), CAVE, and haptic & aural feedback.
Resolution	High	High	Low-Medium
Sense of Immersion	Low	Medium-High	High
Interaction	Low	Medium	High

In non-immersive VR systems the sense of immersion is low due to the lack of immersive input and output devices which would provide control surface and natural feedback similar to real world, as shown in Table 1 (Mujber et al. 2004). For instance, if a keyboard and a mouse are used to control a car in VE, the sense of immersion is low, because such input devices are far from a steering wheel, pedals and a gearstick, which are normally used to control a car. Furthermore, to provide an immersive experience, the controls should not only look like their real life counterparts, but also act like their real life counterparts.

In semi-immersive VR systems additional monitors, sensors, and more intuitive controls increase the level of immersion compared to non-immersive VR systems (Mujber et al. 2004). For example, a semi-immersive system could utilize desktop-computer providing stereoscopic image of the target system, projecting it with large screen monitors or by projector in order to visualize the VE and virtual prototype in a bigger scale. Control is performed for instance by keyboard, mouse, space balls, joysticks or data gloves with location tracking sensors. Depending on the output and input devices of the system, the immersion level is in low-medium -scale.

In fully immersive systems the output device is usually projector system, head mounted display (HMD), or CAVE. The controlling is done by a movement tracking system, which can be linked for instance into data gloves, helmets, shoes, or tools used in the manufacturing process. The level of immersion varies between medium and high.

According to Bernard (2005), semi- and fully immersive systems can also include haptic sensors, which provide tactile and kinetic feedback to simulate contact forces, weight of object or provide tactile feedback of object’s shape. These haptic devices raise the immersion level even further, since they can give realistic feedback from the target system visualized in the VP system. However, Mihelj et al. (2014) state that the haptic cue rendering (i.e. haptic feedback) is one of the most challenging technical problems in VR systems. Direct physical interaction with requires bidirectional communication between the VE and the user through a haptic display, which receives and generates mechanical stimuli at the same time (Mihelj et al. 2014). Haptics are currently limited to be used only in very simple VEs due to the complexity of the task (Mihelj et al. 2014). Hence, utilization targets including haptic feedback are also limited to simple prototypes and environments.

According to Choi & Cheung (2008), fully immersive VR systems are often characterised by CAVEs and other displays consisting of multiple screens, while as semi-immersive systems usually include only large desktop monitors or a pair of old LCD projectors. However, as the categorization by Mujber et al. (2004) has a third category, the difference between semi- and fully immersive systems is not only the output device, but also the level of interaction, which refers to the type of input devices. Thus, great amount of immersive input devices combined with a visually imposing output device usually distinguishes fully immersive VR systems from semi-immersive-systems. Otherwise these systems can be very similar.

External disturbances shown in Figure 8 are environmental distractions that affect negatively to the immersive experience provided by VR system by possibly diminishing the efficiency of the product evaluation process. The higher the level of immersion provided by virtual reality system, the less prompt the user is to these disturbances. However, the higher the level of immersion, the more expensive the systems become. Fully immersive systems are usually only affordable only by large companies, due to their high cost. In addition, the size and complexity of fully immersive systems are factors that are hard for small companies to overcome. (Choi & Cheung 2008)

Thus, the selection between different VR systems must be done carefully in order to select a VR system with an appropriately realistic visualization. Selecting the right VR system has a significant role in reducing the time it takes to bring a new product on the market (Mihelj et al. 2014). If the target application for VR implementation is well-known while deciding the size and complexity of the VR system, the most cost-efficient choice is easier to make. An example of a semi-immersive CAVE is shown in Figure 13.

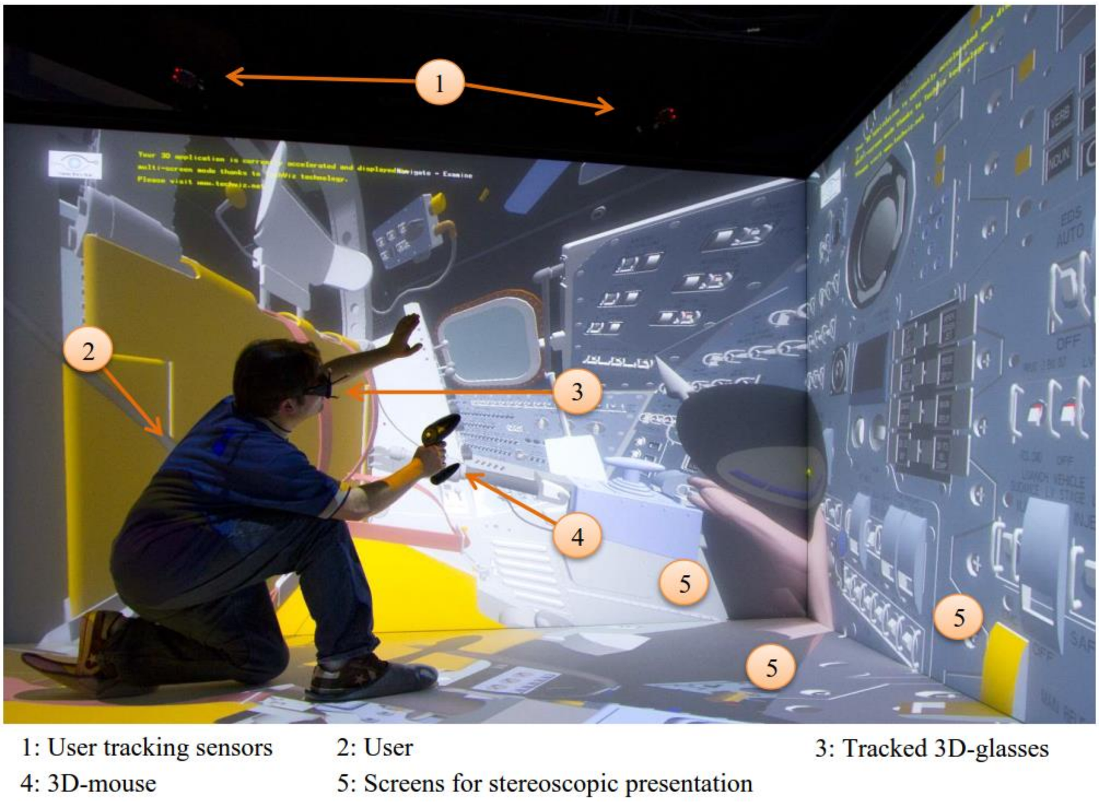

Figure 13. *Apollo 2 cockpit environment in CAVE (TechViz 2015).*

VR technologies have developed significantly during the past decades (Seth et al. 2011). The ultimate objective is to provide an invisible interface which would allow the user to interact with the VE as he/she would with real life (Seth et al. 2011). The human-computer interface plays an important role in VR systems (Leu et al. 2013), whereupon it should be intuitive and easy to use in order to facilitate quick adoption and acceptance among its users.

To make the quick adoption and acceptance among users possible, the interface between a user and a VE should provide a sense of presence to the user in a way, which makes the user to believe he or she is immersed in the VE. For example, VR systems can be used in hardware-in-the-loop (HIL) -simulations. In HIL-simulation a hardware component (e.g. NC control unit) is coupled with a simulation environment to test and develop control systems. It can also be used in training purposes. (Controllab 2015; Pürzel et al. 2013)

Car driving simulator with real steering wheel and pedals for controlling the car in a VE is an example of a system, which combines the realistic control surface and the immersive experience of a VR system. These enhanced controls make the VR experience even more immersive. However, HIL-simulations and other intuitive controlling methods usually require programming and expert knowledge in VR system development. Thus, they are more expensive to implement compared to more simple control solutions.

3.2.3 Virtual prototyping in early stages of product development

Based on the definition of a prototype by Ulrich & Eppinger (2008), virtual prototype is an analytical and focused mock-up of the product. However, with the help of sensors and stereoscopic image, interaction with the virtual prototype can be made more tangible (Wang & Tsai 2011). Probably one of the greatest differences of virtual prototype compared to physical and analytical prototypes is its ability to combine advantages from both types. Virtual prototype can be highly flexible due to its 3D CAD model -nature, while at the same time it can provide aural, haptic, and enhanced visual feedback traditionally experienced only by physical prototypes. Virtual prototype provides information about the spatial relationships (Wang & Tsai 2011), which can be equated with the spatial information of the physical prototype. As stated earlier, VP describes the construction and testing of a virtual prototype. It can be applied starting from early design phases and continuing until the very last phases of product development process.

VP can be utilized in multiple different applications. Manufacturability studies, assembly order and methods planning, human factors and ergonomics evaluation, safety and critical task evaluation, and design aesthetics evaluation are just few examples of possible applications for VP (Aromaa et al. 2014; Cecil & Kanchanapiboon 2007; Leino 2015; Seth et al. 2011). For instance car manufacturers utilize virtual prototypes to design and evaluate drivers' interfaces in VEs (Leino 2015). There is ready VR systems available on the market, for example TechViz XL provided by TechViz, which can be used to different kinds of virtual prototyping applications and targets (TechViz 2015).

As assembly processes often form a great part of a product's costs, it is important to design assembly processes early in the design stage. Seth et al. (2011) support this statement by arguing that assembly planning is a vital and critical part of the product development process. Assembly properties planning and evaluation connects the activities between design and production departments. This makes it an interesting implementation target for VP. Mujber et al. (2004) argue that VR has great potential when it comes to manufacturing applications, including assembly planning and inspection.

According to Seth et al. (2011), VR technologies have the capability to support the integration of natural human motions and computer aided assembly planning environment, and to simulate manual interaction -requiring tasks such as assembly methods and properties prototyping. VP of assembly methods, also known as virtual assembly (VA) increases the ability of making encompassing decisions considering design and assembly of a product and thus, improve product quality, reduce costs, and make the time-to-market shorter (Seth et al. 2011). Leino (2015) also argues that product assembly studies and review are the most profitable areas of VP, which also makes the VP implementation in assembly related tasks even more interesting from the point of view of this research.

Assembly and maintenance tasks of complex products with low volume production quantities are to a great extend conducted by manual labour, since the tasks would be either too complicated or too expensive to execute by automation and assembly robots. Design engineers are responsible for allocating appropriate work tasks for the production workers and for the whole technical system with decent ergonomic properties (Leino 2015). Assembly planning can be done today by utilizing 3D CAD -models, which are assembled and examined on 2D computer screen (Seth et al. 2011). These activities are performed either during informal meetings between design engineers or during design reviews, presented earlier in Chapter 3.1.4.

However, as assembly tasks get more complicated, assembly planning by utilizing 3D CAD software takes significantly longer time, and is also prone to errors (Seth et al. 2011). Furthermore, ergonomics, such as difficult assembly operations, are hard to evaluate based on these traditional evaluation methods (Seth et al. 2011). Leaving the human factor without attention during assembly planning can lead to inefficient or incorrect operations, which causes futile costs and work in the upcoming phases of product development process (Seth et al. 2011). VR technologies could be utilized to take human factors into account better during the early design phases. This could eliminate some of the errors related to assembly properties before the design is released for fabrication of the first physical prototype.

The visibility, posture, reach, physical and mental stress of an assembly worker could be taken better into account with the help of VP (Leino 2015). By VP, early concepts can be imported into VE during the early phases of product development process. VA can be performed during design reviews and other collaborative activities in order to evaluate assembly properties long before these properties could be evaluated with physical prototypes. VA can help utilizing the expert knowledge held by an assembler by including him/her in assembly planning and giving a sense of presence in the virtual world (Seth et al. 2011). Being immersed into the VE, the assembly worker can for example examine the assembly order, comment it and give enhancement suggestions orally to other participants based on his/her expert knowledge. This facilitates better assembly planning decisions, since critical assembly tasks can be evaluated before manufacturing an actual physical prototype (Seth et al. 2011). Other aspects that could be evaluated by VA include clearance for tooling, part orientation during assembly, and assembly space clearance with different module combinations, as seen in Figure 14.

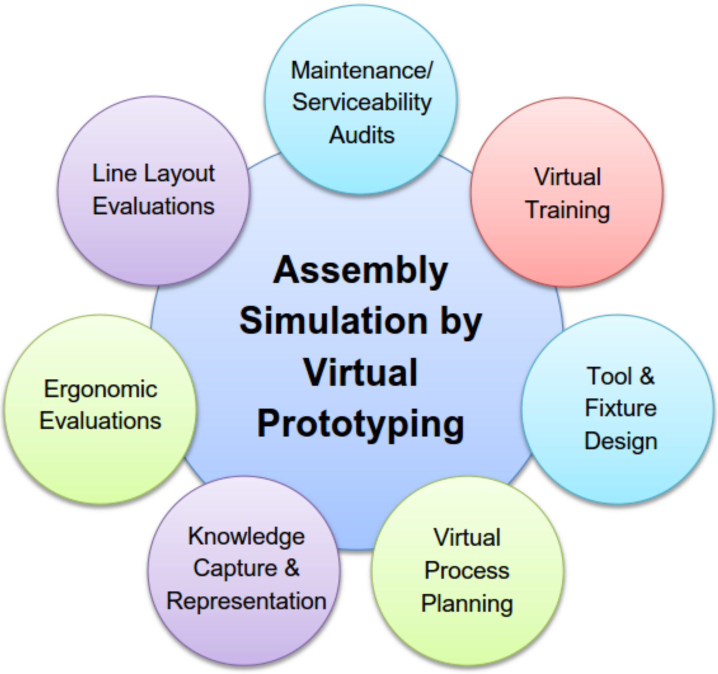

Figure 14. *VP applications for assembly simulation, adapted from (Seth et al. 2011).*

Liu et al. (2015) classify VA into constraint-based virtual assembly (CBVA) and physics-based virtual assembly (PBVA). The former represents an assembly simulation, where parts of the assembly are located using real-time or predefined recognized constraints. Parts can be moved freely in the VE, and finally assembled in their ideal position, thus mimicking the ideal dimensional state of the whole assembly. However, the drawback is that the assembly errors made by the user cannot be simulated because of the predefined positions of the parts. In PBVA, physical laws, forces and torques applied upon parts can be utilized along with visual feedback to improve the immersion of the system. Linear speeds and acceleration of parts along with assembly errors can be simulated by PBVA. Currently, this technology is an interesting research topic, but it involves several challenges and drawbacks regarding its efficient implementation, which make its utilization in this research disadvantageous.

VP is traditionally applied in the very last stages of product development process to verify the design solutions of the product (Alanen et al. 2013). However, this research aims to implement VP into the early phases of product development process, starting from the concept development phase introduced in Chapter 3.1.1, since VP is argued to help the communication of tacit knowledge between different stakeholders (Leino 2015). A natural place for VP implementation during the early development phases are design reviews. Gathering participants responsible for the design and development of the product as well as the manufacturing and assembly tasks of the product, design reviews have great potential for VP implementation because of their concurrent and collaborative engineering nature. In addition, Choi & Cheung (2008) argue that the sense of immersion plays a significant role in enhancing the design review practices.

The sense of immersion of design reviews could be enhanced by VP already in the early design and development phases, before fabricating the physical prototype. Industrial examples of VP in design reviews are presented in Chapter 3.2.5. However, it should be noted that VP should not be seen as a tool, but a resource that has a complex synergy with both technical and organizational resources (Leino 2015).

3.2.4 Benefits and challenges of virtual prototyping

Compared to physical prototypes, virtual prototypes can be constructed during the development phase for early evaluation of different features and functions of the upcoming product without the need of preparing the manufacturing documents, ordering or manufacturing the items, and assembling the prototype physically. Thus, many key factors such as manufacturability, product shape and assembly properties can be evaluated and optimized quickly without significant resources (Choi & Cheung 2008). VP helps to reduce development time and costs significantly (Choi & Cheung 2008).

A study conducted by Bochenek & Ragusa (1998) argues that the level of immersion plays important role in design reviews conducted in VE, when it comes to detecting errors and improving the overall design process. Furthermore, according to Leino (2015), design reviews utilizing VP could benefit from the augmented features of the virtual prototype. These features are intended to provide information to help users perceive and understand certain features of the system. These features or cues can include for instance colour coding representing weight of items presented in the VE. This characteristic can be very useful, since the technology available is not capable of presenting all the real-physics -based phenomena in the VE (Leino 2015). Thus, virtual prototypes can be modified to present additional information compared to physical prototypes. For instance, the drawing number and revision of an item could be included in the virtual prototype to help detecting the items that are being inspected in a complicated assembly consisting of multiple individual entities.

Bernard (2005) argues that behaviour and simulation models of virtual engineering environments are the main factors for success in industry applications. These models include, for instance, dynamic visualization and interaction, movement tracking, collision detection, and 3D-projection of numerical models (Bernard 2005). Today VR technologies are easily available and more affordable, which facilitates possible investment decisions (Aromaa et al. 2014). For instance, the relative price of computing power is decreasing continually, thus allowing more complex VP applications with the same amount of investment.

Aromaa et al. (2014) argue in their paper that the main benefits of VP are reduced costs, reduced time-to-market, knowledge sharing and user participation. The benefits of VP are categorized by three different beneficiary points of view: company/business, managers/designers and users/operators (Aromaa et al. 2014). From company’s point of view, the benefits are reduced costs, reduced time-to-market and reduced amount of physical prototypes, which also lead to increased productivity and competitiveness. VP can also facilitate better quality and customer satisfaction. These may be due to the fact that the iteration of VP process is significantly cheaper compared to physical prototyping (Choi & Chan 2004). In addition, based on empirical studies by Leino (2015) it is argued that VP can lead to improved processes and organizational structures.

From managers' and designers' point of view, VP can facilitate better product lifecycle management, design decision-making, learning and better understanding of complex product data. Early testing, analysis and design fault recognition help to manage later design phases and enhance the designers' experience. In addition, conduction and testing of futuristic ideas and evaluation of safety critical tasks are made possible by VP, which are remarkable advantages compared to physical prototyping. (Aromaa et al. 2014)

Visualization of new, futuristic concepts can facilitate creativity and lead to even better designs. New simulation methods are possible in VP (Bernard 2005), which provide flexibility compared to physical prototyping. It has been reasoned by Leino (2015) that by utilizing VP in product development, products and modules can be introduced to standard production with better maturity level. This leads to smaller amount of engineering changes of the physical product.

Better user participation and requirements definition are one of the benefits of VP for users and operators. VP provides realistic immersive experience with visualisation and natural interaction, which facilitates better user acceptance (Aromaa et al. 2014). By participating in the design process, users and operators can affect to the design of ergonomics, usability, safety and comfort of the design (Aromaa et al. 2014). 3D CAD software can be utilized in design reviews for evaluation where 3-dimensional digital mock-up is presented as a 2-dimensional image on a computer screen or a projector. This model depicts the product better than a traditional 2-dimensional drawing, but requires that the people participating in the review have to prepare a mental image of the configuration (Watanuki 2010). Thus, it can be difficult to grasp the overall size, volume and weight of the product (Watanuki 2010). VR system on the other hand can present the product as a 3-dimensional virtual mock-up, also known as a virtual prototype. According to Watanuki (2010), this makes it easy to create a 3-dimensional mental image of the product. In addition, volume and size evaluation is much easier, since the product is presented in full-size (Watanuki 2010). This facilitates better design analysis during concurrent engineering activities.

Utilizing Virtual Reality (VR) technology in CE and design reviews is justified, since it could provide means for better communication between team members with different expertise by enhanced user perception and user interface, and improve the outcome of product development process altogether (Aromaa et al. 2014; Leino 2015). VR technologies can provide strategic support for the company as well as help to validate product designs earlier in the development process (Bernard 2005). Even though VP has great potential as a tool for increasing efficiency and effectivity of product development process, there are also some challenges, which affect to the utilization rate of VP.

The decision to implement VR technologies into a company's product development process is strategic, but it is also an investment decision, which should be rationalized by benefits, that would follow the implementation. Especially quantitative benefits would be extremely helpful, since they can be used in the investment calculations. However, quantitative benefits of VP are still quite scarce in literature as stated by Ottosson (2002). This might be due to the large amount of variables that affect the benefits and costs of VR technologies (Leino 2015), which make the quantitative research fairly difficult. Product development projects are traditionally long-term and highly individual, making the comparison between normal product development projects and VP utilizing product development projects even harder. Companies which utilize VR technologies tend to use it in many different applications. This makes it even harder to define how much each application target affects to the total benefits. Hence, investment decisions regarding the technology are guided by impressions and feelings (Ottosson 2002). The lack of evidence of the quantitative benefits can be overwhelming to companies. This is definitely one of the biggest challenges of VP.

The direct advantage that VE provides to the user depends on the user's background and experience. For instance, an experienced design engineer familiar with engineering tools might not benefit as much from the 3-dimensional full-size presentation and the overall improved visual presentation as a junior engineer, assembly worker, or an ergonomics expert (Leino 2015). Design engineers are used to work with the 3D CAD model, which is why they can understand it better compared to other stakeholders with less experience with engineering tools. Hence, VP as a visualization tool is more beneficial for the users with less experience with engineering tools. This should be noted when selecting the VP implementation target.

Furthermore, knowledge is needed to utilize VR software and to prepare virtual prototypes and VEs for VP purposes (Ottosson 2002). Leino (2010) also states that VR system is often utilized by experts who are not involved in product development. This can easily have a negative effect on the efficiency of VP, because the design engineers have to communicate their needs regarding VP to the experts running the VR system. However, today companies like TechViz offer VR software and hardware combinations that are intuitive to use and utilize the 3D CAD model created by design engineers without the need for conversion (TechViz 2015). VR system should be simple enough to be utilized by design engineers to facilitate better adoption and more efficient utilization.

Utilization of VP usually requires 3D CAD model optimization and CAD-VR conversion due to computational limitations. This causes extra work, which is not needed if the 3D CAD model is used as is in 3D CAD software for design evaluation, for example in design reviews. These are pure technical limitations, which might become as obstacles for some companies. However, Leino (2015) states that challenges as well as the interest considering VP have been shifting from technical issues towards value thinking and system processes. For instance, the understanding and knowledge considering the real value of VP among companies is insufficient (Leino 2015). This means that while companies are aware of VP as a technology and they recognize the benefits it could offer, they do not actually understand the true value of VP. Utility of VP is highly promoted, while at the same time there is a relatively low level of real adoption in industry (Leino 2015). This low amount of industry adoption creates low amount of evidence regarding the true value and benefits of VP, which together create a vicious circle. This is probably one of the greatest challenges of VP.

3.2.5 Previous applications

The benefits of VP are widely recognized (Aromaa et al. 2014; Bernard 2005; Cecil & Kanchanapiboon 2007; Choi & Chan 2004; Mujber et al. 2004; Weidlich et al. 2007). However, examples about the practical benefits observed by implementing VP in industries and organizations are much harder to find. This chapter presents applicable examples of implementing VP in industrial applications. The example cases are relevant from the research point of view, as they utilize VP in product development projects and in design reviews between design engineers and production workers.

The first application example deals with VP implementation in fusion engineering. In a study by Keller et al. (2015), fusion reactor component optimization was made by utilizing VP. There is a big difference between fusion reactors and forest machines as products, but both of them present a complex design task, which includes multiple modules and sub-systems to be integrated by CE. According to Keller et al. (2015), the aim of the research was to consider functionality, integration, human accessibility, and assembly & maintenance properties already in the early design stages by utilizing VP in design reviews. TechViz software was used to produce a 1:1 scale stereoscopic image of the fusion reactor component as a virtual prototype (Keller et al. 2015). In addition, a haptic device for force feedback, a motion head tracking system for following the user, and a controller for immersive interaction with the VE were utilized in the design review (Keller et al. 2015).

VP in design reviews helped to detect inconsistencies and design optimization needs of the fusion reactor component more efficiently inside models and machine sub-systems (Keller et al. 2015). Based on these observations, several corrections to the design of the fusion reactor could be done (Keller et al. 2015). Keller et al. (2015) further state that the same errors would have been spotted during the assembly, but this would have led to ECRs and delays in the schedule. Based on these observations, VP utilization target was successful. Early elimination of errors leads to fewer costly ECRs. This will eventually decrease the amount of resources spent during product development process. Hence, similar application targets should be considered also in this research.

Keller et al. (2015) also argued that VP improved the communication between design teams of the fusion reactor component. It is not specified whether the design teams included production workers responsible for conducting work tasks related to fusion reactor components' assembly. However, in this case communication is enhanced by utilizing VP, which also means that knowledge sharing is enhanced. It was also stated that the big screen helped the design review participants to understand the magnitude of the components, as the system could be presented in 1:1 scale (Keller et al. 2015). This could also be one reason why the communication and knowledge sharing is enhanced. Full-size presentation depicts the prototype under review more realistically, and it may also help different members of the design team to parallel the virtual prototype to a mental image of a physical prototype.

Computing power was stated to limit the complexity of the fusion reactor component models, although the complexity could be limited by using configuration management models (CMM) or smaller partitions of the whole assembly (Keller et al. 2015). This observation raises doubts about the capabilities of TechViz and other similar software which do not require conversion. Even if TechViz software is capable of utilizing 3D CAD models without conversion, the size of complex models limits the size of possible assemblies that can be prototyped with VP. It seems that optimization is needed regardless of the VR software, when handling significantly large assembly models.

The second VP application example relates to Metso, a global technology corporation and manufacturer of services, equipment and systems in mining, construction, pulp & paper and oil & gas industries with customers in more than a hundred countries around the world. During the VP implementation projects, the participating company was called Metso Mining and Construction (Metso MAC), whose main products were crushers, feeders, conveyors, screens, and mobile crushing units. During years 2006–2014 the company was participating in 3 relatively large research projects, during which VP was introduced and implemented in product development process. (Leino 2015)

In the second research project that Metso participated, VP was utilized in design reviews to develop internal productisation and collaboration between design and production departments (Leino 2015). A new generation engine module was chosen as the development target. According to Leino (2015) the overall goal of Metso was to reduce the time-to-market and number of engineering changes by proper implementation of VP. Hence, Metso's objectives are similar compared to the case company's objectives. The engine module is smaller compared to a whole forest machine as an implementation target, but both of them represent similar optimization tasks regarding manufacturability and assembly properties.

Metso’s engine module’s assembly, maintenance, safety, and structural problems were evaluated in design reviews collaboratively with different stakeholders, including an assembly worker, design engineers, a manufacturing manager, product development engineers and assembly foremen. Figure 15 depicts a design review situation, during which the assembly worker observes the engine module by utilizing HMD and visual user tracking, while other participants were discussing about possible solution alternatives to the problems identified and evaluated during the design review. (Leino 2015)

Figure 15. *Design review situation, during which a worker is performing an operation in VE (Leino 2015).*

According to Leino (2015), changes to the engine module structure, assembly tasks, and assembly sequence were made based on the observations made during the VP design review. This is supported by the observations made in the first application example by Keller et al. (2015). In addition, a faulty 3D model was also repaired, since the review board noticed inconsistencies in it with the help of VP (Leino 2015). Based on these application examples, design reviews with VP technology seem to help noticing design errors and inconsistencies. One significant reason for this is probably the user tracking, which allowed immersive exploration of the virtual prototype. The same level of immersion cannot be experienced by utilizing 3D CAD software for design evaluation. In addition, the collaborative nature of design reviews involving multiple stakeholders is probably one significant reason why these errors and inconsistencies are observed. While cross-functional stakeholders assemble in one place to evaluate certain features of a product such as assembly properties, the virtual prototype is evaluated from multiple organizational perspectives. This is definitely helpful when aiming to observe all the possible errors and inconsistencies in the design.

Leino (2015) further states that communication between different stakeholders participating in the engine module design reviews was enhanced. Furthermore, it was estimated by Metso that VP could contribute to effectivity and efficiency in the form of time and cost savings in product development projects (Leino 2015). Indeed, VP has potential in similar application targets, and Metso has noticed it. Even though the technology was stated to be not quite there yet in terms of technological maturity, it seems that Metso has recognized the benefits that VP could offer. Indeed, similar case studies are great opportunities for companies to familiarize themselves with VP and realize the possible benefits it could offer.

The third and final application example concerns tractor development by VP technology. Valtra incorporation is the leading manufacturer of agricultural tractors in the Nordic countries, selling Valtra tractors in over 75 countries worldwide. The company manufactures annually 24,000 individually customized tractors in total. Valtra has two major factories; one in Brazil and the other in Suolahti, Finland. The latter includes part of the research & development activities as well as the administrative offices along with a significant part of the manufacturing and service activities. (Valtra Inc. 2015)

The VP utilization at Valtra is a continuum to the development of 3D modelling. Before VP was implemented at Valtra, 3D CAD software was used in design reviews to evaluate and validate the current state of the product-in-development by examining the assembly by projecting a 2-dimensional image of the 3-dimensional assembly onto a screen by a video projector for further inspection. Since 2005, Valtra has been investigating the use of VR in product development. The first implementations were project-minded collaborations with VTT, which were successful implementations as such, but the technology itself was not seen mature enough for successful implementation in daily use. At that time, the utilization of VR technologies took significant amount resources, which deteriorated its functionality. 10 years of researching and gradually implementing the technology has led to the comprehensive utilization of VP in research & development activities. Today, Valtra utilizes VP daily to develop its mass-customized tractors. (Piippo et al. 2015)

From technical point of view, Valtra utilizes an active shutter 3D system, visual user tracking, aural feedback, and a 3D-mouse for interaction with the virtual prototype and overall navigation (Piippo et al. 2015). The system itself is non-moveable; a specific room is allocated for the VR system. The prototype is rendered on a powerwall, which is roughly 3.5 meters wide and 2.5 meters tall, thus enabling the evaluation of the virtual prototype nearly in 1:1 scale. These features define it as a semi-immersive VR system based on the categorization introduced in Chapter 3.2.2. Haptic input and output devices are not currently used at Valtra.

VP at Valtra is utilized in several activities: collecting customer requirements and feedback, analysing concepts before physical fabrication, design reviewing purposes among cross-functional and cross-site teams, planning assembly orders and balancing the assembly stages, and training workers (e.g. assembly workers) (Piippo et al. 2015). Hence, Valtra's VR system has a high utilization rate. The system can be utilized easily and comprehensively in daily work, which is definitely one important reason why it has been accepted so well at Valtra. Indeed, the most important factors for Valtra regarding the VP system are its user-friendliness and good accessibility (Piippo et al. 2015). The current system is built upon Valtra's 3D CAD system, which means there is no need for separate conversion from 3D CAD to virtual prototype. According to Piippo et al. (2015), this is a major advantage; after the 3D assembly is invoked in CAD software, the virtual prototype is available for use in minutes. This allows fast response to the observations and change requests made during design reviews.

According to Piippo et al. (2015), the benefits of utilizing VP are also wide-ranging; problems related to the product-in-development can be noticed and solved earlier, which facilitates shorter lead-times and also better quality. As Valtra's development process is shortened, there is a significant reduction in development costs and thus, a shortened break-even time (Piippo et al. 2015). This indicates that VP implementation at Valtra has been successful. It is essential to notice that since Valtra utilizes the technology in multiple activities, the total quantitative benefits are probably caused by the combination of different VP activities, not by a single VP activity. In addition, design engineers get the feedback from customers and other stakeholders inside the company more quickly, since the VP is more illustrative due to the third dimension compared to the nearly 1:1 scale (Piippo et al. 2015).

Piippo et al. (2015) state that the difference between a traditional 3D CAD model and a VP is not significant to the design engineers who are used to work with 3D models, but for customers and other stakeholders it makes a huge difference, since these stakeholders can comprehend the product-in-development much better before there exists any physical prototypes. Furthermore, the amount of physical prototypes at Valtra is reduced, since prototyping can be done by VP, which requires only the 3D CAD assembly models (Piippo et al. 2015). Valtra is aware that physical prototypes cannot be eliminated completely. However, Valtra aims to minimize physical prototyping by increasing analytical prototyping with VP. Finally, the VP facilitates the collaboration with Valtra's sister companies, and also with the partners in cooperation, who are responsible for designing tractor accessories (Piippo et al. 2015).

The technology was quite well received at Valtra. Although there were some sceptics during the investment proposals, the feedback has been generally positive, especially from assembly workers (Piippo et al. 2015). In the future, Valtra plans to further develop the VR system for example by integrating HIL-testing and simulations (e.g. dynamic simulation models) into the VR system (Piippo et al. 2015). These development targets indicate that Valtra has faith in the technology, and wants to utilize it even more in the future. Such future plans require visible benefits and support among employees in order to be realized, and Valtra seems to have both of those. Obtaining the possible benefits of VP requires commitment and faith towards the technology. In Valtra’s case, this implementation seems to have paid off.

Based on the three application examples, the main benefits of VP are earlier detection of design errors and inconsistencies, and enhanced communication between cross-functional stakeholders. Evaluation of assembly properties was one of the implementation targets in each of these examples. It seems to utilize the major benefits of VP: user tracking for assembly clearance inspection and user immersion, 1:1-scale presentation for enhanced visual information, utilization of production worker’s tacit knowledge by involving them in early evaluation of the design, and offering a common communication platform for different cross-functional stakeholders.

3.3 Impact and requirements of virtual prototyping implementation

In order to successfully implement a new technology like VP to a company and obtain benefits it could bring, the implementation itself must be well planned and managed throughout the process. New work processes and procedures, such as new technologies, can be introduced to companies over quite short time frames. However, organizational cultures might also need to change along with the new processes and procedures, which may take significantly longer time than the actual introduction of those processes (Price & Chahal 2006). It is also important to consider all the possible activities, interfaces, and divisions that VP would have an impact on. Even though a new technology like VP holds great potential and there are successful implementations among other companies, the benefits cannot be gained without compensation (Leino 2015).

Ameri & Dutta (2005) divide organizations into three basic elements: process, information and people. The communication and knowledge loops between these three elements can be managed by product lifecycle management (PLM). In its essence, PLM is a business activity for product-centric environment creation (Stark 2015), and it is used to connect different stakeholders during the product’s entire lifecycle and to provide a common platform for collaboration (Ameri & Dutta 2005). Leino (2015) states that a company’s internal productisation by utilizing VP should be supported not only from design process perspective, but also from product model data management perspective. This means that different items, product variations, and assembly variations should be managed in a controlled manner to support their efficient utilization in VP activities. Furthermore, Alanen et al. (2013) argue that model-based design practice and VP should be seen as a part of the introduction and development of PLM system. Hence, before implementing VP, its impact on company-specific PLM should also be considered, since the goal is to integrate the technology fully into the PLM and processes of the company to help gain the possible benefits and thus, return for the investment (Leino 2015). This chapter aims to discuss the most important requirement for successful VP implementation. The impact of VP on the three organizational elements will be discussed.

3.3.1 Impact on work processes

Gomes De Sá & Zachmann (1999) present in their paper the impact VR technologies could have to product development process. The impact is presented in Figure 16.

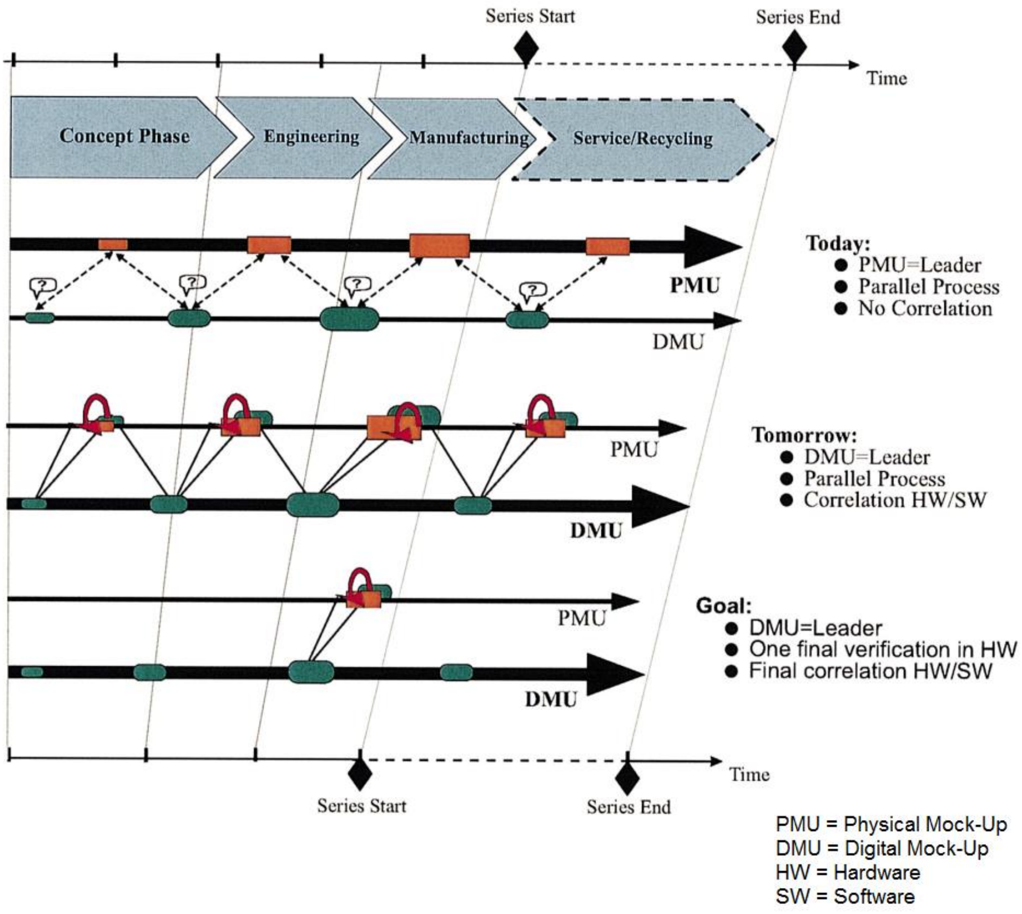

Figure 16. *The effect of transition from physical to digital mock-ups (Gomes De Sá & Zachmann 1999).*

Figure 16 depicts how utilization of digital mock-ups (DMU) would influence the product development process. Today, companies' product development processes are equivalent with the second product development process shown in Figure 16. Physical prototypes, known as physical mock-ups (PMU), work as the leader of the process, while the analytical prototypes, known as DMUs, work as a parallel, supportive process for the PMUs. Comprehensive VP implementation requires the process to become driven by DMUs, which is the third product development process in Figure 16. The objective is to front-load the different product development phases, and to verify these phases as early as possible by utilizing CE and VP.

In practice, production workers could be included in design evaluation activities such as design reviews to comment on the product design based on virtual prototype before fabricating physical prototypes. Because of the enhanced visual information obtained by 3D and full-scale presentation of VP, production workers could evaluate the design during the design phases and thus, frontload their evaluation activities, which could lead to fewer ECRs in physical prototyping. This would lead to earlier accomplishment of sub-goals and productisation milestones, since there is no need to wait for the physical prototype (Leino 2015). To make this possible, the 3D models and simulations should act as the starting point for definition of requirements, needs, and goals, which will eventually become reality during the design and development phase (Alanen et al. 2013). As shown in Figure 16, the DMU-driven processes reach the series start phase earlier compared to the PMU-driven process, which is one benefit of VP implementation introduced earlier in this thesis.

Piippo et al. (2015) stated that before Valtra implemented VR technologies to their product development process, the 3D modelling practices were developed to support VP design reviews early in the product development process. In practice this meant that virtual assemblies drafted from 3D assemblies should include all the possible items, modules and sub-assemblies to support reliable CD and decision making process during design reviews. If the virtual prototype assembly is not complete, it is much harder to evaluate certain properties, such as assembly maintainability properties and assembly tool clearances reliably. In addition, Piippo et al. (2015) stated that the assembly structure must be managed thoroughly to further support easy and fast VP utilization in product development projects. PDM system should support easy creation of configured variants, which could be prototyped with VP.

3.3.2 Impact on information and communication flows

VR system affects also on the information and communication flows inside the company. From information point of view, virtual prototypes are 3D CAD designs that have been converted to a VR-suitable format and modified to meet the needs of the VP activity. As the virtual prototype is being created based on the current product design made in 3D CAD software, the 3D model data can be drawn either straight from the 3D CAD software or from the product data management system, which is connected to the 3D CAD software (Leu et al. 2013). CAD-VR -middleware utilizes the 3D CAD design information for preparation and producing the virtual prototype. Hence, the 3D CAD models should be available and up to date in order to be comprehensively utilized in VP activity.

For instance, TechViz XL is a core product of TechViz, which utilizes a 3D model of the product opened in 3D CAD software to present it in a VE (TechViz 2015). It is built upon the 3D CAD software, and no CAD-VR conversion is needed; the 3D model can be inspected in the VE almost immediately after it is opened in the software (TechViz

2015). However, based on the first application example in Chapter 3.2.5, the complexity of 3D CAD geometry might be limited due to limitations of VR software and hardware. This means that the 3D CAD models need to be either optimized, or the evaluation should be divided in smaller entities. To perform these activities efficiently, the product data should be well managed to support easy and fast optimization and also CAD-VR conversion.

Leino (2015) states that VR as a technology and VP as a methodology should be seen as parts of the company's PLM architecture and model, which are responsible for handing the digital information as well as controlling the virtual product processes. According to Piippo et al. (2015), Valtra also recognized that the overall product data management (PDM) should be at a sufficient level to support the efficient utilization of VP. Furthermore, Valtra discovered that it should be able to control their activities, functions and the information flow of these activities and functions before the implementation (Piippo et al. 2015). In practice, this meant that all the parts of a tractor must be included in the 3D assemblies, and the assemblies should be managed in a controlled manner to support reliable evaluation and validation. Indeed, the combination of VR technologies and efficient product lifecycle and data management brings the added value to Valtra (Piippo et al. 2015). This is definitely the case with other companies; VP technology requires systematic PDM, which supports efficient and daily utilization of the technology.

The data flow between VR system, PDM system and CAD software is shown in Figure 17.

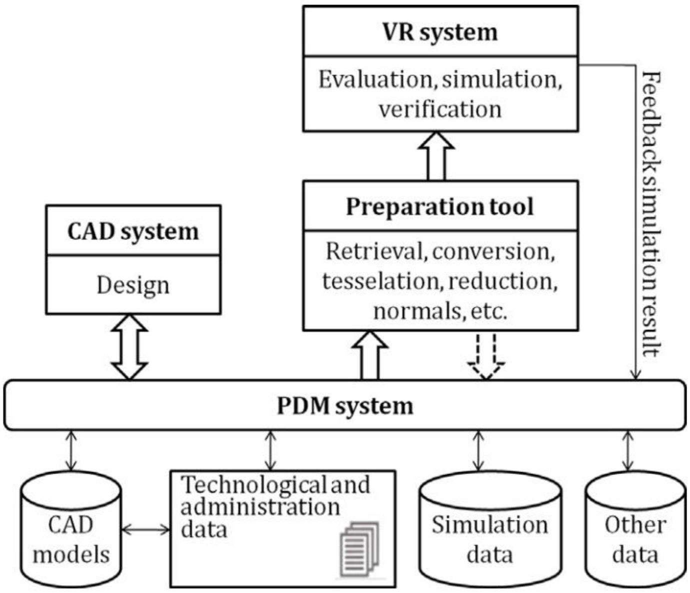

Figure 17. *Data flow between VR system and CAD (Leu et al. 2013).*

As shown in Figure 17, VR system creates a new feedback channel from production workers to PDM system to be used by other stakeholders. In traditional product development process without the implementation of VP, the feedback regarding problems with the current design of the product noticed by production workers during the fabrication of a prototype should be documented and entered into the PDM system to complete the feedback loop. However, Riege & Zulpo (2007) argue that since production workers' work tasks don't necessarily involve the frequent use of computers to share knowledge, these computers might not support the knowledge transfer within their community or to another communities, e.g. design engineers. By implementing VP, production workers would have the ability to give feedback orally to methods engineers and design engineers while at the same time demonstrating it with the virtual prototype, which could help to document the expert knowledge of production workers (Seth et al. 2011), and possibly further enhance the amount of communication. Since new feedback is received, the VP activity should have a documentation methodology, which would support the new feedback channel.

Cross-functional design reviews with multiple stakeholders confront different ideas to come up a solution (Matta et al. 2013). The feedback loop from VR system to PDM system should be supported by the PDM system; the new feedback should be collected, stored and managed in a way that would facilitate better decision making, product quality and faster product development project lead-time during current and future product development projects. In other words, information and knowledge obtained by VP should be available to all employees to support future learning and decision making. Decision making process' efficiency in complex design environment is highly dependent of the availability of the decision support system, since it enables the reuse of existing knowledge (Ameri & Dutta 2005). Tacit knowledge capturing offers the possibility to enhance the efficiency of product development teams and thus, the overall product development process (Goffin & Koners 2011).

3.3.3 Impact on people

Chapter 3.1.2 examined the impact of concurrent and collaborative engineering considering people involved in product development at design community level. This chapter is concentrating on discussing the impact of VP at individual and organizational level. Although the benefits of VR technologies are recognized and these technologies are implemented successfully by major industries such as automotive and aircraft industries, there is still significant doubt towards VP implementation into current product development processes. It is well known that new technology can cause fear and resistance towards implementing it. In addition, the benefits of VR technologies are not always visible, which may also have a negative effect on peoples' attitudes towards implementing these technologies (Aromaa et al. 2014). Thus, the challenge is to provide enough evidence about the significance, impact, and value of VR technologies to support investment decisions (Leino 2015). For effective introduction of change, e.g. new technology implementation, change management is required (Gill 2002).

Introducing new technologies in the workplace is a challenging task for change practitioners and managers alike. It is quite common that many of these projects end in failure, or fail to deliver anticipated results. Becker (2010) argues that by implementing a change management plan that takes into account unlearning, some of these failures could have been less disastrous. In this context, unlearning means the process, by which an organization and an individual acknowledges and relinquishes prior learning and behaviour in order to facilitate the learning of new information and behaviour (Becker 2010).

To achieve full value and maximum benefits from a new technology, the company has to focus on the human element as well as the impact the new technology has on employees (Becker 2010). Employees of the company have learned certain habits during their work careers. According to Gill (2002), resistance to change these habits is very common. Beliefs and behaviours developed inside an organization inflicts defensive routines, which can further inhibit change and prevent unlearning (Becker 2010). Furthermore, it is important to acknowledge that the ability and willingness of employees inside the organization to try new things and relinquish old ways are critical factors for overcoming organizational inertia and facilitating effective innovation (Becker 2010). If the atmosphere among employees towards change is negative already from the beginning, the importance of well-managed change is even more significant.

Becker (2010) researches in his paper individual and organizational factors that influence unlearning during technology implementation. The first individual factor of Becker (2010) is *positive prior outlook*, which refers to the outlook the individual has prior to the change, i.e. understanding why the change is needed. An adequate preparation and support should be given to the employees by manager responsible for planning and implementing new technology to give a positive overall understanding why the new technology is being implemented (Becker 2010).

The second individual factor is *feelings and expectations*, which highlights individuals' feelings and expectations prior to and during implementing change, e.g. new technology (Becker 2010). Indeed, change has an effect on emotional elements. For instance, individuals are concerned about the consequences the implementation of new technology has on their current work. Gill (2002) states that one of the most powerful forces of resistance to change are emotional in nature. The new technology is compared to the old technology before and during the change. Changes in work related tasks may take the individuals out of their comfort zone, which often causes resistance or inertia towards the change. Becker (2010) suggests that besides effective communication, employees should be involved in planning and implementing the change. If employees can influence on the change and their opinions are listened, their feelings and expectations to change might become more positive.

Positive experience and informal support is the third individual factor, which refers to the encounters of the individual during the change and unlearning process. As argued by Becker (2010), this factor refers more to the informal support and experience employees receive informally from other colleagues, their manager or supervisors. Encouraging positive outlook also by informal ways further encourages unlearning (Becker 2010). For instance, if employees can see and hear that managers and supervisors see the new technology as an improvement compared to present methods, their belief is also affected positively. Indeed, top management's commitment to change is evident (Gill 2002). However, it should be noted that this also works in the other direction; if the change is seen as 'another management fad', it would likely decrease the level change acceptance and unlearning (Becker 2010).

The fourth individual factor is *understanding the need for change*. This refers to the need to reinforce the need for change after the new technology has been implemented. Often the emphasis is to communicate the need for change before the actual change process, which should be reinforced after the implementation. This could be done by showing explicit results of the new technology's benefits and comparing these results with the old system and methods. If these positive outcomes are communicated to employees, it might help the unlearning process. (Becker 2010)

Fifth and the final individual factor is *assessment of the new way*, which relates to the employee's personal feeling and evaluation of the new technology after the implementation. It is the personal opinion the employee has whether the new system is better or worse than the old one. It is important to acknowledge that this comparison is an ongoing process after the implementation. Employees should be able to share their thoughts and hear others' opinions in return. In optimal situation the widespread positive outcomes demonstrate the potential benefits to those who are having short-time difficulties due to the recent change. (Becker 2010)

The first of the two organizational factors is *history of organizational change*, which relates to the previous change the organisation has undergone during the past and how well the change has been executed (Becker 2010). According to Becker (2010), this factor represents a significant challenge on those who are responsible for the change, particularly in a case where change has been poorly managed by the organization in the past causing reluctance among employees to unlearn. Indeed, poor management of change often causes change programmes to fail (Gill 2002). The past cannot be changed, but by acknowledging those mistakes, can help to manage the change better in the future. Becker (2010) further argues that no change is better than poorly managed and executed change, when considering the future of the organization. Thus, change should be well planned and organized; otherwise the result is probable failure.

The second organizational factor by Becker (2010) is *organizational support and training*, which basically relates to the information sessions, training sessions and documentation instructions addressed to the employees regarding the processes and procedures of the new system or technology. Relevant, practical and timely training can facilitate employees’ unlearning process (Becker 2010). However, it is important to notice that the support and training should not only concern the new technology, but it should also include instructions and guidance that takes the old technology into account. Creating a connection between the old and the new technology is important, since it can facilitate the overall unlearning process (Becker 2010).

4. CURRENT STATE ANALYSIS

Current state analysis of the case company aims to examine the case company’s current product development process. The focus is in product update projects, early phases of product development projects, and design review activities. Qualitative interviews were performed to analyse the product development process and communication channels between different stakeholders inside the case company in the context of early design phases, design reviews and prototyping. This will provide valuable information for the VP implementation method development.

Interviewees included design engineers, a cabin design engineer, a production development manager, a production system manager, and project managers. In addition, methods engineers responsible for designing the productive processes e.g. welding, assembly, and machining were also included as interviewees to represent workers and their work tasks, since they have deeper understanding regarding the manufacturing methods, machinery, and their capabilities and limitations. Furthermore, methods engineers are an important link considering the communication and information flow between design engineers and production workers. 10 individuals were interviewed in total during the interview sessions.

The interviews were started by questions about the overall communication between design engineers and production department. Secondly, interviewees were asked to tell about the case company’s design review customs. More specific questions were posed to acquire more knowledge about the design reviews, their strengths and weak points. Practical examples acted as conversation openers, and they also gave more freedom and room for the interviewees’ own opinions. Next, additional questions were asked about the development direction an interviewee would like design reviews to develop in the future. Agenda, timetable, frequency and goals of optimal design reviews were inquired in order to figure out guidelines for design reviews including VP. Possible comments and visions about utilizing VP in design reviews were also charted after a short introduction of VR technologies and VP. The interviews lasted approximately 40 minutes each, ranging from 20 to 80 minutes. The interview framework is shown in Finnish in Appendix 1.

4.1 Product development process

The case company’s product development process was the first thing to be researched and analysed in order to understand the case company’s individual workflow and help to discover possible implementation targets and methods for VP later during the research. It was conducted that the case company's product development process resembles the process presented by Ulrich & Eppinger (2008) introduced in Chapter 3.1.1. The generic product development process of the case company is shown in Figure 18**Error! Reference source not found.**.

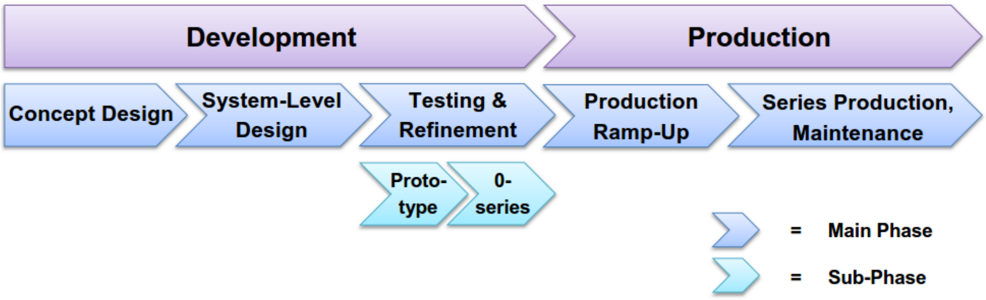

Figure 18. *The case company's generic product development process, adapted from (Kekkonen 2015).*

The process starts by analysing the needs of current markets in order to discover possible product concept ideas. Product should serve the needs of one or several customer segments. Without proper target market analysis, new products and product updates might fail to deliver customer satisfaction, leading to unsatisfying sales numbers and other harmful side-effects. Hence, the planning phase is also a vital phase for the case company, even though it is not visualized in Figure 18. Overall, the first tasks of a new product development project resembles Ulrich's & Eppinger's (2008) phase 0**Error! Reference source not found.**.

The actual development stage starts with concept design phase as visualized in Figure 18. Current items and modules that could be used and new ones to be designed are discussed in order to plan the conceptual design of the product. In product update projects an existing product is developed by adding new features, improving or replacing older features, or by doing face-lift -related changes. Thus, the existing product can be utilized to provide the main component layout structure for the product update project. In this case the design team would already have a basic frame to start with, which would ease the workload during concept design phase.

In system-level design phase the concept chosen during the concept design phase is designed in detail, keeping prototype fabrication in mind. The shift from concept design to system-level design phase is very similar as the shift from phase 1 to phase 2 by Ulrich & Eppinger (2008). As the planning proceeds, detailed drawings and 3D models are engineered (e.g. product structure, modules, module combinations and interfaces, subassemblies, and modules). Tool planning, production phase planning, jig planning, quality plan preparation, and investment clearings regarding new production machinery and equipment needed to produce certain features are also essential tasks during this phase. One of the main goals of system-level design phase is to produce the required plans, documents, and other supportive elements for the first physical prototype fabrication (Huhtala & Ruohomäki 2014). Hence, the system-level design phase at the case company includes both system-level and detail design phases by Ulrich's & Eppinger's product development process presented in Chapter 3.1.1. This is quite normal, since due to CE and simultaneous product development, different modules, items, and structures are designed simultaneously. This makes it is hard to distinguish the two phases from each other.

Testing & refinement phase of the case company resembles Ulrich's & Eppinger's phase 4, which is also called as testing and refinement phase. The phase is divided to two sub-phases, which are prototype and 0-series phase. During the prototype phase the case company fabricates the first complete physical prototype of the product. If the upcoming product is very complex, or it has a significant amount of new or renewed structures and items, the company might manufacture more prototypes than one. The prototype is manufactured to ensure it can be manufactured with current manufacturing methods and assembled in planned assembly order, both without any significant problems. The full physical prototype is also used to test the performance of the product.

The testing & refinement phase has also room for the iterative product development process by Bordegoni (2011); the company can prototype smaller entities of the product to make sure they can be fabricated without critical problems. Hence, prototypes can sometimes be only a part of the final product, for example a crane or a front frame of a forest machine's body. The functionality can be evaluated by installing these prototypes into older machines and dummy-structures. Items and subassemblies of the product are tested with the prototype considering their quality, manufacturability, and assembly properties. Prototyping at the case company is aimed to eliminate all the possible design errors and inconsistencies before taking the design into following phases.

Production workers evaluate physical prototypes' manufacturability, assembly properties, and service properties during the fabrication process. As stated before, the fabrication of the first full physical prototype is an important activity; it provides information regarding the current readiness degree of the product as well as current state of the design in terms of manufacturability and assembly properties. Based on observations and ECRs reported during the fabrication of the prototype, changes and corrections are made into the original design by taking the design again to the system-level design phase and collaboratively finding the best possible solution to overcome each and every reported problem. The changes can include for example assembly order changes for better assembly properties, geometrical changes to specific items to ease their fabrication or to fit better to the assembly, or material/fabrication method changes (e.g. flame cut vs casted part). If possible, the changes in the design are also implemented in the prototype which was built earlier. This makes sure that the physical prototype represents the current design state of the product.

After the physical prototype is finished and possible changes noticed during the fabrication of the prototype are made to its design, the prototype is taken to field testing to evaluate its functionality in its working environment. For example, it is essential for a forest machine to test it on an uneven surface to evaluate stability while performing cutting actions and other movements. This field testing contributes to the overall iterative design process, and it is a good place for the user of the forest machine to contribute to the design of the machine by giving feedback to the designers. A test report is conducted based on the field tests in order to document the performance, observations, and change needs considering the current design.

Manufacturing of the 0-series follows the fabrication of the first prototypes after the required changes are made to the design of the product. The 0-series -machines are complete machines, which are used to test the product more thoroughly in its working environment. The idea is to collect information about the performance of the machine and point out strengths and development needs of the current design, which will further help to tweak and improve the current design even more before production ramp-up. In addition, same aspects that were evaluated during the fabrication of the prototypes are evaluated: manufacturability, assembly properties, workload balancing between work stages, and overall performance of the machine.

Final accessories needed during series manufacturing are finalized, work instructions are made and workers are trained, which all aim at the series production and ramp-up of the production. Since the products of the case company are complex machines with low volume production and high customization possibilities, the role of physical prototypes, also known as PMUs, is significant. In conclusion, both physical prototypes and 0-series machines play an important role in the product development process and CE activities.

The development stage is followed by production stage, which includes production ramp-up and series production & maintenance phases. The former is also included in the product development process by Ulrich & Eppinger (2008). Once the development of the product is finished, the series production of the product can finally be launched gradually. Product development process ends to the series production & maintenance phase, as the production of the new product is ramped-up and series production and maintenance activities are working at full capacity.

Even though the product development process is described with clear sequential phases in Figure 18, the true process is more concurrent and iterative because of the complexity of products the case company develops. The process resembles the simultaneous product development process by Kamrani & Nasr (2010) introduced in Chapter 3.1.1, since designing and testing of different features is done simultaneously. This means that the prototyping sub-phase can sometimes be started already during earlier development phases, even though it is not visualized in Figure 18. Hence, CE and simultaneous product development are already familiar modes for the case company. This is beneficial from VP implementation point of view, because CE and simultaneous product development are indispensable requirements for efficient VP utilization.

4.2 Design reviews

Throughout the development process, regular design reviews (also called as project meetings inside the case company) are held regularly at the case company, representing the formal communication form. Design reviews include participants from different functional departments, for example design engineers, methods engineers, sales representatives, procurement representatives, and managers, such as product, quality, and project managers. Traditionally these regular design reviews do not include production workers, since their perspective is represented by methods engineers.

As presented in Chapter 3.1.4, design reviews are intended to provide information about the current design situation, help to evaluate the current design, and highlight possible features and functions in the design that need to be changed. Design reviews are useful places for the case company to tackle design problems by concurrent and collaborative engineering. Design review participants have an opportunity to comment on the design and give suggestions to improve different aspects of the product, such as material properties, clearance between specific modules, manufacturability, assembly properties, and human factors & ergonomics based on their own expertise.

One of the interview topics was to figure out the current design review customs of the case company. Based on the interviews, the fundamental features and activities of current design review practices with their strengths and weaknesses are aggregated into Table 2.

Table 2. *Strengths and room for improvement regarding the case company's current design review practices.*

Features and activities	Strengths	Room for improvement
Design reviews are held regularly to facilitate project management and collaboration between different functional stakeholders.	▪ Regular information about the current state of the project ▪ The schedule of the project remains clear to all participants	▪ Smaller design reviews to tackle more specific problems would be appreciated
Product design is reviewed from multiple angles of expertise during a same design review.	▪ The big picture becomes more clear to everybody involved ▪ Chance to speak out and present own opinions and concerns	▪ Discussion may sometimes drift into topics that concerns only a part of the review board, e.g. weldability

Design reviews work as a communication channel between different departments of expertise in order to tackle different design problems	▪ Enables bidirectional commenting and evaluation of the design ▪ Responsibility to tackle specific design problems can be shared ▪ Task scheduling by design reviews possible	▪ Design reviews were hoped to be a bit more guided and structured to avoid drifting from the topic ▪ Assertiveness and clearer definition of responsibilities would make design reviews better off
During early phases of product development process a product is reviewed by utilizing 3D CAD software Solidworks in design reviews.	▪ 3D models can be utilized as such straight from the design table ▪ Diverse selection of design tools is available (section cut, hide/show item, measurement tool etc.)	▪ Some product features are hard to evaluate based on 3D model shown in 2D screen (e.g. scale, assembly properties) ▪ Heavy assemblies take time to open and do not always run smoothly ▪ Full 3D models cannot always be evaluated, since all the parts are not necessarily modelled during the early design phases
Maximum of 20 stakeholders with different expertise participate in design reviews.	▪ Great amount of tacit knowledge available	▪ Methods engineers should be more involved already during the early phases of development to evaluate manufacturability and assembly properties ▪ Sometimes only a small group participates to the discussions
1-2 hours is a normal duration for a design review.	▪ Considered as a suitable length	▪ Shorter meetings to tackle more specific problems in smaller groups before the actual design review could increase the efficiency
A meeting memo is done by the project manager to document the activities and decisions made in a design review.	▪ Flexible and not too bureaucratic	▪ Occasionally the documentation could be more extensive

Design reviews are a vital part of the case company's product development process. Their most important function stated by interviewees is the schedule tracking of the product development project. Design reviews are designed to perform as regular meetings between product development team members, usually including design engineers, methods engineers, and upper managers. Overall, design reviews are stated to be useful among the interviewees; good features of the case company's current design reviews are listed under strengths -column in Table 2**Error! Reference source not found.**. However, interviewees also mentioned some features regarding these design reviews that could be improved, which are listed under the room for improvement -column in Table 2**Error! Reference source not found.**.

Project manager is traditionally responsible for leading the conversation during the design reviews by guiding the conversation and presenting discussion topics. In general, the current design reviews have an agenda; during each design review, features of the reviewed product that need further observation or changes are listed, and responsibility is divided among the participants to correct these features until the next design review. These listed features are examined in the next meeting to make sure all the possible problems are solved, or how their change process is proceeding if they are not finished.

Clearer goals and more assertive structuring were desired features by half of the interviewees to make current design reviews more efficient. However, a majority of the interviewees noticed that too bureaucratic practices would complicate and slow down the overall development process. Thus, a balance between these two ends should be found in order to make design reviews more efficient. The design review chairman is responsible for controlling these meetings in order to keep the discussion on-going and in the topic, while making sure that all matters under discussion were examined.

3D CAD software as a visualisation tool was also stated to have its strengths and weaknesses. As items, modules and subassemblies are designed in 3D CAD software, they can be presented quite flexibly straight from the design table. 3D CAD software Solidworks utilized by the case company has multiple functionalities and tools to modify and visualize the current product design by a digital mock-up. These tools include e.g. section cut, hide/show function for specific items and subassemblies, and measurement tools for distance measurements. Hence, as a design and communication tool for design engineers, the 3D CAD software seems to work quite well.

On the other hand, the software itself was stated to be sometimes quite heavy for reviewing purposes; to review a large assembly or multiple subassemblies simultaneously, these modules and items must be invoked, which can take some time depending on the complexity of the invoked entities. Thus, the reviewing agenda has to be well defined to make sure that the right modules, subassemblies and items are invoked to support efficient design review. Furthermore, complete product assemblies with all the items and modules being invoked is not running very smoothly, since every detail in the product is included. The product under review can be controlled by rotating, zooming, and flipping it, but getting it to the right position for inspection can take some time. 3D CAD software is essentially design software, which is not optimized for reviewing purposes.

In addition, some features of the design were stated to be hard to evaluate by 3D CAD software, which provides 2D projection of a 3D model. These features include size and scale properties, assembly properties and housings, such as hydraulic housings. It was specified by design and methods engineers that imagining the model in 3D based on the 2D image on the screen was quite easy for them, since they were familiar with the model. This is supported by the same observation made at Valtra (Piippo et al. 2015). It was argued by the interviewees that problems may easily arise in situations where a production worker, who is not familiar with engineering tools (e.g. 3D CAD software), has to evaluate certain features, for instance space requirements and ergonomics regarding the assembly phase. It turned out that sometimes as production workers are occasionally invited to the design department to comment on a certain feature of a product based on the 3D CAD presentation, they do not convey their concerns, opinions or suggestions to design engineers and other participants.

One possible reason for this is that the assembly is quite hard to evaluate, since the 3D CAD is not as visual and graspable as the physical prototype from assembly worker’s point of view. In addition, if some items and modules are missing, imagining them as parts of the whole assembly does not make the evaluation any easier. This easily leads to a situation where workers will not comment on the current assembly based on the 2D projection of a 3D CAD model, since the visual information is inadequate for them.

It has been argued in the literature sited by Bassanino et al. (2014) that 3D CAD has its limitations regarding the facilitation of multi-functional collaboration, since collaborative and multi-disciplinary design requires additional support to provide an integrated platform for all the stakeholders. Typical 3D CAD software does not necessarily allow design teams to combine their design data in such way which would allow design options’, changes’ and optimisations’ exploration (Bassanino et al. 2014). In this case the greatest challenge seems to be the collaboration and communication between production workers and design department. Design engineers can utilize engineering tools for communication, whereas production workers don not utilize such tools. This makes production workers’ participation in design evaluation harder. Furthermore, as production workers are used to evaluate the design while fabricating it, trial and error -like actions are important for evaluating manufacturability and assembly properties. However, 3D CAD software does not support this kind of evaluation from production workers’ point of view.

Smaller meetings were suggested by 3 interviewees to tackle more specific problems, which do not concern all the participants. However, recap design reviews with larger groups would support these smaller meetings, as these design reviews could recap all the problems, suggestions and decisions made in the smaller meetings. In addition, participants would have more space in the smaller meetings to bring up ideas when compared to larger design reviews, where the loudest participants are usually given the floor. Current level of documentation was seen adequate by most interviewees, although some stated that more thorough documentation would do no harm. It was agreed by the interviewees that decisions should be able to conduct afterwards based on the documentation. Thus, it should be consistent and well structured.

Overall, the current design reviews were argued to suit quite well in their purpose regardless of the minor problems presented earlier. All the interviewees regarded these design reviews as important and vital part of product development projects. Design reviews help to coordinate and schedule work tasks during product development projects, while keeping all the participants up to date regarding the current design state of the product. The major development target regarding design reviews is the involvement of production workers in a way that would allow intuitive evaluation of manufacturability and assembly properties from production worker’s point of view. It is worth noticing that major part of the design activities and communication between different stakeholders take place between design reviews, referring to the informal communication between different stakeholders. This informal communication is elaborated in the following chapter.

4.3 Information and communication flows

The case company has concentrated most of its research & development and manufacturing & assembly activities in one location. This brings many advantages regarding the communication between different departments, since different stakeholders responsible for the product during different lifecycle phases of the product can communicate daily face-to-face with each other. Design reviews, project meetings and other collaborative activities are rather easy to arrange, even on a short notice. Different design teams are responsible for different sections of the product, and project meetings and design reviews are a way to organize this work and lead the collective of team towards common goal.

PDM system is utilized to control information flows regarding the product: its structure, items and their revisions. In addition, formal feedback from production to design department regarding features, problems and notifications concerning the product-in-development is done by engineering change requests (ECRs) and also during design reviews. However, it was stated by one of the interviewees that not all the ECRs and other suggestions made by production workers during manufacturing of the first prototype make it to the 0-series, which can cause extra work during the 0-series fabrication. This is a very common problem among companies designing as complex products as forest machines, which is mainly caused by the strict timetables and item order schedules.

For instance, during the fabrication of the first prototype, design errors and inconsistencies regarding manufacturability or assembly properties are noticed. ECR is done to prevent the error happening again during later phases of the product development project. However, since the timetable is tight and some items take a significant amount of time to manufacture, items that are affected by the ECR may have already been ordered in advance to keep up with the schedule. Hence, sometimes there is no possibility to change orders regarding them, since their manufacturing process has already begun or they are already being delivered from a subcontractor.

To avoid repeating the same errors again during later phases, ECRs and other changes should be done before ordering the parts that are included in the upcoming 0-series product. However, this can cause significant delays in the product development schedule, if ordering the next batch of the items is delayed until no more ECRs come up. Hence, these changes should be striven to be done earlier during the development process. This would give more time to the design engineers to react on the changes, leading to higher readiness degree of the product during the time when the manufacturing documents of the product are prepared for fabrication of the first physical prototype. Earlier detection of design errors and inconsistencies would require earlier evaluation of manufacturability and assembly properties. As noted before, this is problematic by utilizing only 3D CAD software, since production workers do not convey their concerns easily based on the visual presentation of such software.

In addition to design reviews and other formal project meetings, design engineers and production department communicate by unstructured communication channels as noted previously. For example, during early design phases, when physical prototypes could not yet be manufactured, a design engineer can invite a representative from the production line to evaluate the current design by showing it with 3D CAD software (e.g. Solidworks). This way the design engineer can receive comments and development suggestions regarding the product to make it easier to fabricate. This communication works also in the opposite direction; if there arises problems regarding the manufacturability and assembly properties during testing and refinement phase of a product, a design engineer responsible for designing the part/module of the product causing the problem can be invited to the factory floor to inspect the problem with production workers. The problem can be discussed and solutions can be developed together to make the fabrication easier the next time.

However, this informal communication has two major downsides. The first one concerns the documentation of these informal meetings. Since face-to-face communication is used, problems and decisions are not necessarily documented in any way, or at least there are no requirements to do so. This easily leads to a situation where the information and knowledge stays tacit among the peoples involved noticing, reporting and correcting design faults. Design engineers who corrected the fault in product design might remember to avoid repeating the same mistake in the future. This might also be the case with their colleagues, if the information is shared viva voce. However, without proper documentation there exists a risk that the mistake is repeated by a new design engineer, or even by one of the existing engineers, who has forgotten why the change had to be done in the first place. Hence, as argued by Riege & Zulpo (2007), this knowledge should be codified in order to create value from received information. This might be the case even if there exists documentation about the changes, but which are unstructured or defective, and thus will not facilitate learning (Matta et al. 2013).

The second downside is the difference between design engineers’ habits regarding their use of initiative to figure out design dilemmas with production workers and their foremen. Multiple interviewees concluded that ‘it [communication] depends highly on the person you are dealing with’. Since this informal communication is not obligatory, some do not utilize it as much as others. This is due to the fact that every design engineer and product developer has a unique way of working (Ottosson 2002). For example, a part of the design engineering team might want to validate the current design of the product by reviewing it together with representatives from manufacturing and assembly departments, while the rest trust themselves and the feedback loop provided by the company’s product data management (PDM) tools.

Based on the interviews, the informal communication and ability to take initiative to ask for feedback about the design decisions was argued to be extremely helpful and appreciated from design and methods engineers’ point of view. On the other hand, if design engineers would be constantly asking comments and improvement suggestions from the production representatives, it would set more challenges on keeping up with the overall project schedule. However, if communication during early design phases helps to eliminate errors that would cause problems during the upcoming product lifecycle, the overall cost saving would become bigger. This is due to the fact that once a change is done later in the product development process, its overall cost is substantially higher than the cost of the early change (IEC 61160 2005). Thus, a common platform for efficient communication arranged at specific times during product development projects could help the overall communication and early detection of inconsistencies and design optimization needs. Finally, it could lead to shorter product development projects and thus, decreased overall costs. This kind of communication platform was also suggested by Riege & Zulpo (2007).

4.4 Selecting the target application for virtual prototyping

The basic principle and benefits of VR technologies were introduced to the interviewees during the interviews. Majority of the interviewees were looking forward to see the technology in action with their own 3D CAD product model as a virtual prototype. However, many of the interviewees also doubted the benefits of the technology; it was questioned whether the technology would bring any value for users familiar with 3D CAD software, since those users are used to view the product as a 3D geometry from 2D screen.

The interviewees also were inquired about the possible application targets for VP after the key benefits of the technology were introduced to them. Several suggestions came up, including welding clearance and jig testing, assembly properties, assembly clearance, assembly variations, assembly instructions and training, assembly order phasing and line balancing, and maintainability reviews. As can be noticed, most of the proposals are assembly related; it was argued that assembly planning would be a good implementation target, since it is one of the most challenging tasks to evaluate during design phases. It was stated that although many features and functions of the product could already be simulated by using CAD/CAM software, evaluation of assembly properties contains more manual work tasks, which are hard to simulate by CAD/CAM software. It was also conjectured that VR applications would be most beneficial in situations, where the knowledge and opinions of assembly workers could be utilized in order to make sure the assembly order is acceptable and different module combinations could be assembled within the current facilities and production systems.

One of the major problems between the collaboration between engineers and production is related to the feedback collecting from assembly workers. As design engineers review the assembly with assembly workers, the aim is to acquire comments and approval regarding multiple properties regarding the assembly and different factors related to it. However, it was stated that the assembly workers participating in design reviews hardly comment on the assembly. There might be several reasons to this. Firstly, the agenda of current design reviews might not support the involvement assembly workers, since the product is reviewed from design engineering point of view rather than the assembly point of view. Secondly, even though assembly workers would be involved and the product was reviewed from assembly point of view, they are usually involved not until the design is almost finished. In these situations most items cannot be changed even though there arises some inconsistencies and optimization needs, since they are already being ordered.

Other reasons are related to the 3D CAD software as a visualization tool. The 3D CAD assembly review might lack a consistent structure, which would take care of that every item and aspect is considered. In addition, a 3D CAD assembly presented as a 2D image might have its limitations regarding the visual information it provides especially to the assembly workers not familiar with a CAD-generated image without stereoscopic effect. Furthermore, assembly workers do not have the ability to explore the design freely, since the 3D CAD assembly is operated by design engineers. This makes the evaluation of the design regarding assembly properties even harder. CAD software does not provide an integrated platform for production workers’ and design engineers’ collaboration.

Thus, a more practical prototype of the assembly should be utilized in this case to make the situation even more realistic in order to receive more comments from the production workers. For example, tools like ratchets and wrenches should be included in the VE along with the virtual prototype. They could be used to evaluate assembly clearances and ergonomics during assembly tasks. If the production worker’s hands are tracked and animated in the VE, these tools and also the bare hands can be utilized to check clearances more intuitively. The production worker should be able utilize his/her experience and expertise in the VE as he/she could do in real working environment.

The case company builds forest machines to order; every finished product that comes out of the factory can have different module combination depending on the needs and preferences of the customer. However, due to limited resources, usually only a few module combination can be tested in the physical prototyping phase. It would be beneficial to test all the possible module combinations during the development phases in order to make sure that all the combinations are acceptable in terms of assembly clearance and order. This is also a promising target for VP utilization.

The problem with examining different module combinations with 3D CAD software is that there is no environment, which would present the restrictions regarding the surrounding assembly space. Also in this case, the stereoscopic image and user immersion provided by VP could be utilized to help discovering the limitations regarding different module combinations. By taking the actual assembly line environment to the VR system and making it as the VE, the virtual prototype of the assembly could be reviewed in its natural assembly environment. This could help the assembly workers to comment the assembly even more, but also help the designers to discover limitations of different module combinations, as the assembly environment takes better form also in their minds.

However, the assembly line environment was not available as a ready 3D CAD model, which meant that it could not be imported as VE. Furthermore, evaluation of all the different module combinations would be an interesting implementation target, but it would cause a significant amount of work, in terms of CAD-VR conversion. This is because the CAD-VR conversion is not automated in anyway, because the VP technology has never been implemented before. Hence, module combination evaluation is not the best first implementation target for VP, if the aim is to investigate the benefits the technology could offer to the case company.

The communication enhancement between design engineers and production department is one of the main research problems of this thesis. Thus, choosing a VP application connecting both of these stakeholders is clearly a logical decision; VP can bring benefits to design reviews between cross-functional engineers as can be conducted based on the application examples in Chapter 3.2.5. As the communication between engineers and production is the development target, a VP activity connecting these stakeholders should be chosen. Thus, assembly phase -specific evaluation of assembly properties collaboratively with assembly workers was chosen as the implementation target for VP. If the case company recognizes the benefits it could offer to them, the same benefits can be further expanded to module combination evaluation and assembly line environment, since the revolve around the same topic.

5. DEVELOPMENT AND IMPLEMENTATION

This chapter aims to describe the development process of the VR technologies' implementation method. A VP system suitable for the case study will be concluded and an implementation method to support the VP system is developed based on capabilities and requirements of the system. Conclusions are based on the literature review, examples found in the literature (see Chapter 3.2.5), observations, discussions and interviews made earlier during this research. Furthermore, the demonstration of the developed method is introduced and explained through in this chapter.

5.1 Choosing the suitable virtual prototyping system

In order that VP would be useful to the case company, it should support the transformation from customer needs and requirements into a complete system (Alanen et al. 2013). Thus, the magnitude of the system should meet the needs of the utilization target. The preferences of a suitable VR system are as follows:

- VR system output:
    - powerwall with active or passive 3D technology, or HMD supported with an extra 2D display;
- VR system input:
    - visual tracking of the user's head and hands;
    - intuitive controller for easy navigation and exploration.

These preferences are justified in the following paragraphs.

Multiple stakeholders are going to participate simultaneously in the evaluation of assembly properties. Thus, the output of the VR system should allow the system to be viewed by multiple users simultaneously. The first option is to provide a powerwall system, which is capable of presenting the virtual prototype in 1:1-scale. In this case all the participants can view the virtual prototype as a 3-dimensional model. The second option is to utilize HMD and a supportive 2D display. In this case the main user (e.g. the assembly worker) views the virtual prototype with the HMD, while the other participants can inspect the virtual prototype simultaneously from an external display. This way the main user can view and evaluate the virtual prototype as a 3-dimensional model, while the other participants can evaluate it from a normal display providing a 2D image.

The VR system should provide an immersion level that would facilitate the assembly task evaluation during different assembly phases. Hence, the user should be capable of moving around in VE and inspect the virtual prototype of the product from natural directions and positions. Furthermore, clearance evaluation is a key element in assembly evaluation, which requires motion sensors for user state and action tracking as input devices. Hence, user’s head and hands should be tracked in order to make the user feel more immersed in the VE. This would allow crouching as well as the ability to inspect and evaluate the assembly from natural angles. User’s hands should be tracked and further displayed in the VE when needed along with critical tools used during the assembly phases; this would allow the assembly worker to simulate specific assembly tasks and evaluate the clearance, accessibility, ergonomics, and safety factors while performing it. Along with visual user tracking, this kind of evaluation requires stereoscopic image, which provides a full-scale image of the reviewed prototype. Thus, the low-immersive VR systems are excluded from the options.

Haptic cue rendering would increase the level of immersion provided by the VR system, but increase the complexity and price of the system substantially. The use of haptic sensors would make the leap towards VP implementation too ambitious, because today the haptic cue rendering technology is mainly limited on simple VEs. This limits complex forest machines and their accessories out. VR system without haptic cue rendering is cheaper, which can make the difference when it comes to the investment decision towards this technology. In addition, VR systems can be expanded afterwards, and haptic information could be implemented once the technology is matured enough to be used in more complex VEs. Once the VR system and its supporting methodologies are implemented into the product development process, the need for haptic cue rendering can be defined more accurately. The tasks that could benefit from haptic sensors and feedback can be discovered and jointly agreed before implementing haptic cue rendering. Thus, a semi-immersive system without haptic sensors and feedback is enough for the implementation target of the case study.

To facilitate better adoption and utilization of the VR system in the long term, it should be either built upon the existing 3D CAD software to support instant 3D model rendering, or the CAD-VR conversion should be automated as far as possible to shorten the optimization time to its bare minimum. This would also allow the flexible usage of the VR system. VR systems that can utilize 3D CAD models without conversion are scarce in the industry, whereas VR systems that need CAD-VR -conversion are easily available and highly customizable. It depends on the application target which one of the mentioned VR systems is the most suitable. From the point of view of this research, both of the alternatives can be utilized in the evaluation of assembly properties. As stated before, selecting a specific software and computer hardware is left out of the scope of this research.

Since VR system is going to be used by different stakeholders with different expertise, the system should be easy to learn and utilize even without any prior knowledge regarding it to facilitate fast learning, positive VR experience, and future utilization. The interface has to be simple enough; the manipulation of the virtual prototype and the VE should be as easy as possible; this would make the system easier to use by individuals not familiar with any kind of CAD software (e.g. production workers). A 3D-mouse would be a good option, since it can be operated by one hand while the other hand is left available. Another option is a controller used in gaming systems because of its good availability and familiarity. In this case, a gaming controller is chosen as a control interface between the user and the VR system. Gaming controller allows easy exploration of the virtual prototype due to console gaming -like controls and quick switching between assembly stages and steps.

5.2 Collaborative design review phasing

Since current regular design reviews were found functional during the interviews, they should not be changed, but supported by additional collaborative design reviews involving assembly workers to evaluate the assembly properties of the system. VP is used as a communication platform during these collaborative design reviews to support early involvement of different stakeholders and utilizing those stakeholders' tacit knowledge. The first task when developing the actual implementation method is to define the clear phases during the product development when these collaborative design reviews are conducted to be as beneficial as possible. The aim was to find the best phases for collaborative design reviews during concept design and system-level design phases, since during those phases there is the possibility to influence the product design before physical prototypes are being manufactured. Based on the literature review and the case company analysis, three vital points for collaborative design reviews utilizing VP were developed. These collaborative design reviews during the phases of a product update project are presented in Figure 19.

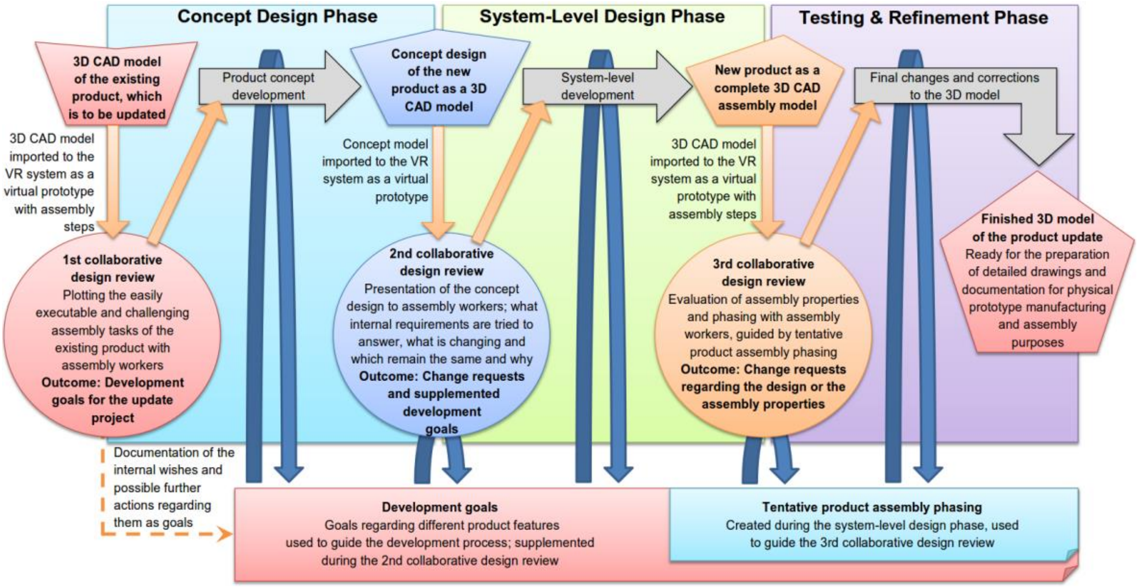

Figure 19. *Collaborative design reviews during development phases of a product update project.*

Each of the collaborative design reviews shown in Figure 19 are elaborated in the following paragraphs.

First collaborative design review

When a new product update project is started, the 3D CAD model of the current product provides the basic layout for the product update. It might change and develop already at the very beginning of the concept design phase, but it provides a good starting point for the whole development process. Since the product update project is all about updating the current product to meet the new customer requirements, it would be natural to consider also the requirements coming inside the company. These requirements and change requests are assembly, manufacturing, and service workers' and their foremen's observations regarding what could or should be done differently in order to make the product easier to fabricate and maintain. This kind of observations and change requests are made during the series production of the current product, and most of them are passed to the design department as ECRs and already corrected during the series production by changing item features by doing new revisions of them. However, the observations are, as the name suggests, mainly concentrated on changing the current design. It would be beneficial to also communicate about the good features related to the current product; the features that are good and should be kept the same during the product update project. Naturally, the project update project is a good place for the design engineers to rethink the design, manufacturability, assembly properties, and maintainability of the product. Thus, evaluation of the current product collaboratively with assembly workers would give the designers a possibility to see the problematic and good features of the current design from assembly worker's point of view.

The 1st collaborative design review is visualized as a red circle in Figure 19. By this collaborative design review timed at the beginning of the product update project, improvement suggestions could be collected from different stakeholders. These suggestions are documented as development goals for the upcoming development project along with new customer requirements to support CE. Furthermore, well-designed features regarding manufacturability, assembly properties, and maintainability of the current design could also be noted and documented for the upcoming development project as development goals; this would facilitate learning in design teams and ensure that the good solutions are retained if possible. Hence, the purpose of the 1st collaborative design review is to collect the best and the most challenging features of the current product regarding its assembly properties to be reformed as goals for the product update project. This is visualized with an orange dashed line in Figure 19. As stated in Chapter 3.1.2, clear goals facilitate cross-functional integration and communication between different stakeholders. When all the stakeholders have agreed upon the goals, those goals are pursued collaboratively.

The difference compared to past would be that the production workers would have a better chance to utilize and share their tacit knowledge; give suggestions and opinions regarding the current design of the product-in-development. This could also encourage the assembly workers and other possible stakeholders involved in the 1st collaborative design review to present their ideas and improvement suggestions. The assembly workers would have a chance to contribute to the product design by giving suggestions to make their own work tasks easier regarding the updated product. They could also be more eager to comment on the current design compared to past, since the virtual prototype would provide more immersive and intuitive experience compared to traditional 3D CAD models. As the analytical, virtual prototype is closer to reality, commenting and knowledge sharing before fabricating the physical prototype is enhanced. The assembly workers could contribute to the design of the upcoming product update already during the concept design phase. If this activity is well planned and supported by the whole organization, several additional errors could possibly be already eliminated during the concept level and system-level design phases. Once the assembly workers realise they have the ability to contribute to the overall design and make their work tasks easier to perform, communication may be enhanced.

Second collaborative design review

After the 1st collaborative design review the concept design phase is started. Development goals for internal requirements created during the 1st collaborative design review guide the concept design phase along with customer requirements. This is visualized by a blue arrow in Figure 19 (first from left). As a result, a concept design or designs are created, which all try to answer as many internal and external requirements as possible. Before taking the concept design into system-level design phase, the concept design is presented to assembly workers in 2nd collaborative design review, which is visualized with a blue circle in Figure 19. Since 3D CAD is used to sketch different concept designs already during the concept design phase, the concept designs are in suitable format to be utilized as virtual prototypes, even though the design is incomplete. While presenting the concept design of the product to the assembly workers, the design engineers could inform which of the internal and external requirements are tried to fulfil and which ones are not while further explaining the design decisions. Having a chance to see all the wishes that are tried to fulfil, assembly workers could realize that their comments regarding the old product have been taken into account. This could further enhance the communication in future product development projects.

The 2nd collaborative design review makes sure that the assembly workers are kept updated about the current state of the design. The internal requirements can be supplemented, as the assembly workers now have a better understanding of what to expect from the upcoming product update. In addition, even large changes to the design are possible, when they are made this early. These activities are visualized with a blue arrow (second from left) in Figure 19. Hence, the concept design is discussed through with the assembly workers to find any inconsistencies, troubles, or concerns regarding the design. The main features of the updated product are agreed before continuing to the system-level design phase. This makes the 2nd collaborative design review an important event for all the stakeholders to influence on these features before moving to the next phase.

Informal collaborative design review meetings

Once the concept design is finished the product update project moves to the system-level design phase. Development goals created during the 1st collaborative design review and further supplemented during the 2nd collaborative design review guide the development process, which is visualized as a blue arrow in Figure 19 (third from left). Due to simultaneous product development and CE different parts, structures, and modules are developed simultaneously during the design phases. The product-in-development is reviewed regularly in project meetings, taking care of congruence and scheduling of the design work. Even though manufacturability studies of single items and simple sub-assemblies can be conducted quite reliably by existing CAD/CAM software well before the physical prototype is manufactured, the assembly properties of the whole product are hard to evaluate in an adequate level. This is because some items, modules or features might be missing, since they have not been designed yet. As noted by one of the interviewees, this would make the evaluation of assembly properties of the entire product extremely difficult and unreliable. Thus, it is not possible to effectively evaluate the whole assembly process during the design process.

However, assembly properties of smaller aggregates could be evaluated by VP in collaborative design reviews to support traditional development process. Since smaller entities are under discussion, the collaborative design reviews can be more informal compared to the three other design reviews held during the product update project. All potentially challenging assemblies that would be tested by physical prototypes should be first evaluated by VP regarding their assembly properties to point out any inconsistencies or design optimization needs before the documentation and orders regarding the items included in the assembly are done and released into production. Even though these informal collaborative design reviews are designed to be held during the system-level design phase, their amount and timing are not specified. Hence, the responsibility is in the hands of design engineers and project managers to make sure that the assembly properties of the problematic modules are evaluated collaboratively utilizing assembly workers and methods engineers before preparing the manufacturing documents and passing the modules forward.

Third collaborative design review

Before preparing the detailed drawings and documents for the manufacturing of the first physical prototype, the assembly should be evaluated by VP in the 3rd collaborative design review, which is visualized as an orange circle in Figure 19. This 3rd collaborative design review is performed in the end of the system-level design phase, when the main items and modules are included in the 3D CAD model of the updated product. The assembly is inspected together with assembly workers to evaluate the current design, its assembly order, and possible problems that might come up during the assembly of the prototype.

During the system-level design phase a tentative product assembly phasing has been developed, including assembly steps and stages. The phasing is based on the development of the product update as well as the development goals created during earlier collaborative design reviews. From the evaluation point of view of assembly properties, this assembly phasing is in important position, because it provides the framework for the upcoming 3rd collaborative design review. The assembly order phasing guides the conversation topics; each assembly stage is examined sequentially to evaluate whether assembly workers recognize any problems with the product regarding its assembly properties. This is visualized by a blue arrow in Figure 19 (fourth from left).

Additional module combinations and variant configurations should also be tested during 3rd collaborative design review to make sure that even the most complicated assemblies can be assembled regarding clearances, assembly order and other aspects related to assembly properties. Practical, tacit knowledge of the assembly workers could be exploited to support and complete the knowledge provided by methods engineers. If any inconsistencies or optimization needs are discovered, possible solutions should be discussed collaboratively during the 3rd collaborative design review in order to find the best solutions for those issues. Once decisions regarding the inconsistencies and optimization needs are made, required changes are applied to the product design (visualized in Figure 19 by the last grey arrow from left).

3rd collaborative design review is repeated until the assembly properties of the virtual prototype are approved by methods engineers and assembly workers. Finally, the detailed drawings and documents can be prepared and the manufacturing of the first physical prototype can be started. This new feedback channel could help to catch inconsistencies and design errors. Persons responsible for assembling the product could inspect the assembly, assembly order, and different phases during it to check for any possible problems that might come up during the assembly before the product continues to the fabrication of the first physical prototype.

Implementation method overview

The phasing of the collaborative design reviews is shown in Figure 20.

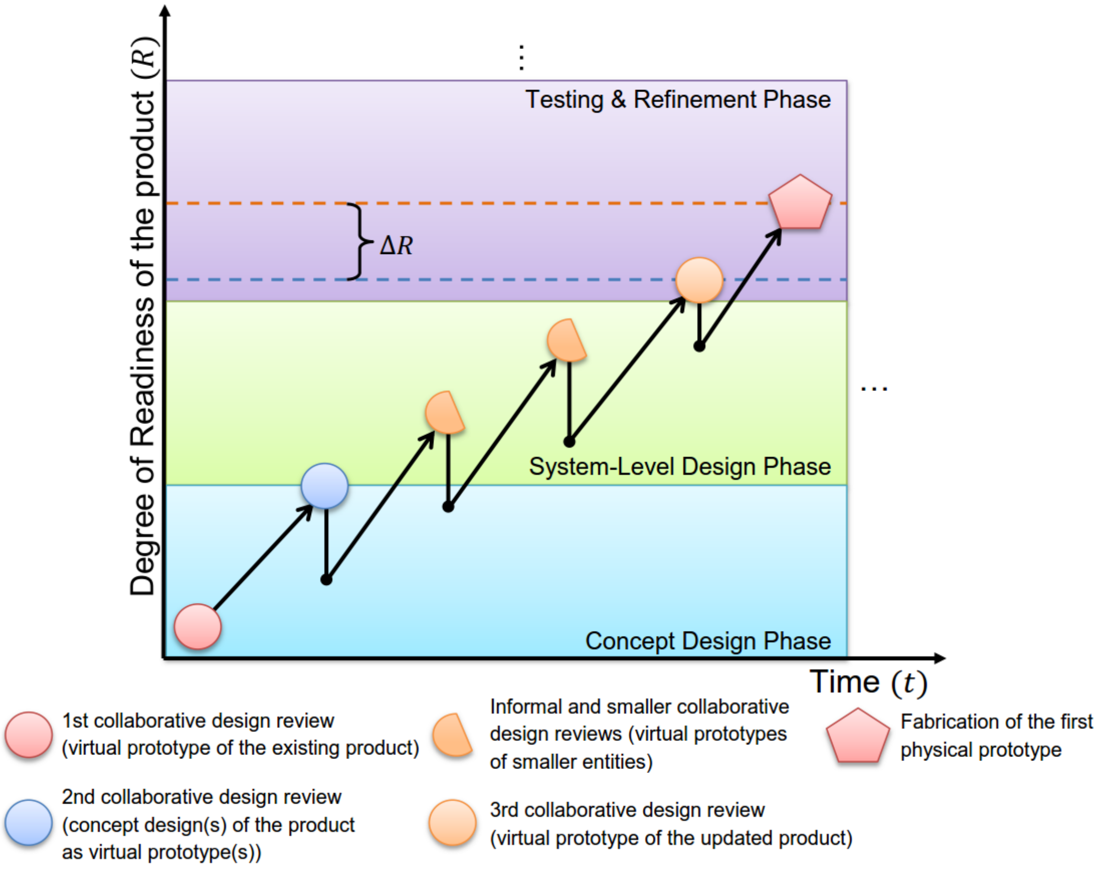

Figure 20. *Collaborative design review activities during a product update project.*

The vertical axis in Figure 20 describes the readiness degree of the product-in-development and horizontal axis describes time, known as R and t respectively. As shown in Figure 20, the product update project is started with the 1st collaborative design review of the existing product (the red circle) and followed by the 2nd collaborative design review between the concept and system-level design phases (the blue circle). Good features and features that could be improved are discussed, documented, and supplemented for further development as development goals during the first two collaborative design reviews. Assembly workers and methods engineers are included in both of these design reviews.

As the design process progresses, project meetings are continued, during which the core design stakeholders are involved. As modules and sub-assemblies are being designed, the most complicated ones should be checked regarding their assembly properties with assembly workers. The aim is to eliminate all the possible errors before preparing the manufacturing documentation and ordering the items, or releasing the modules and sub-assemblies into the production. These informal collaborative design reviews are illustrated by split circles in Figure 20. The back steps in Figure 20 regarding the degree of readiness result from the design errors and change needs noticed during the collaborative design reviews.

Once the system-level design phase is almost finished, the virtual prototype of the updated product is reviewed and evaluated again with assembly workers and methods engineers in the 3rd collaborative design review, which is visualized by an orange circle in Figure 20. Based on the observations regarding the assembly properties, possible inconsistencies in product design are corrected before final manufacturing documents are prepared in order to fabricate the first physical prototype of the product (visualized with a red pentagon in Figure 20).

In the current product development process, the first prototype is build earlier compared to the VP-implementing new process. However, there is a difference in the readiness degree between these two, known as ΔR. In practice, this means that while utilizing VP in product development process, the product design level is more ready, because more problems and inconsistencies are observed and reacted to before the first physical prototype is built. Thus, fewer changes have to be done after the physical prototype is manufactured at the first time, which would directly correlate to cost savings and faster ramp-up, since fewer items have to be re-designed, manufactured or ordered, and re-prototyped.

The informal and smaller collaborative design reviews shown in Figure 20 are not visualized in Figure 19, since there is no defined time or amount for these design reviews except the system-level design phase. Arranging three major collaborative design reviews according to Figure 19 and Figure 20, there is the possibility that they could be arranged in external location. As a first step towards VP utilization, this would be beneficial by multiple reasons; firstly, it is an opportunity to test and learn about utilizing VR technologies in product development process without any major investments. Secondly, users get to see their own assemblies in VE, and the benefits would become more concrete and visible to them. This is because they can get to know the technology while interacting with a familiar 3D model. VP testing in external location is also a chance to convince different stakeholders about the usefulness of the technology. Thirdly, the CAD-VR conversion could be optimized to support easier VP implementation and utilization in the future. Fourthly, while performing collaborative design reviews, company’s own needs and requirements evolve and become clearer, which would help while doing the possible investing calculations regarding the first own VR system. Finally, once the process is optimized, an external virtual laboratory could be even utilized in future's product update projects to measure and gain practical benefits regarding the implementation method.

If both the technology and implementation method are seen useful for the case company and the technology is seen to have potential benefits on other sectors during product development projects, a possible future goal would be a VP system owned by the case company located near both the R&D and production facilities. This would allow flexible utilization of the technology also during the system-level design phase. The system could be utilized to support collaboration, communication and overall product development, since the near location would make it available for utilization at all times. Along with assembly studies, the system could be utilized for instance in marketing, training and supply network activities to enhance these activities.

5.3 The structure and documentation of design reviews

As noted by the interviewees, current design reviews were hoped to be a bit more structured than before to facilitate efficient collaboration, progress, and decision making. In addition, as mentioned in Chapter 3.1.2, clear goals and guidelines help cross-functional integration and thus, CE. It was also noted that procedures and guidelines should be created in order to control the cross-functional collaboration to tackle the complexity related to it. As current design reviews can include up to 20 participants, it is vital to provide structured framework for the event to help the chairman of the collaborative design reviews to guide the conversation and to make sure that critical topics are talked through and possible observations are documented. When evaluating assembly properties, it is important to discuss all the possible critical assembly steps with assembly workers to ensure that every critical factor that could be evaluated is examined before taking the 3D assembly into physical prototyping phase.

Checklist approach came up with 3 interviewees; the list would include the most important and critical features in the design, which should be discussed during the virtual assembly simulation. To avoid clumsy bureaucracy, the list should be condensed into a few bullet points, which would cover all the necessary topics. One of the challenges of the checklist approach was argued to be the high amount of possible product variations in the case company's production, which would make the checklist construction more complicated. However, it is safe to say that conducting the checklist with a couple of vital topics for discussion is better than an unstructured design review, which relies on the participants' own initiation to bring up all the relevant topics. In both cases there can be left some room for open discussion. In addition, the checklist can be further expanded and individualized as the stakeholders of collaborative design reviews come up with topics which are discussed in these design reviews regularly, but are not yet in the checklist.

The case company has envisioned and tested a checklist approach in design reviews regarding earlier product development projects. In their list, the approach is done from assembly phase -point of view; each assembly phase is listed, and every item installed during that assembly phase is listed under it to cover up all the items, modules and sub-assemblies. The assembly is examined item by item while examining the assembly-in-construction with 3D CAD software. The list is boarded as follows:

- Assembly stage 1
    - Module 1
    - Item 1
- Assembly stage 2
    - Item 2
    - Item 3
    - Module 2
- Assembly stage 3
    - Module 3
    - Module 4

This list should be used to guide the conversation during the collaborative design reviews. In the 1st collaborative design review the assembly phasing of the existing product is used as a structure for the design review and as a documentation template. This makes sure that all the different modules and items are examined. It also ensures that the development goals are connected to the assembly phasing of the existing product to help understanding the product in the right context. The same documented assembly phasing list is also used in 2nd collaborative design review to guide the event and to check which of the goals can be achieved. During system-level design phase a tentative assembly phasing list is produced, which is used and optimized in the 3rd collaborative design review in the same way; each assembly step is talked through and possible observations are documented using the assembly phasing list as a template. Different assembly orders can also be tested to find the most reasonable assembly order. Pictures, such as 2D-screenshots of the situation under discussion could be provided to support the documentation. The level of extra work is reasonable, but the written media is enriched. This enriched information would facilitate the indirect communication and hence the overall interaction between stakeholders.

A supplementing sub-list could be used to support thorough evaluation of the whole assembly. The sub-list could include the five following points:

- collision inspection;
- assembly order;
- assembly clearance and ergonomics;
- hose routing and mounting clearance;
- screw hole alignment.

As new items and modules are being installed in the current assembly, it is important to evaluate whether there exists any collisions. Thus, collision inspection would be a good starting point for the checklist examination. Collision inspection could be followed by assembly order examination, which is also a vital subject when evaluating the assembly. Assembly order examination is done to make sure that that all the parts can be assembled in the designed order. Sometimes assembly orders have to be changed, because some other item is blocks the installation of the next item in order. Figure 22 depicts collision between two items (left figure) and the principle of assembly order examination (right figure).

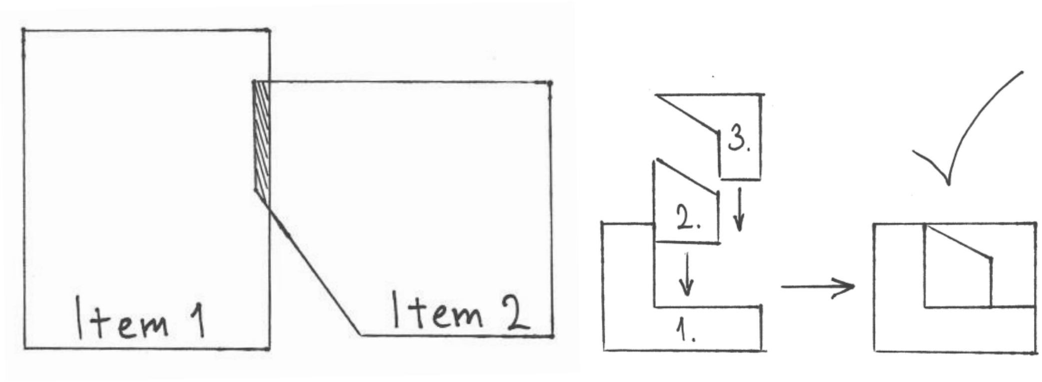

Figure 21. *Collision detection and assembly order examination.*

In the left figure of Figure 22, collision between items 1 and 2 is visualized with a darker area. This kind of collisions should naturally be avoided, since they cause problems when fabricating the product physically. Acceptable assembly order of a simple assembly is shown in the right figure of Figure 22. If the item 3 was installed before the item 2, the item 3 would block the item 2 to be installed from the same direction. Unnoticed problems with the assembly order can lead to costly iteration during physical prototyping or even more expensive ECRs, if the assembly order mistakes are noticed not until during the ramp-up of the product.

Once observations regarding the assembly order are made, the clearance and ergonomics of different assembly tasks should be evaluated extensively enough. Hose routing clearance is made separate from the assembly clearance, as it requires more attention, since hoses are extremely hard to simulate in 3D CAD environment. Screw hole alignment would be the last point on the checklist; it is important to inspect all the possible holes twice before releasing the design into manufacturing document preparation, since screw holes can easily be misplaced while the design develops.

Consistency of the documentation is eligible, and should be implemented to the feedback loop of the VR system presented in Chapter 3.3.2. The assembly phasing list presented earlier should be used as a documentation template in collaborative design reviews, since it is already structured according the assembly order. The sub-level list could also be used to further categorize the observations made while examining the virtual prototype in VE. Observations, change requests and other remarks are written down in the documentation template, and supportive screenshots can be added to describe the situation even better.

5.4 Case study regarding the implementation method

Different possible products of the case company were compared to each other in order to find the most interesting implementation target. In addition to forest machines, the case company also manufactures harvester heads and cranes for individual use. During the research it was found out that even though harvester heads and cranes are important parts of the forest machine, their complexity is significantly lower compared to the actual forest machines. Harvester heads and cranes require less development resources, since they are significantly smaller aggregates than a whole forest machine. Thus, the design task regarding harvester heads and cranes is much easier compared to a forest machine, and there is less need for a VP system. Hence, a forest machine was chosen as the demonstration target, since it represents the more challenging design tasks inside the case company. Since the case company had one ongoing forest machine update project in motion, there appeared a chance to demonstrate the technology in a real product development project.

5.4.1 Collaborative design review implementation

The case company had already once tested a design review during one product update project, which involved assembly workers to evaluate the assembly properties of a certain product during its development. Since an ongoing product update project was in motion, there was an opportunity to test and evaluate the new design review method in it. The product update project had already undergone the concept level and most of the system-level design phases, but no physical prototype had yet been built. This meant that the 3rd collaborative design review presented in Figure 19 could be tested and evaluated by the stakeholders.

The collaborative design review including design engineers, methods engineers, production and production manager and production workers was arranged in January 2016 at the case company’s premises. A project manager acted as the chairman of the design review, controlling the discussion and guiding the flow of topics. The product under review was the same that was intended to be reviewed in VR system later on. The first 4 assembly stages were examined in detail during this review. Simple assembly phasing list with 4 assembly stages and assembly steps guided the design review, while the actual product was reviewed by utilizing Solidworks 3D CAD software. Production workers along with other participants were able to comment on the current product and reveal their thoughts and possible concerns regarding it. The product was analysed by examining each assembly step at a time. Once comments and remarks came up, they were documented along with further actions by a project manager. Screenshots were also used to illustrate some of the topics better. The documentation was shared with the participants and other important stakeholders via PLM system. The design review took approximately 2 hours with a 15 minute break in the middle of the event.

5.4.2 Demonstration of virtual prototyping

To evaluate the assembly properties of the product by VP, the same product used in the collaborative design review described in previous chapter was used. The first 4 assembly stages were also agreed to be simulated in the VR system, since those steps included the most complex installations e.g. hoses, motor and a significant part of the hydraulics. An older frame structure of the same product was used to test how well the case company’s 3D CAD models could be imported into the VR system of the test facility. The frame structure’s assembly model could be imported without any optimization, which was stated to be a good result. However, this assembly was only a small part of the whole assembly, and its size was well under 200 megabytes. This meant that the file size would be significantly greater in the new 3D CAD assembly, which could cause problems when importing it to the VR system.

As the new 3D CAD assembly of the product was forwarded to the test facility, it was discovered that the size of the assembly was significantly greater compared to the test assembly. It was approximately 4.5 gigabytes, which meant that it was over 20 times larger than the original 3D CAD test assembly. The assembly was attempted to be converted to from SLDASM-format to STEP AP214 -format without any optimization, but this was discovered to be an impossible task. The assembly was too complex to be converted to VR-suitable format. This meant that the assembly needed to be optimized; redundant individual parts from the assembly properties point of view were either suppressed or solidified into a one part. This simplified the product structure and reduced the complexity of the 3D CAD model significantly from the point of view of the VR system.

The amount of assembly stages was reduced by 2 because of schedule limitations. Even though bolts, nut, washers, and other small components were suppressed or solidified into a one part, the overall geometry of the main components remained unchanged during the optimization. This is crucial from the evaluation point of view of assembly properties. The optimization took approximately 6 person-workhours, and the resulted 3D CAD assembly was approximately 220 megabytes in size. The size is not comparable to the original size since the latter 2 assembly stages were removed along with the parts and subassemblies included in those stages. Once the assembly was optimized, the model was converted into a STEP AP214 -format utilizing 3Ds Max program and finally imported into Unity 3D VR software, which was used to run the VR system.

Active 3D shutter glasses and head tracking was used to enhance the immersive VR experience by providing a realistic visualization to the user by changing the visual output of the system based on the position and orientation of the main user's head. A game controller was used to control the position of the user inside the VE, and it was also tracked, which meant that the hand holding the controller could also be tracked and visualized in the VE. User's head and hand tracking was based on visual tracking, and it utilized infrared sensors and markers. A triple-screen powerwall setup with active 3D-technology was used to provide the visual output of the system. The VR system is shown in Figure 22.

Figure 22. *Virtual reality laboratory utilized during the VP demonstration day.*

The VP demonstration day was held shortly after the collaborative design review. The day was arranged at a test facility, shown in Figure 22. A total of 11 participants from the case company participated in the demonstration day. The participants included many of the same individuals who participated in the collaborative design review held a couple of days earlier on the case company's premises: the project manager, a production manager, a production development manager, a design manager, design engineers, methods engineers, and an assembly worker. The morning of the demonstration day was used for VR system exploration. The participants had the ability to familiarize themselves with the VR system, its controls and functionalities by exploring different kind of virtual prototypes. Besides examples regarding the evaluation of assembly properties, other VP implementation targets were presented to the participants in order to illustrate the capabilities of VP.

Once the participants had familiarized themselves with the VR system, the case company's own product was reviewed as a virtual prototype. The virtual prototype was configured in a way that the user could insert a new part to the assembly by taping a specific button in the controller. The assembly phasing corresponded the same phasing that was used in the collaborative design review implementation. All the participants had the ability to explore the virtual prototype and discuss about the assembly properties related to different assembly steps. The user was able to move around the virtual prototype and also through it to explore different viewing angles as shown in Figure 23.

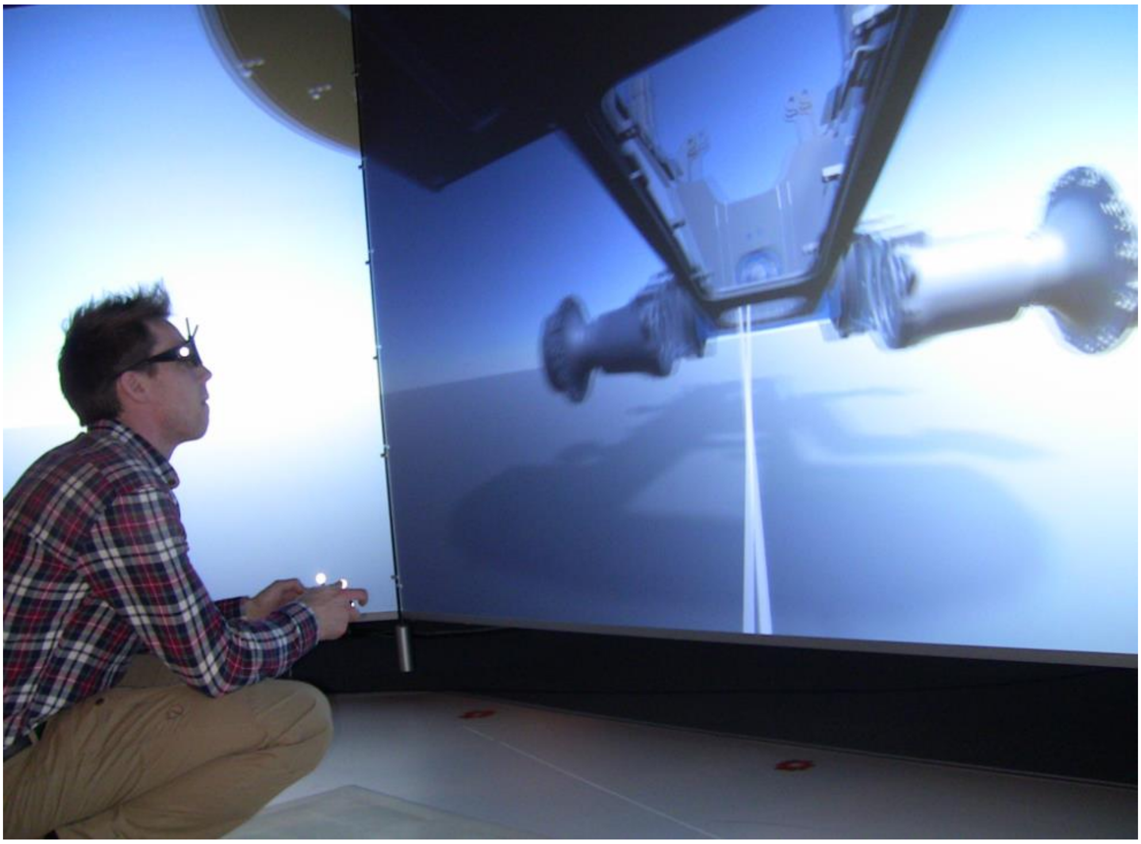

Figure 23. *A user exploring different possible viewing angles in VR system.*

The participants were observed and discussed with during the entire day to collect personal experiences regarding the technology and its performance. Since the main objective of the demonstration day was to show the capabilities of VP to the case company's participants, no structured collaborative design review was held. Once all the participants had had an opportunity to review their product as the main user and get to know the technology and its possibilities, an open discussion was started to determine the participants' experiences and opinion about the usefulness of VP in assembly properties review task. Furthermore, the implementation method and collaborative design reviews were also one of the main topics of discussion, as they were elaborated to the participants. The feedback was collected orally and by the inquiry shown in Appendix 2.

6. RESULTS, OBSERVATIONS AND EVALUATION

This chapter presents the inquiry results as well as comments and observations regarding the collaborative design review and the VP demonstration. The results are then analysed, and the experiences regarding VP implementation are compared to previous industrial applications and related observations.

6.1 Inquiry results

As stated before, a total of 11 participants from the case company answered the inquiry (see Appendix 2) and participated on the open discussion during the demonstration day. Observations were also made and documented by the author of this thesis to complete the results. Inquiry statements 1–15 are listed down below for results evaluation.

1. The virtual prototype gave a more realistic impression of the machine.
2. VR technologies helped to perceive the magnitude of the prototype better compared to the Solidworks 3D model.
3. ‘Twiddling tools’ of the virtual prototype were appropriate/suitable regarding the assembly simulation as well as the overall design review.
4. Moving around in the virtual environment (around the virtual prototype) was difficult.
5. The virtual prototype could help realize potential design errors and problems more easily than just a Solidworks 3D model.
6. VR technologies are sufficiently mature to be utilized in product development.
7. Collaborative design reviews between design and production departments are useful and they should be continued in the future.
8. Installation clearance could be assessed better with the virtual prototype compared to 3D model presented in Solidworks.
9. Use of VR technologies could facilitate the evaluation of assembly properties in future product development projects.
10. 1:1-scale presentation allowed by VR technologies was not particularly useful for the assessment of items’ assembly properties.
11. The three-dimensionality of the virtual prototyped helped to perceive the structure of the 3D model better compared to the 3D model displayed in Solidworks.
12. VR technologies should be utilized in the future as a communication platform in the case company’s product development.

13. VR technologies helped or could help to evaluate assembly clearance adequacy of items and hoses.
14. The participants understood each other's comments regarding the features of the prototype more easily thanks to VR technologies.
15. Use of VR technologies in this format could support the new collaborative design review practice as well as improve earlier consideration of matters related to manufacturing and assembly properties.

Apart from other statements that are positively worded, the statements 4 and 10 are negatively worded, which is taken into account when evaluating the results. The mean values of each questions' answers are shown in Figure 24.

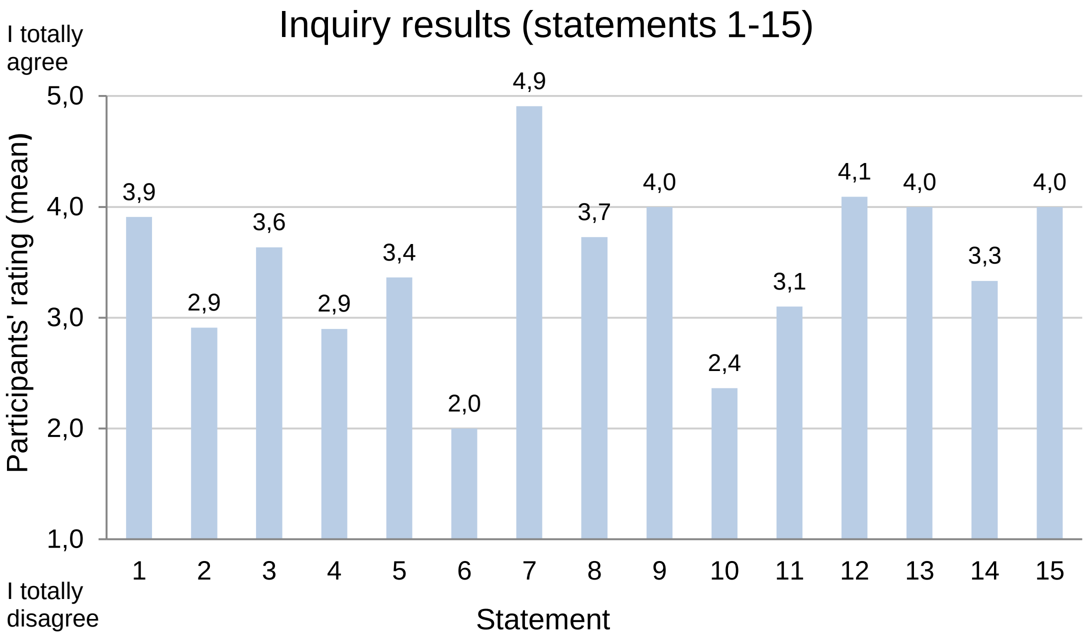

Figure 24. *Columns showing the mean results regarding the inquiry questions 1–15.*

The higher the mean participants' rating is, the more that specific statement is agreed among participants. Distributions between different answer alternatives regarding the statements 1–15 are presented in Appendix 3. The inquiry also included four open questions. These questions and participants' answers to the questions are collected into Table 3.

Table 3. *Open inquiry questions 16–19 with the answers by participants.*

16. What was the greatest benefit of VR technologies?

- The prototype feels more realistic and is easier to perceive
- Freer viewing angles
- Big screen
- Ability to evaluate the cabin view from driver’s point of view
- Ability to evaluate assembly clearances
- Virtual prototype lowers the threshold to discuss with stakeholders
- Introducing the prototype to production workers
- Ability to present assembly instructions

17. Besides assembly simulation, are there any other applications where this technology could be utilized?

- Marketing
- Training of new production and service workers
- Work instructions
- Layout-planning of production facilities

18. What should be improved or changed in order to make the utilization of VR technologies more efficient in product development and in collaborative design reviews in particular?

- The case company must develop its systems and product structure
- 3D CAD models should be instantly exploitable without optimization and conversion
- Taking the 3D model from CAD to VR system should be automated
- If the models would not have to be lightened, I would see a lot of opportunities for VR technologies
- Optimization or duplicate structure should not be needed

19. Other comments regarding the technology?

- This technology has a bright future ahead of itself, if exporting of 3D CAD models to VR system becomes easier
- There are clear benefits/application targets in the future if the virtual prototypes can be generated automatically
- The use of the technology causes nausea and headache
- The technology brings only marginal benefits to the current state of product development, since 3D models are missing

In addition to the inquiry, observations and oral comments were captured and documented to further support the inquiry results. These notations are regarded in the following evaluation chapters of the results.

6.2 Collaborative design review

Based on the inquiry’s statement 7, collaborative design reviews between design and production departments were unanimously seen as useful. Based on discussions with representatives from design and production departments, the 3rd collaborative design review was seen very helpful, since there was an opportunity to see the product-in-development before the first prototype was manufactured. Hence, different assembly properties -related features could be reviewed and evaluated collaboratively, and more tacit knowledge was available to be used in evaluating the assembly properties of the product.

During the collaborative design review at the case company’s premises, design engineers asked comments from the assembly workers regarding assembly clearance of different modules and hose routing, whereas the assembly workers revealed their concerns regarding the current design state of the product by referring to existing products that had some problems with same features. Design review participants, including the assembly workers, came up with couple of different solution proposals to the features that were causing discussion regarding their assembly properties. Actions to solve these problems were documented in writing and by adding screenshots to visualize the problem, and responsibility to alter these features was shared among the relevant actors.

When the participants were asked about the usefulness of the checklist-approach, no clear comments came up. However, from spectator point of view the checklist that divided the work stages and different items and modules to be assembled during these stages guided the collaborative design review successfully. It also provided a base frame for the documentation of the design review. The checklist helped the project manager to guide the discussion while also making sure that all the assembly tasks were talked through. Based on these observations, the checklist proved to have potential, and it should be utilized and developed further to support product variations. From spectator point of view the length of 2 hours was suitable to cover all the topics without being too long.

The collaborative design review taking place in the very beginning of product update project aroused the participants’ interest and caused a lot of discussion. Even though one assembly worker claimed that the presence of assembly workers would not be useful during that design review, arguments defending the involvement emerged among other participants. Participants defending the 1st collaborative design review stated that the first collaborative design review would enhance communication between design and production departments by giving the assembly workers the possibility to comment on the current design of the product considering its good and difficult features, thus taking wishes of the production department into account as development goals. Even though all of the internal wishes could not be taken into account during the update project, they would be acknowledged and solutions to some of the wishes can be explored.

It was also stated that while the 1st collaborative design review would be useful for receiving feedback from assembly workers regarding the current design, it would also be a chance for the design engineers to introduce the customer requirements to the assembly workers and other internal stakeholders. Design engineers could explain why some of the design solutions causing trouble for example in the production or in service related tasks had to be done in that specific way to fulfil those requirements. All in all, the 1st collaborative design review received positive feedback, and the case company is willing to test it in their following product development projects.

Having the 2nd collaborative design review right after the concept design phase is finished was also seen useful among the participants. The assembly worker also agreed that involving production workers in this stage would be useful, since those workers would be able to see the concept design alternatives of the product, comment the alternatives, and participate on the discussion regarding the concept design that is chosen for further development. Having the 2nd collaborative design review before starting the system-level design phase is also beneficial, since in this stage the concept design can be altered quite radically without causing as significant amount of rework as would be need if the same changes were done later during the product update project. It should be noted that while the 1st and 2nd collaborative design reviews were not tested during the case study, no evidence whether they actually would be useful was obtained during this research. However, the participants agreed that the case company should test these design reviews during future product update projects, at least by utilizing 3D CAD software for visualization.

Collaborative design reviews during the system-level design phase caused a lot of discussion among the participants regarding their necessity. One of the design engineers argued that if the amount of these collaborative design reviews is too high, design engineers would have to spend a significant amount of time in these design reviews, which would decrease the time available to be used in actually designing the product. Hence, it was argued that informal meetings between production workers and design engineers would be enough to tackle smaller problems. The fact that the design engineers together with methods engineers already communicate actively with the production by asking feedback regarding different problems is a huge benefit. However, defining the clear stages where collaborative design reviews should be arranged aims not only to utilize the tacit knowledge of production workers, but also increase the overall communication between production and design department. Thus, design engineers are responsible for involving the production workers in the design work also during the system-level design phase. Currently, this is realized for some, but not all the stakeholders involved in developing the product.

During the demonstration day, design engineers mentioned that the collaborative design reviews during the design phases might have some level of resistance amongst some design engineers. Since the product is in development, it is not finished during these events. Based on this it was aggravated by one of the participants that the collaborative design reviews might become as occasions where other stakeholders come together and ‘criticize all the things that have not yet been done by design engineers’. In addition, the feedback from production revolves currently around negative observations, e.g. what should be changed, what should be done differently, or what is simply a bad solution. This kind of remarks should be taken seriously, since concentrating only on the negative features of the design might become one of the main reasons why change at individual and organizational level towards new design review practices happens slowly, or becomes completely rejected. Hence, feedback from positive product features should be encouraged and documented to enhance the positive attitude towards these collaborative design reviews.

Even though the usefulness of the collaborative design reviews was recognized, it was agreed that the timing of the tested 3rd collaborative design review was not right, since there was no time to react on some of the change requests and other concerns that came up during the event. Some of the items requested to be changed were already finalized and either released for production or ordered from subcontractors so that they would arrive before the first physical prototype is being assembled. Hence, observations considering these items are not implemented in the first physical prototype. Since these collaborative design reviews are quite new to the case company, the current product development schedules and activities of the case company are not yet optimized for this kind of collaborative design review practices. This also affected to the fact that some features were already clinched before the design review.

It was agreed by the participants that all the collaborative design reviews should be tested in practice during the future product update projects, starting from the very first phase of a product development project. Before VP system is implemented, the case company could use their 3D CAD in visualization. Involvement of different stakeholders, trying different phases for the collaborative design reviews during design phases, and comparing these alternatives would help to find the best practice for the case company. In addition, it would provide valuable information about the true value of the implementation method.

6.3 Virtual prototyping demonstration

Most of the feedback collected during the demonstration day regarding the visual performance of the VR system was rather positive. Based on the first inquiry statement, majority of the participants agreed that the virtual prototype provided a more realistic mental image of the product when compared to a 3D CAD model, making it easier to perceive. This result is further supported by the answers for the open question number 16. In addition, one of the greatest benefits the virtual prototype provided was the ability to inspect it flexibly from different angles allowed by the user tracking. Participants were able to crouch, walk through the prototype, and inspect the different assembly tasks with simple actions. User tracking was found particularly useful by the participants, since it provided the ability to move around the prototype intuitively as the participants could do with a physical prototype, yet having the ability to jump to different positions right away. This observation is supported by corresponding discoveries made at Metso (Leino 2015). Animation of the user’s hands in the VE by user tracking allowed assembly clearance evaluation, which was one of the biggest benefits of VP compared to 3D CAD.

The participants had mixed opinions when asked about the benefits compared to the ability of a 3D CAD model to describe the size and structure of the prototype (see statements 2 and 11). This can be caused by the fact that most of the participants were frequent 3D CAD users. Hence, they are familiar with the 3D model regarding its scale and structure, which affects to the benefit they gain from the real-size and 3-dimensional presentation. The same observation has been made at Valtra; design engineers benefit less from VP, since they are already familiar with the current product design (Piippo et al. 2015). This result was acknowledged already during the choosing of the implementation target for VP. However, majority of the participants agreed that the real-size presentation would be beneficial for the users not familiar with engineering tools (e.g. 3D CAD software), for example assembly workers, service & maintenance workers, and other stakeholders during the product lifecycle.

Leino (2015) stated that the advantages of utilising VP compared to traditional engineering tools come from the ability to make better product-related observations while enabling the communication for the stakeholders who are not familiar with engineering tools. Keller et al. (2015) also noted that while VP facilitated earlier observation of design errors and inconsistencies, it also enhanced communication between different stakeholders. These observations are supported by the case study. Even though the case study regarding VP was used to demonstrate the technology, the participants agreed that VP would enhance the communication between stakeholders by lowering the threshold to comment on the design and by making it easier for the design engineers to present the current design for the assembly workers. This observation can also be conducted based on couple of the answers for the inquiry question 16. Enhanced communication could lead to enhanced knowledge sharing, which would be beneficial for everyone participating in product development.

Based on the inquiry statement 4, moving around in the VE was experienced differently between participants; approximately half of them stated that the controls were easily acquired, while as the other half stated that they would need more time familiarizing themselves with the controls. This also impacted the ability to explore the virtual prototype, since many of the participants were experiencing with the technology and controls rather than concentrating on the virtual prototype. This was expected to happen because of the novelty of the technology. Furthermore, Leino (2015) made the observation that the quality of the discussion is improved as the collaborative design review participants gain more experience in utilizing the system and thus focus more on the design review topics rather than VP technology itself. Thus, by utilizing the technology a couple of times, the users would eventually become familiar with the controls, and could utilize it more efficiently.

According to a project manager, the virtual prototype ran smoothly in the VR system; different modules and items could be easily assembled and disassembled just by tapping two buttons in the controller, which made the phasing inspection significantly faster compared to 3D CAD software. Due to optimization, some smaller items of the forest machine were not included in the virtual prototype. One of the participants stated that some errors and inconsistencies tend to be in those places which are thought as irrelevant during the evaluation of assembly properties. To avoid this problem, the virtual prototype could be dealt into smaller entities. These smaller virtual prototypes could be more complex compared to the original, including more details. It should be noted that the optimization itself was not optimized, which meant that more items were excluded from the virtual prototype than what is necessary. Once the capabilities of the VR system to run the case company's virtual prototypes become clearer, more details could be included in future virtual prototypes.

It is good to note that all of the participants were able to change between the different assembly tasks and move in the VE without any significant problems after a one minute presentation considering the controls. From assembly worker point of view this is a huge benefit, since the workers could familiarize themselves with the virtual prototype with their own terms. Since the assembly workers are familiar with the possible difficulties regarding the assembly properties of specific items and modules, they could compare the virtual prototype to a mental image of a physical one. This could lead to earlier detection of design errors and inconsistencies, since the assembly workers could utilize their tacit knowledge in the evaluation.

VP implementation target was seen as successful among the participants. Based on the 5th and 9th statements, most of the participants were positively minded about the ability of the virtual prototype to reveal possible design flaws and problems better compared to a 3D CAD model shown in 2D screen. According to the open question number 16, assembly clearance evaluation was also mentioned to be one of the greatest benefits of VR technologies. The evaluation of assembly properties was also one major successful implementation target in all of the application examples in Chapter 3.2.5. By tracking the controlled used for moving in the VE, users could see their hand animated in the VE, which allowed them to evaluate clearance intuitively. This observation is supported by the 8th statement.

Indeed, immersive VR experience is one of the greatest benefits of VR technologies as well as one of the biggest features separating it from traditional engineering tools. It was stated by a project manager that although the assembly order and phasing is examined in the design reviews utilising 3D CAD software, the concrete assembly task viewpoint cannot be evaluated, whereas VR technologies have the ability to tackle this problem. A design manager mentioned that VP could also be utilized while designing prefabrication entities, which would further help to make the assembly properties better. These observations should be further supported by utilizing VP in collaborative design reviews during the case company's future product update projects.

However, no changes were made to the product design, as was done in the application examples by Keller et al. (2015) and Leino (2015). The reason for this is probably the newness of the technology; the participants were more interested in the technology rather than reviewing the virtual prototype. If VP was utilized in future product development projects, its users would become more familiar with the technology and could utilize it more efficiently, which could lead to detection of design errors and inconsistencies.

Both the design engineers and the assembly worker noted that the VR system would be significantly useful in prototyping stage, since the upcoming product could be introduced to production workers, and solution alternatives regarding hose routing and other tricky assembly properties could be discussed. The participants saw potential in the technology, as can be concluded from statements 12 and 15. Besides assembly properties, other beneficial implementation targets came up during the demonstration day: work instructions, training of new workers, marketing, and customer feedback. These other implementation targets would increase the utilization rate of the VR system and also bring additional value to the customer, since same models used in collaborative design reviews could be utilized in the other implementation targets as well, for example introducing an existing machine to new assembly workers.

While the benefits and potential of the technology were recognized widely among the participants, two significant challenges regarding it were discovered during the demonstration day. The first and foremost problem was the optimization needed to take the 3D CAD model into VE. Indeed, it is extremely important to make the production of the virtual prototype as easy as possible to facilitate better acceptance and utilization of VP. This remark is supported by similar observation made by Leino (2015). In the case study, it took approximately 3 person-workdays to optimize the 3D CAD model, convert it to a VR-suitable format, and program the basic functionalities that allowed the easy navigation and assembly phase manipulation with the gaming controller in VE. It was uniformly agreed by the participants that the 3D CAD model should be able to be used in VR system as a virtual prototype without any optimization. This was justified by the lack of resources in the design department; optimization would increase design engineers' work load, which is not a possibility.

It should be noted that this was the first complete model from the case company that was imported to VE, which meant that there was no clear guideline how to do it most effectively. Thus, the 3 person-workdays included several trials and errors regarding the import format and optimization, which made the total import time longer. Furthermore, the optimization was made by the author of this thesis, elongating the optimization time because of the novelty of the product and its structure. For example, it took only few hours to convert Metso's CAD model into a virtual prototype (Leino 2015). If the CAD model optimization time would be divided among the design engineers, and the 3D CAD assemblies are designed to support the optimization in the future, the time could be reduced significantly. However, it was stated that the optimization need is not the only problem, but also duplicates of the original 3D CAD assemblies designed to be used as virtual prototypes can cause trouble while managing product data. Based on this, the participant stated that the duplicates should be avoided. These observations are clearly visible in the answers for inquiry statement 6 and question 18.

Since the implementation target is the evaluation of assembly properties, the VP implementation target could be performed by a VR system which can utilize 3D CAD models without conversion (e.g. TechViz XL). However, no confirmation was received during this thesis whether this kind of software could run the case company's quite large and complex 3D CAD models as is, without any optimization and with the same hardware used in the demonstration. Based on the VP application target regarding fusion reactor component by Keller et al. (2015), computing power was mentioned to be one of the possible limiting factors while utilizing VR technologies integrated into CAD software. Employees of the virtual laboratory made the same kind of observation; the case company's 3D CAD models might need optimization, even if there is a system that could utilize the models without conversion.

However, it is argued that in the next years the computing performance of computers will face this problem (Keller et al. 2015). Once this happens, the case company could utilize VP without optimization. This would definitely lower the threshold to invest in VR technologies. Till then, the case company must be willing to respectively optimize their 3D CAD models for VP, or utilize VP to evaluate smaller entities at a time. The extra work needed for model optimization would help to decrease the iteration made during later changes. However, the design engineers at the case company do not accept the extra work. Tight schedules and high workloads are significant reasons to this. The design engineers might also resist the extra work, because they have not actually experienced how the benefits of VP could ease their workload during the later product development phases. This highlights the importance of further VP implementations even more. If VP was utilized during a whole product update project as suggested, the design engineers could see the benefits in practice and understand better how much their total workload would be affected while utilizing the technology.

The second challenge was the current product data management customs, which is related to the way the case company is handling their 3D CAD models. To utilize VR technologies starting from the very beginning of product update projects, an up-to-date 3D CAD model is needed to function as the basic layout for the upcoming produce development project. Since older products' 3D CAD assemblies are not updated while a single item or module is changed, they become outdated and do not represent the current state of the product. This is problematic in the 1st collaborative design review, during which the 3D CAD model is used to collect any easy or challenging assembly tasks related to the product that should either be kept the same or changed. As mentioned in Chapter 3.3.1, the product development projects should become driven by

DMUs, in this case known as 3D CAD models, to support VP implementation. The success of the evaluation of assembly properties by VP depends on the 3D CAD model and whether it includes all the relevant items, modules, and hose routings from the evaluation point of view of assembly properties, as physical prototypes do.

The second challenge was also recognized at Valtra, as they decided to concentrate first on developing their PDM system to be driven by 3D CAD models before they implemented VR technologies (Piippo et al. 2015). It was argued that efficient utilization of VP requires effective PDM (Piippo et al. 2015). The need to develop PDM system was noted by majority of the participants during the demonstration day as well as in the answers for the open questions 18 and 19. Not only it would support VP implementation in the future, but it would also help both traditional project meetings and collaborative design reviews that utilize 3D CAD software for visualization.

Even though the biggest concern among the participants regarding VP was the need for optimization, the true challenge seems not to be purely technical; without hands-on experience of the real benefits and value of VP, the participants evidenced their doubts towards the technology, since the discussion was focused around the extra work caused by optimization needs. The presented VP implementation method would require changes in company’s processes and culture, which become easily resisted. This observation is supported by similar findings by Leino (2015). For example, the optimization need is currently seen as an extra work by the case company, not as an activity that would help to improve the product design by replacing some of the iteration made with the physical prototype with iteration made with a virtual prototype, thus decreasing the workload and resources spent during testing & refinement and ramp-up phase. Small gains from VP implementation can be achieved by incremental changes, but greatest benefits are achieved when both the product and business are regarded as an entity (Leino 2015). Hence, it should be internalized that VP implementation has an impact on processes, technology infrastructure and organizations (Leino 2015). This research supports this observation. VP technology is not just a technology that would work in product development projects without further adaptations regarding these different angles. The key factor for successful VP implementation along with suitable product data management is well-organized change management both in individual and organizational level.

7. CONCLUSION

The aim of this thesis was to investigate whether virtual prototyping could be utilized in an international forest machine company’s product update projects. The goal was to support the communication between design and production departments to answer the increasing demand for shorter time-to-market and more efficient production ramp-up. Based on a literature review considering product development, virtual reality technology and its impact on processes, information flows, and people, the case company’s product development process and associated activities were analysed to find the most suitable implementation target alternatives for virtual prototyping. Based on the analysis, the evaluation of assembly properties with assembly workers was chosen as the implementation target and a collaborative design review methodology was developed to support the utilization of virtual prototyping. The implementation method is designed to perform as a framework, which guides the virtual prototyping -utilizing collaborative design review activities during a product update project. The framework for collaborative design reviews during product update projects are visualized in Figure 25.

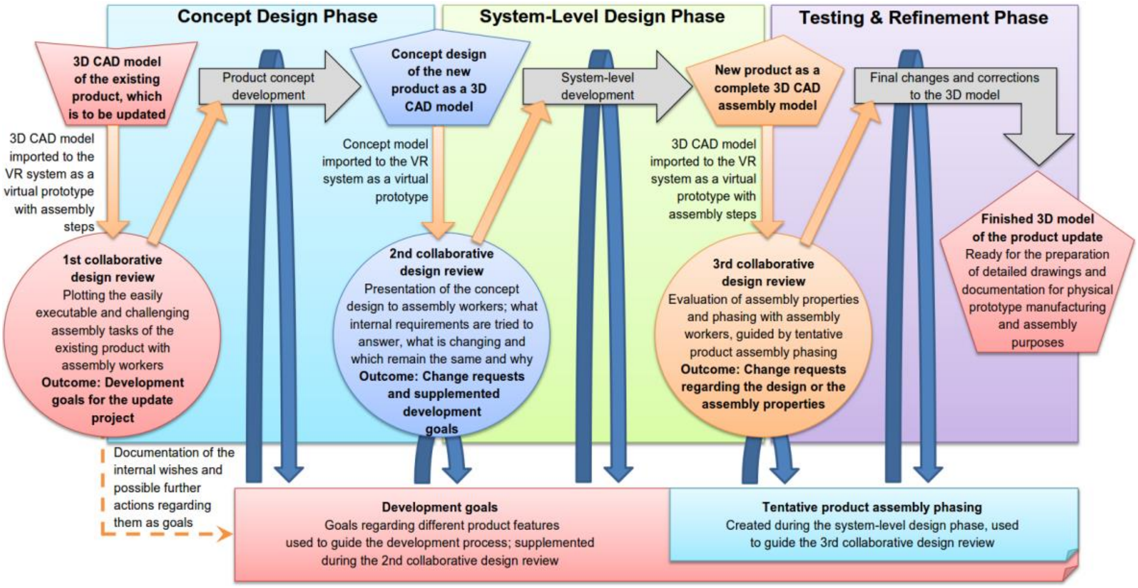

Figure 25. *The framework for collaborative design reviews in product update projects at the case company.*

As shown in Figure 25, three formal collaborative design reviews are held during a product update project to support communication between design and production department from the point of view of the assembly properties. In the 1st collaborative design review the current product that is designed to be updated during the project is reviewed together with design engineers, methods engineers, and assembly workers. The product is gone examined by its assembly phases, and assembly workers are requested to comment on the good and difficult features of the product from their professional point of view. Both good features and change requests are documented by the design review chairman to be further used during the product development phases as development goals, which aim to answer the internal requirements while taking external requirements, e.g. customer requirements, into consideration.

Once the concept design phase has been performed for the product, the 2nd collaborative design review is held. During this stage, all the possible concept designs or the one that has been already chosen for further development are presented to assembly and service workers as virtual prototypes. Design engineers are able to present and explain the concept design of the product; which features remain the same, what has been changed and what are the current challenges in design work. Assembly workers have the ability to ask discuss about the design, learn the direction that the product update project has taken, and express themselves if the design includes any concerning features from their point of view. Even quite radical changes are possible in this early phase.

The 3rd collaborative design review takes place before the testing & refinement phase; during this stage, assembly workers together with design and methods engineers evaluate the assembly properties of the product. The aim is to eliminate all the possible obvious design errors before the final items and modules are either ordered, or released to production for the fabrication of the first physical prototype. All the three collaborative design reviews utilize virtual prototyping as a communication platform.

Figure 26 depicts the utilization of VP in time perspective.

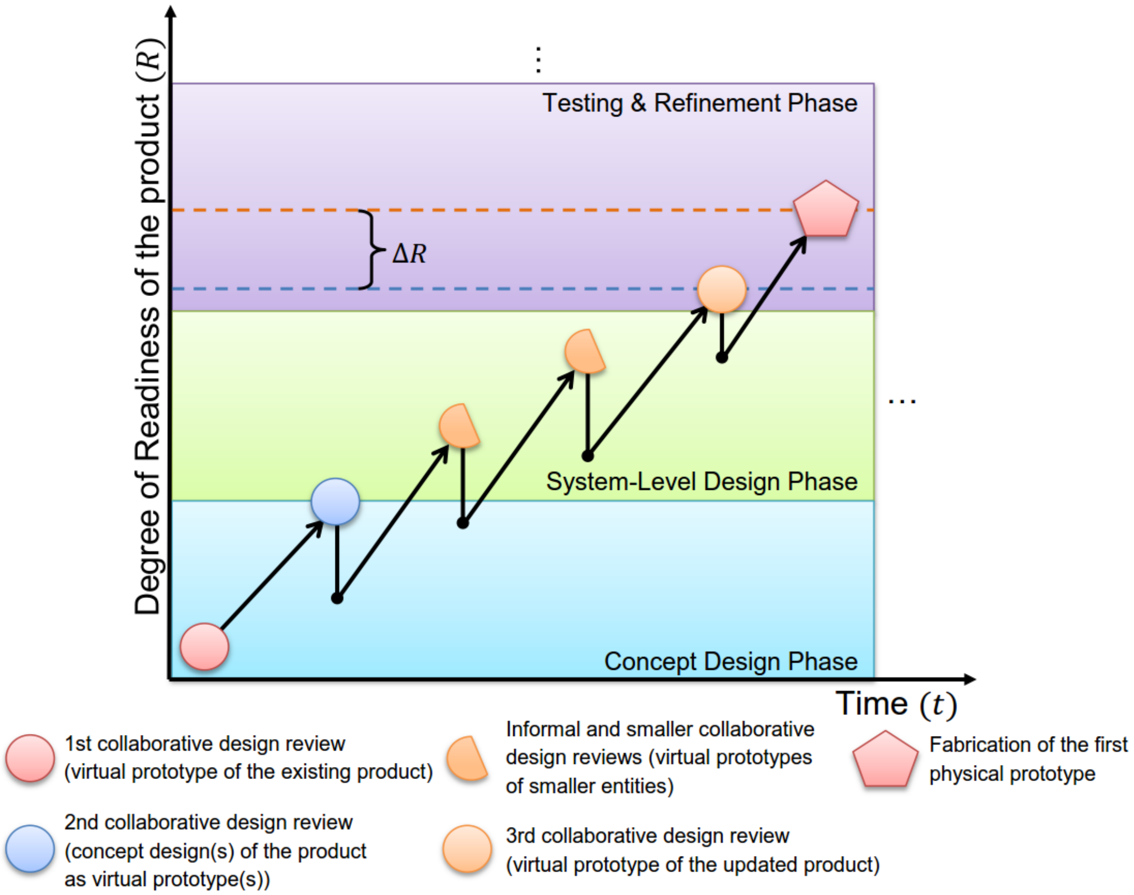

Figure 26. *Simplified visualization of the virtual prototyping implementation method.*

Utilizing virtual prototyping as a communication platform between design department and assembly workers aims to catch possible design errors and problems regarding assembly properties earlier during the design process. Virtual prototyping allows its users without previous experience with engineering tools to explore the product as a virtual prototype more freely compared to a 3D CAD model. Enhanced visual information enables easier assembly clearance and order evaluation from the worker's point of view, which would help the design engineers to collect valuable feedback from the assembly workers regarding different features of the product. As these observations can already be made during the design process while the features can be changed without a significant amount of rework, the product can be taken to the physical prototype fabrication with a better degree of readiness compared to a product development process without virtual prototyping. This difference in product readiness is visualized in Figure 26 by ΔR. The pursued benefit of the implementation method compared to product development process without VP is shown in Figure 27.

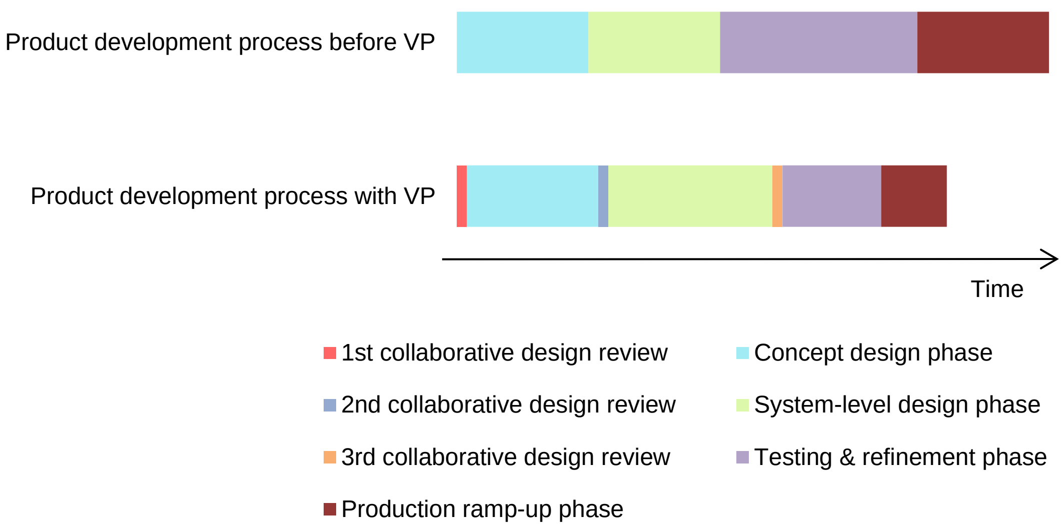

Figure 27. *Pursued benefit of VP compared to traditional product development process.*

As shown in Figure 27, the overall time the product development process takes is shortened due to VP utilization. By increasing iterative design in concept design and system-level design phases by evaluating the design by VP, testing & refinement and production ramp-up phases are shortened. This is because the product's degree of readiness is higher, when it is passed on to the testing & refinement phase (see Figure 26). Assembly properties are evaluated already during system-level design phase, which also eases production ramp-up, thus making it faster.

The 3rd collaborative design review was tested in the case company by utilizing 3D CAD model instead of a virtual prototype to visualize the product. Assembly phasing list including different assembly stages guided the conversation and made sure that all the different items and modules were talked through regarding their assembly properties, including for instance assembly clearance and order. It also acted as the documentation template. Overall, the review was seen useful among design engineers, assembly workers and other participants; possible assembly properties -related problems were noticed during the design review, and alternative solutions for solving the problems were discussed collaboratively.

In this case the 3rd collaborative design review was held a bit too late, since some of the items that were requested to be changed by the assembly workers were already finished and ordered for the first prototype fabrication. Hence, the product development process should be developed to support the 3rd collaborative design review. In practice this means developing the product development from a physical mock-up -driven to digital mock-up –driven process and developing the overall product data management to support wider utilization of virtual prototypes. The 1st and 2nd collaborative design reviews were developed based on the literature review and the interviews and analysis of the case company, but could not be tested in practice during this thesis. However, the case company saw these design reviews as potential places for reviewing the design, and will try to implement them in future product update projects to find whether these design reviews are found to be useful among different stakeholders involved in product development projects.

Virtual prototyping was also implemented in the case company with the same model as used in the tested collaborative design review. The benefits of virtual prototyping compared to 3D CAD as a communication platform were recognized by the case company. Virtual prototype helped to perceive the upcoming product better, especially from the assembly workers' point of view. The case company's design engineers agreed that the technology would have potential in planning assembly clearances of different items and modules because of the 3-dimensional visualization, if the CAD-VR conversion could be eliminated or reduced to its bare minimum. Finding an affordable, flexible, and efficient virtual reality system for the evaluation of assembly properties and developing requirements for product data management to support virtual prototyping utilization is one of the most interesting future research topics.

Overall, the evaluation of assembly properties as an implementation target was seen as successful by the case company. In addition, many other beneficial implementation targets for the technology came up during the demonstration day, including training, marketing, and work instructions. Researching how these other implementation targets could be utilized to further support shorter time-to-market and production ramp-up is also an interesting topic. Furthermore, concrete industrial examples of successful VP implementations as a communication platform would be beneficial to gain more visibility and interest towards implementing it in other companies' product development processes.

To gain more results regarding the benefits of the virtual prototyping implementation method, is should be tested as an entity in the case company's future product update projects. This would provide results whether all the collaborative design reviews ease earlier observation of engineering change needs and utilization of assembly workers' tacit knowledge by providing a communication platform for design and production departments. This requires commitment from the case company, both in organizational in individual level to support successful change management and technology implementation.

Once the concrete benefits of virtual prototyping become visible to the involved stakeholders, the common opinion could be changed from thinking the collaborative design reviews as extra work towards an opinion where the collaborative design reviews are thought as occasions where the design work is oreinted toward the future in order to decrease the amount of rework and ease the everyday tasks of everyone. It would also be interesting to research whether the developed implementation method could be implemented into other companies struggling with similar problems, but have for example decentralized research & development and production activities. This would provide further information about the usefulness of the implementation method.

All in all, the research was quite successful. Both the implementation method and virtual prototyping technology received positive feedback and aroused interest at the case company. Practical examples of the qualitative benefits would have been extremely useful regarding the comparability of the results to provide further information about the true value of the developed implementation method. However, due to the schedule constraints of the research, practical benefits could not be obtained.

Qualitative benefits of virtual reality technology and virtual prototyping are well recognized in the literature, but quantitative benefits are much harder to obtain, and could not be done within the research. The reason for this is that the length of product development projects is usually quite long, especially in the case of forest machinery, and the length reserved for the research was not long enough to fit multiple development projects into the research. In addition, the projects differ greatly from each other in terms of complexity, magnitude and length, which would make their comparison quite difficult. The investment expenses in virtual reality technologies may also turn out to be hard to divide among different projects. In order to obtain reliable information about the quantitative benefits of virtual reality technologies, a sufficient amount of various cases involving the technology in the company must be handled and analysed for credible comparison.

Continuous technological development and digitalization make the utilization of virtual reality technologies more and more tempting in different uses. These technologies are currently receiving a significant amount of attention in different media; one of the main reasons for this are their affordability to private consumers and small companies, and increased technological capabilities. Virtual prototyping has great potential in multiple industrial applications presuming it is implemented carefully by taking its impact and requirements regarding different organizational and individual levels into account. However, it crucial to acknowledge that virtual prototyping should not be treated as a technology, but as a communication platform, which requires adaptation on these different levels to bring its maximum value to its implementer.

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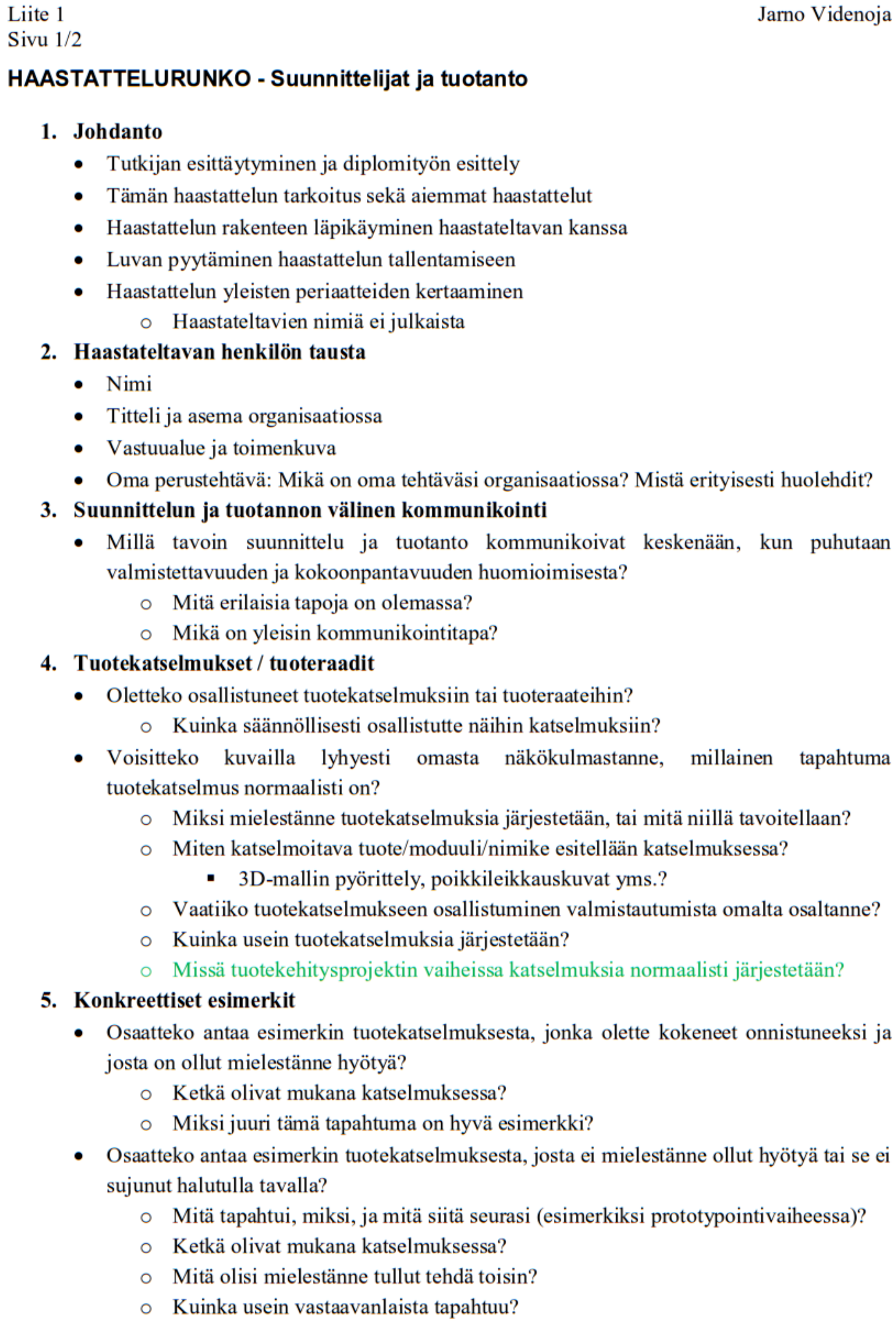
APPENDIX 1: THE INTERVIEW FRAMEWORK



Liite 1
Sivu 1/2

Jarno Videnoja

HAASTATTELURUNKO - Suunnittelijat ja tuotanto

1. **Johdanto**
    - Tutkijan esittäytyminen ja diplomityön esittely
    - Tämän haastattelun tarkoitus sekä aiemmat haastattelut
    - Haastattelun rakenteen läpikäyminen haastateltavan kanssa
    - Luvan pyytäminen haastattelun tallentamiseen
    - Haastattelun yleisten periaatteiden kertaaminen
        - Haastateltavien nimiä ei julkaista
2. **Haastateltavan henkilön tausta**
    - Nimi
    - Titteli ja asema organisaatiossa
    - Vastuualue ja toimenkuva
    - Oma perustehtävä: Mikä on oma tehtäväsi organisaatiossa? Mistä erityisesti huolehdit?
3. **Suunnittelun ja tuotannon välinen kommunikointi**
    - Millä tavoin suunnittelu ja tuotanto kommunikoivat keskenään, kun puhutaan valmistettavuuden ja kokoonpantavuuden huomioimisesta?
        - Mitä erilaisia tapoja on olemassa?
        - Mikä on yleisin kommunikointitapa?
4. **Tuotekatselmukset / tuoteraadit**
    - Oletteko osallistuneet tuotekatselmuksiin tai tuoteraateihin?
        - Kuinka säännöllisesti osallistutte näihin katselmuksiin?
    - Voisitteko kuvailla lyhyesti omasta näkökulmastanne, millainen tapahtuma tuotekatselmus normaalisti on?
        - Miksi mielestänne tuotekatselmuksia järjestetään, tai mitä niillä tavoitellaan?
        - Miten katselmoitava tuote/moduuli/nimike esitellään katselmuksessa?
            - 3D-mallin pyörittely, poikkileikkauskuvat yms.?
        - Vaatiiko tuotekatselmukseen osallistuminen valmistautumista omalta osaltanne?
        - Kuinka usein tuotekatselmuksia järjestetään?
        - Missä tuotekehitysprojektin vaiheissa katselmuksia normaalisti järjestetään?
5. **Konkreettiset esimerkit**
    - Osaatteko antaa esimerkin tuotekatselmuksesta, jonka olette kokeneet onnistuneeksi ja josta on ollut mielestänne hyötyä?
        - Ketkä olivat mukana katselmuksessa?
        - Miksi juuri tämä tapahtuma on hyvä esimerkki?
    - Osaatteko antaa esimerkin tuotekatselmuksesta, josta ei mielestänne ollut hyötyä tai se ei sujunut halutulla tavalla?
        - Mitä tapahtui, miksi, ja mitä siitä seurasi (esimerkiksi prototypointivaiheessa)?
        - Ketkä olivat mukana katselmuksessa?
        - Mitä olisi mielestänne tullut tehdä toisin?
        - Kuinka usein vastaavanlaista tapahtuu?

    - Miksi juuri tämä tapahtuma on hyvä esimerkki?

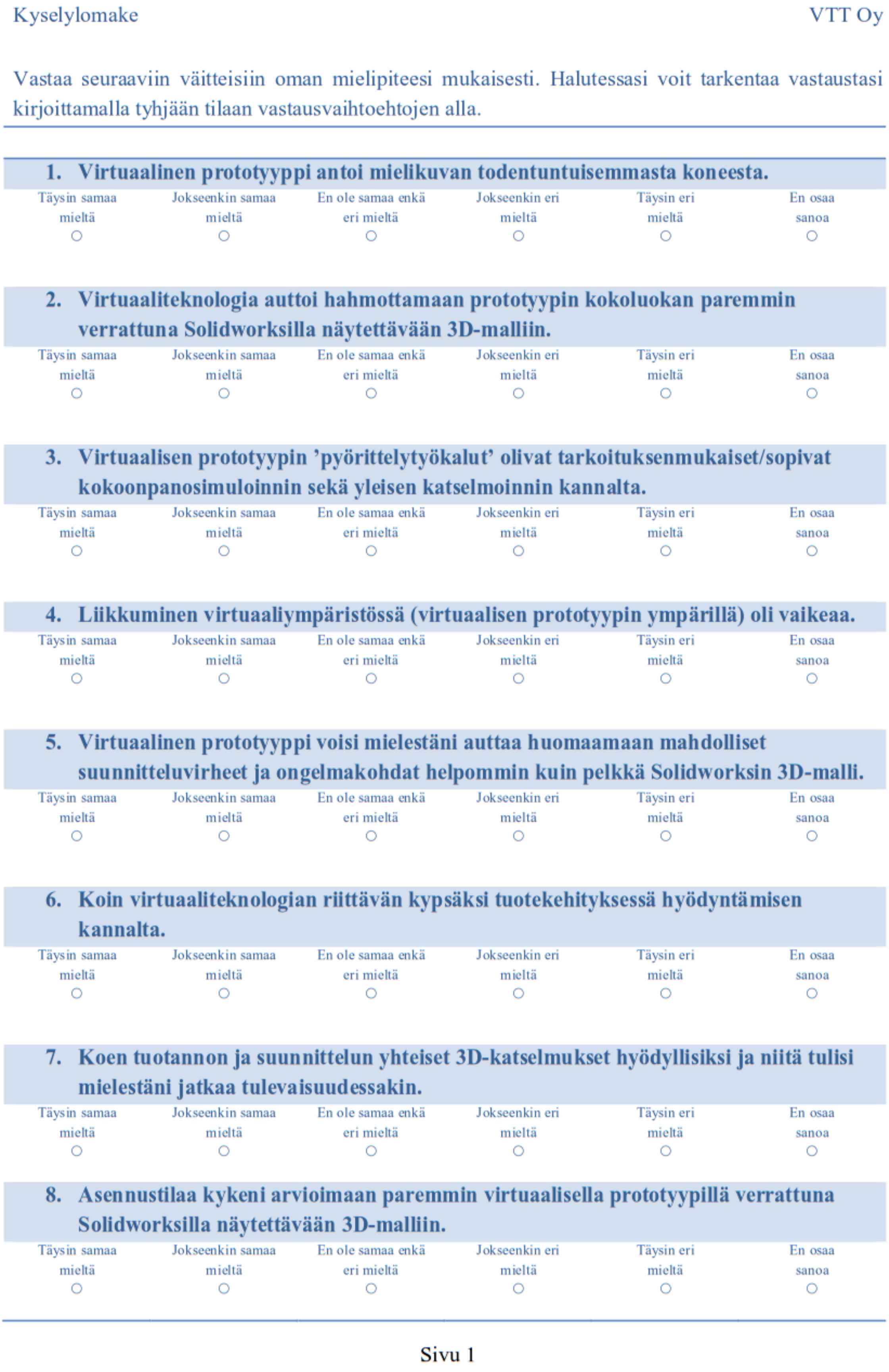
6. **Tuotekatselmukset yksityiskohtaisesti**
    - Osaatteko esimerkkien pohjalta sanoa, mitkä ovat itsellenne suurimmat tuotekatselmuksista saatavat hyödyt?
    - Entä mitkä ovat suurimmat ongelmat, joihin tulisi vaikuttaa?
    - Missä tilanteissa tuotekatselmuksen järjestäminen on mielestänne välttämätöntä?
    - Koetteko tuotekatselmukset hyödyllisiksi oman tehtävänne suorittamisen kannalta?
    - Ovatko katselmuksissa käytetyt tuotemallit olleet sellaisia, että niiden pohjalta on kyennyt tekemään parannusehdotuksia?
        - Ellei, niin miten niitä voisi parantaa?
        - Havainnollistaako 3D-malli mielestänne riittävästi tuotetta?
    - Ovatko tuotekatselmukset mielestäsi riittävän hyvin ohjattuja ja kontrolloituja?
    - Miten tuotekatselmukset dokumentoidaan?
    - Onko parannusehdotusten esiintuominen tehty helpoksi katselmuksissa?
7. **Optimaalinen tuotekatselmus**
    - Kuinka usein tuotekatselmuksia tulisi mielestäsi järjestää?
    - Missä tilanteissa tuotekatselmuksia tulisi järjestää?
        - Esim. missä tuotesuunnittelun vaiheissa koette niiden olevan tarpeellisia?
    - Kuinka kauan tuotekatselmuksen tulisi kestää?
8. **Virtuaaliprototypoinnin esittely**
    - Tuleeko mieleenne tuotteen piirteitä, joiden tarkastelussa kolmiulotteisuus sekä reaalikoossa esittäminen olisivat erityisen hyödyllisiä?
    - Mitkä 3D-CAD-ohjelmiston toiminnot tulisi mielestänne soveltaa osaksi virtuaaliympäristössä tapahtuvaa protoamista ja testausta?
    - Kokisitteko hyödyllisenä, mikäli voisitte tutustua katselmuksessa läpikäytävään malliin etukäteen?
        - Esimerkiksi jos 3D-malli olisi helposti katselmoitavissa ennen virallista katselmointia, jotta siihen voisi tutustua vähän tarkemmin
9. **Muut parannukset**
    - Olisiko mielestänne olemassa muita tapoja parantaa suunnittelun ja tuotannon välistä kommunikaatiota?
    - Onko mielessänne muita keinoja, joiden avulla valmistettavuuden ja kokoonpantavuuden vaatimuksia voitaisiin ottaa paremmin huomioon suunnittelussa?
    - Mitä voisitte mielestänne itse tehdä parantaaksenne tuotekatselmuksia?
10. **Haastattelun lopetus**
    - Onko herännyt kysymyksiä aiheeseen liittyen?
    - Olisiko mielestänne tarve keskustella lisää jostain jo käydystä aiheesta?
    - Kiitokset haastattelusta!

Värikoodaus

🟧 - Erityisesti tuotannon työntekijöille osoitetut kysymykset

🟩 - Erityisesti suunnittelijoille ja vastaaville tahoille osoitetut kysymykset

APPENDIX 2: INQUIRY QUESTIONS



Kyselylomake VTT Oy

Vastaa seuraaviin väitteisiin oman mielipiteesi mukaisesti. Halutessasi voit tarkentaa vastaustasi kirjoittamalla tyhjään tilaan vastausvaihtoehtojen alla.

1. Virtuaalinen prototyyppi antoi mielikuvan todentuntuisemmasta koneesta.

Täysin samaa mieltä	Jokseenkin samaa mieltä	En ole samaa enkä eri mieltä	Jokseenkin eri mieltä	Täysin eri mieltä	En osaa sanoa
○	○	○	○	○	○

2. Virtualiteknologia auttoi hahmottamaan prototyypin kokoluokan paremmin verrattuna Solidworksilla näytettävään 3D-malliin.

Täysin samaa mieltä	Jokseenkin samaa mieltä	En ole samaa enkä eri mieltä	Jokseenkin eri mieltä	Täysin eri mieltä	En osaa sanoa
○	○	○	○	○	○

3. Virtuaalisen prototyypin 'pyörittelytyökalut' olivat tarkoituksenmukaiset/sopivat kokoonpanosimuloinnin sekä yleisen katselmoinnin kannalta.

Täysin samaa mieltä	Jokseenkin samaa mieltä	En ole samaa enkä eri mieltä	Jokseenkin eri mieltä	Täysin eri mieltä	En osaa sanoa
○	○	○	○	○	○

4. Liikkuminen virtuaaliympäristössä (virtuaalisen prototyypin ympärillä) oli vaikeaa.

Täysin samaa mieltä	Jokseenkin samaa mieltä	En ole samaa enkä eri mieltä	Jokseenkin eri mieltä	Täysin eri mieltä	En osaa sanoa
○	○	○	○	○	○

5. Virtuaalinen prototyyppi voisi mielestäni auttaa huomaamaan mahdolliset suunnitteluvirheet ja ongelmakohdat helpommin kuin pelkkä Solidworksin 3D-malli.

Täysin samaa mieltä	Jokseenkin samaa mieltä	En ole samaa enkä eri mieltä	Jokseenkin eri mieltä	Täysin eri mieltä	En osaa sanoa
○	○	○	○	○	○

6. Koin virtuaaliteknologian riittävän kypsäksi tuotekehityksessä hyödyntämisen kannalta.

Täysin samaa mieltä	Jokseenkin samaa mieltä	En ole samaa enkä eri mieltä	Jokseenkin eri mieltä	Täysin eri mieltä	En osaa sanoa
○	○	○	○	○	○

7. Koen tuotannon ja suunnittelun yhteiset 3D-katselmukset hyödyllisiksi ja niitä tulisi mielestäni jatkaa tulevaisuudessakin.

Täysin samaa mieltä	Jokseenkin samaa mieltä	En ole samaa enkä eri mieltä	Jokseenkin eri mieltä	Täysin eri mieltä	En osaa sanoa
○	○	○	○	○	○

8. Asennustilaa kykeni arvioimaan paremmin virtuaalisella prototyypillä verrattuna Solidworksilla näytettävään 3D-malliin.

Täysin samaa mieltä	Jokseenkin samaa mieltä	En ole samaa enkä eri mieltä	Jokseenkin eri mieltä	Täysin eri mieltä	En osaa sanoa
○	○	○	○	○	○

Sivu 1

9. Virtuaaliteknologian hyödyntäminen voisi mielestäni helpottaa asennettavuuden ja kokoonpantavuuden arvioimista tulevissa tuotekehitysprojekteissa.

Täysin samaa mieltä	Jokseenkin samaa mieltä	En ole samaa enkä eri mieltä	Jokseenkin eri mieltä	Täysin eri mieltä	En osaa sanoa
○	○	○	○	○	○

10. Virtuaaliteknologian mahdollistama reaalikoossa näyttäminen ei ollut erityisen hyödyllistä nimikkeiden asennettavuuden arvioimisen kannalta.

Täysin samaa mieltä	Jokseenkin samaa mieltä	En ole samaa enkä eri mieltä	Jokseenkin eri mieltä	Täysin eri mieltä	En osaa sanoa
○	○	○	○	○	○

11. Virtuaaliprototyypin kolmiulotteisuus auttoi hahmottamaan 3D-mallin rakenteen paremmin verrattuna Solidworksilla näytettyyn 3D-malliin.

Täysin samaa mieltä	Jokseenkin samaa mieltä	En ole samaa enkä eri mieltä	Jokseenkin eri mieltä	Täysin eri mieltä	En osaa sanoa
○	○	○	○	○	○

12. Mielestäni virtuaaliteknologiaa kannattaisi hyödyntää tulevaisuudessa kommunikaatioalustana case-yrityksen tuotekehityksessä.

Täysin samaa mieltä	Jokseenkin samaa mieltä	En ole samaa enkä eri mieltä	Jokseenkin eri mieltä	Täysin eri mieltä	En osaa sanoa
○	○	○	○	○	○

13. Virtuaaliteknologia auttoi tai voisi auttaa eri nimikkeiden ja letkutusten tilavarausten riittävyyden arvioinnissa.

Täysin samaa mieltä	Jokseenkin samaa mieltä	En ole samaa enkä eri mieltä	Jokseenkin eri mieltä	Täysin eri mieltä	En osaa sanoa
○	○	○	○	○	○

14. Osallistujat ymmärsivät toistensa kommentit prototyypin piirteisiin liittyen tavallista helpommin virtuaaliteknologian ansiosta.

Täysin samaa mieltä	Jokseenkin samaa mieltä	En ole samaa enkä eri mieltä	Jokseenkin eri mieltä	Täysin eri mieltä	En osaa sanoa
○	○	○	○	○	○

15. Virtuaaliteknologian hyödyntäminen tässä muodossa voisi mielestäni tukea uutta suunnittelun ja tuotannon välistä 3D-katselmuskäytäntöä sekä parantaa valmistukseen ja kokoonpantavuuteen liittyvien asioiden aikaisempaa huomioimista suunnittelussa.

Täysin samaa mieltä	Jokseenkin samaa mieltä	En ole samaa enkä eri mieltä	Jokseenkin eri mieltä	Täysin eri mieltä	En osaa sanoa
○	○	○	○	○	○

16. Mikä oli mielestäsi tärkein virtuaaliteknologian tuoma hyöty?

17. Onko mielessäsi muita sovelluskohteita case-yrityksessänne, joissa tästä teknologiasta voisi olla hyötyä?

18. Mitä pitäisi parantaa/muuttaa, jotta virtuaaliteknologian hyödyntäminen olisi tehokkaampaa tuotekehityksessä sekä erityisesti 3D-katselmuksissa?

19. Muuta kommentoitavaa hyödynnettyyn teknologiaan tai tähän päivään liittyen?

20. Oma tehtävänimikkeeni case-yrityksessä on:

APPENDIX 3: INQUIRY ANSWERS (STATEMENTS 1–15)

Statement	(5) I totally agree	(4) I somewhat agree	(3) I do not agree or disagree	(2) I somewhat disagree	(1) I totally disagree	(0) I cannot say*	Mean
1	2	7	1	1			3.9
2		2	6	3			2.9
3		9		2			3.6
4		4	2	3	1	1	2.9
5		7	2	1	1		3.4
6		1	1	6	3		2.0
7	10	1					4.9
8	1	6	4				3.7
9	1	9	1				4.0
10		2	3	3	3		2.4
11	1	3	3	2	1	1	3.1
12	3	6	2				4.1
13	1	9	1				4.0
14	2		6	1		2	3.3
15	1	9	1				4.0

*: ‘I cannot say’ -answers are excluded from the mean calculation.