**Simo-Pekka Leino:
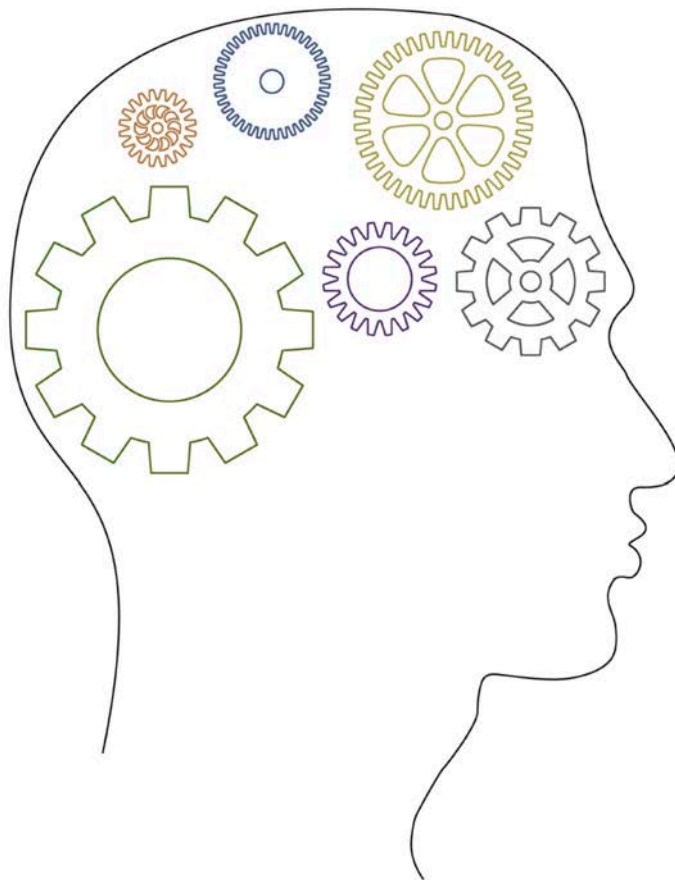Reframing the value of virtual
prototyping**

Intermediary virtual prototyping – the
evolving approach of virtual
environments based virtual prototyping in
the context of new product development
and low volume production

VTT

Reframing the value of virtual prototyping

Intermediary virtual prototyping – the evolving approach of virtual environments based virtual prototyping in the context of new product development and low volume production

Simo-Pekka Leino

Thesis for the degree of Doctor of Technology to be presented with due permission for public examination and criticism in Konetalo Building, Auditorium K1702, at Tampere University of Technology, on the 22nd of May 2015 at 12 noon.

"*Nowadays people know the price of everything and the value of nothing*"
(Oscar Wilde)

Preface

They say that people should have dreams. I have been privileged to reach many of my dreams in my life. Among other I have sailed across the Atlantic Ocean, I have got a wonderful family and friends. A doctoral thesis has been one of the dreams in my life, as well. This thesis is a result of my journey and the learning process as researcher.

I started my career as a researcher at the end of the 1990s at VTT. My research has been mainly related to virtual prototyping all the time, but the focus and interest has been shifting from simulation techniques towards using them in industrial product design and development. On the other hand, I became increasingly interested in design science as well. As my home base at VTT has been in a team whose mission is to promote human factors in system design, I wanted to combine these three dimensions in my research.

Fortunately, I had an opportunity to co-operate with Prof. Asko Riitahuhta from Tampere University of Technology (TUT) some years later. I found my scientific breeding ground, and I was accepted as a doctor candidate at TUT. I am deeply grateful to my supervisor Prof. Riitahuhta for patient piloting and encouraging me on this long journey. From TUT, I thank also Prof. Asko Ellman, Dr. Tero Juuti, Dr. Timo Lehtonen, and Mr. Petri Huhtala for excellent advice on my doctoral studies, and especially Dr. Antti Pulkkinen for giving valuable feedback on my thesis.

I was lucky to find an excellent supervisor and mentor from VTT, as well. Many thanks to Dr. Tapio Koivisto for excellent and inspiring discussions and guidance on my research. From Tapio, I learned a lot about scientific method, but he also expanded my thinking "outside the box". I also want to express my gratitude to the pre-examiners of this thesis, Prof. Pertti Saariluoma from the University of Jyväskylä and Prof. Christian Weber from the Ilmenau University of Technology, for their excellent comments and suggestions, which helped me to improve and finalise the thesis. I am honoured to have Prof. Saariluoma and Prof. John Kunz from Stanford University as opponents in the defence of this thesis.

I was privileged to have an opportunity to work for almost ten years as a researcher on three large projects (Virvo, ManuVAR, Manu) around the same research topic and even in collaboration with the same case company, Metso Mining and Construction (MAC). I express my acknowledgments for all the parties that were funding and supporting the research (Tekes, EU, Fimecc, companies, and

"*Real happiness lies in the completion of work using your own brains and skills*"
(Soichiro Honda)

Academic dissertation

Supervisor   Professor Asko Ellman
                Mechanical Engineering and Industrial Systems
                Tampere University of Technology, Finland

Thesis   Professor em. Asko Riitahuhta
Advisors   Mechanical Engineering and Industrial Systems
                Tampere University of Technology, Finland

                Dr. Tapio Koivisto
                Business Ecosystem Development
                VTT Technical Research Centre of Finland Ltd

                Dr. Antti Pulkkinen
                Mechanical Engineering and Industrial Systems
                Tampere University of Technology, Finland

Pre-examiners   Professor Pertti Saariluoma
                Department of Computer Science and Information Systems
                University of Jyväskylä, Finland

                Professor Christian Weber
                Department of Mechanical Engineering
                Ilmenau University of Technology, Germany

Opponents   Professor Pertti Saariluoma
                Department of Computer Science and Information Systems
                University of Jyväskylä, Finland

                Dr. John Kunz, Executive Director Em.
                Center for Integrated Facility Engineering, Stanford University
                California, USA

Contents

Appendices

Abstract
Tiivistelmä

Abbreviations

2D	Two dimensional
3D	Three dimensional
ARC	Areas of relevance and contribution
BOP	Bill of processes
CAD	Computer aided design
CAE	Computer aided engineering
CAx	Computer aided (any application)
CE	Concurrent engineering
COTS	Commercial off-the-shelf
CPM/PDD	Characteristics-Properties Modelling/ Property-Driven Development/Design theory
CRA	Constructive research approach
DFA	Design for assembly
DFX	Design for ..
DHM	Digital human model
DM	Digital manufacturing
DRM	Design research methodology
DS	Design science
EBOM	Engineering bill of material
ECM	Engineering change management
ECR	Engineering change request
EDM	Engineering data management

ERP	Enterprise resource planning
ETO	Engineer to order
FBSM	Function-behaviour-structure-model
FEM	Finite element method
HCD	Human centred design
HF/E	Human Factors / Ergonomics
HMD	Head mounted display
HW	Hardware
ICT	Information and communications technology
IT	Information technology
IVP	Intermediary virtual prototyping
MAC	Mining and Construction (business line of Metso company)
MBOM	Manufacturing bill of material
MIP	Metso Innovation Process
NPD	New product development
PDM	Product data management
PDP	Product development process
PLM	Product lifecycle management
RBV	Resource-based view (to firm)
ROI	Return on investment
STEP	Standard for the exchange of product model data
SW	Software
TS	Technical system
TTS	Theory of Technical Systems
UCD	User centred design
UI	User interface
VE	Virtual environments
VP	Virtual prototyping, virtual prototype
VR	Virtual reality
VTT	VTT Technical Research Centre of Finland Ltd

"*Product development,…., is like sailing: proficiency is gained through practice,
but some theory of how sails work and some instruction in the mechanics
(and even tricks) of operating the boat help tremendously*"

(Karl T. Ulrich, Steven D. Eppinger)

1. INTRODUCTION

This research is about investigating how the business and organizational value of virtual prototyping aided by virtual environments could be modelled in the context of product design and development in manufacturing industry. In this research, virtual prototyping is briefly defined to mean using computer simulations of a physical product in order to analyse and evaluate certain properties and phenomena related to it. Furthermore, in this research, virtual environments are used as a means for analysis and evaluation of the product properties and phenomena. This evolving conceptual definition will be further clarified and conceptualized later in this thesis. This research is important, because knowledge about value of virtual prototyping is lacking, both in literature and in industry. This fact seems to retard the adoption of virtual prototyping in industry. Based on dialogue between empirical case study material and theory, this research establishes a framework as the basis for value modelling.

This research originates from engineering design science. However, the theoretical frame was expanded towards the dimensions of virtual environments, product design and development, social aspects, and business management; because it was evident that the engineering design theory could not alone solve the complex research problem, and explain the empirical findings. Thus, this research contributes to engineering design theory by conceptualizing virtual environments based virtual prototyping, and by establishing conceptual bridges between the disciplines of engineering design, virtual prototyping, human factors/ergonomics, social science and business management. Furthermore, this thesis aims to promote the value of design theory to the other disciplines mentioned.

Entry point of the research

The entry point for this research is the relatively long experience of the author in applied research in virtual prototyping in manufacturing industry context. The author of this thesis has been investigating and developing virtual prototyping and virtual environments as part of product processes in close co-operation with several industrial companies for more than fifteen years. During that time period, there has been a significant improvement in virtual prototyping technology going on, both in software and hardware. As the technology has become more mature, the focus of research and development has extended from technology demonstrations

to more serious utilization for instance in the product design and development processes. However, a lack of knowledge of the real benefits and value of virtual prototyping seems to be a deterrent to the wider adoption of virtual prototyping in industry. At least part of the reason for that is insufficient conceptualization of virtual prototyping, i.e. it is not clear what it means and where it belongs. The aim of this thesis is by means of scientific research to increase knowledge of the contribution of virtual prototyping and its impacts in a practical industrial context.

The chapters that follow will familiarize the reader with the context and problems as well as the focal concepts of the dissertation. Firstly, general challenges in industry, especially in product development are briefly introduced. These are the challenges that are targeted at the highest level. Secondly, it is explained how virtual prototyping is proposed as a solution for the challenges mentioned in the literature. However, after that it is reasoned that there is a lack of evidence as regards industry how virtual prototyping actually contributes to solving the challenges, and there is a gap in the literature about this evidence as well. Finally, after this orientation on the research, the actual research gap and research problems will be stated.

General challenges in industry

Industry is facing dramatic changes in running their business nowadays. Particularly in Finnish manufacturing industry, where products are typically expensive business-to-business investment commodities or services related to them, changes are substantial on the global market. The present economic recession makes the situation even more challenging in general. These dynamic business environments increase the need for flexibility of engineering activities (Durmusoglu, 2009), (Horváth et al., 2010), (Huet et al., 2007). Globalization, together with increasing environmental awareness, shortening product lifecycles, more complicated and customized products and complex[1] supply chains have posed new challenges for corporations (Ameri & Dutta, 2005).

The significance of product development as an enterprise function seems often to be understated. Product design and development is often considered more as a cost-generating support function than a value-creating competitive advantage in the value chain. This is the approach, for instance, in the famous model of (Porter, 1985). However, global competition, general technological advancements, market changes and product life cycles all force companies to develop new products frequently (Unger & Eppinger, 2011). Growing service business demand is one driver for product life thinking, which has probably increased the interest in product and service design and development. On the other hand, fierce competition and a demand for customized product and services force companies to introduce, faster

---

[1] In business management, it is helpful to understand the difference (Amaral & Uzzi, 2007) between the notions of complicated (have many interacting components through pre-defined rules) and complex systems (have many components that can autonomously interact through emergent rules), because often business systems, organisations and processes are treated by engineers like complicated linear and causal systems.

and more profitably, better and more complex products with decreasing product lifecycles (Ameri & Dutta, 2005), (Kropsu-Vehkaperä et al., 2009), (Stark, 2006). Therefore, an effective product development process is vital for corporate success (Ameri & Dutta, 2005), (Durmusoglu, 2009) and product development teams are pushed to enhance their practices to match current industrial trends in terms of multidisciplinary involvement, integration of tools and processes and worldwide distribution of partners and stakeholders (Huet et al., 2007). However, product development does not become effective and productive spontaneously or just by command of management of the enterprise. The increasing complexity of new product development requires solutions that benefit from interdisciplinary research practices (Alves et al., 2007).

Despite the importance of effective product development, the majority of companies and their value chains lack the capabilities to effectively generate new products and sustain them over their lifecycles (Koudal & Coleman, 2005). Because the products are more complicated and the value networks are more complex, companies require a more holistic product lifecycle approach and efficient co-operation across disciplines. (Gerritsen et al., 2011), (Zhang et al., 2008). This approach also increases the management of product-related knowledge for product development (Ameri & Dutta, 2005), (Durmusoglu, 2009). However, according to (Ameri & Dutta, 2005), in most businesses even 60% of total operational time is waste, i.e. work that does not add value to a product or process, and a major portion of the waste is caused by a lack of efficient knowledge management.

Monolithic design teams can no longer efficiently manage the product development effort (Ameri & Dutta, 2005). Therefore, product development, design and production systems are nowadays often networked, which makes collaboration and information sharing more challenging. However, most global companies lack the technologies necessary to run the innovation and production lifecycle process effectively, including product data management and product lifecycle management systems, which are implemented extensively by just 8% of the firms (Koudal & Coleman, 2005). Additionally, the complexity of information grows and techniques to access information are required (Amditis et al., 2008).

Virtual prototyping as a proposed solution for the general challenges

New methodologies have been developed as candidates for solving the challenges described above. They include, for instance, advanced computer modelling and simulations, product information lifecycle management, and connections between the virtual and physical worlds (Horváth et al., 2010). As an example of those new technologies, virtual reality (VR) is seen as the next step in the evolution of traditional computer-aided design (CAD) systems that dramatically changes computer user interfaces in engineering design (Amditis et al., 2008) because a VR-based virtual environment system addresses the totality of design and prototyping by providing the user with a higher level of interactivity than can be afforded by CAD systems (Kalawsky, 1993). Traditionally, the major industrial fields that drive the development of new VR technologies are aerospace, automotive, engineering and

design, energy and construction, entertainment and culture. As a pioneer industry, the automotive sector has been utilizing VR from the early 1990s, whereas other fields have only recently been involved (Amditis et al., 2008).

This research aims to contribute to the field of engineering design and product development where so-called virtual prototyping methodology based on virtual environments is at the focus. Virtual prototyping is widely seen as an enabling technology for intensifying product processes (Leino & Riitahuhta, 2012). It has been claimed e.g. that virtual prototyping enables shortened product development cycles, reduced physical prototyping costs, better decision making, and better quality of products (Cecil & Kanchanapiboon, 2007), (Choi & Guda, 2000), (Seth et al., 2011), (Wang, 2002), (Amditis et al., 2008). Virtual prototyping techniques also facilitate better concurrent engineering and communication among cross-functional teams (Ovtcharova, 2010). By using virtual environments, users are not bounded by limitations presented by the real world, but the technique could be used to prototype a product during the early part of its life cycle (Kalawsky, 1993). Thus, the virtual environments enable engineers to consider product lifecycle downstream issues earlier in the product design phase, and make design changes even in the conceptual design stage (Cecil & Kanchanapiboon, 2007), (Seth et al., 2011). Hence, one of the main benefits of virtual prototyping is the flexibility of product development (Horvath & Rudas, 2007b), because, with a virtual prototype, useful feedback can be obtained early in order to improve the design. Additionally, the interactivity of virtual environments allows exploration into alternative design configurations before the product is manufactured (Kalawsky, 1993).

The terminology of this relatively new engineering discipline is not yet stabilized. Nevertheless, the conceptual definition of virtual prototyping by (Wang, 2002) is endorsed in this dissertation:

"Virtual prototype, or digital mock-up, is a computer simulation of a physical product that can be presented, analysed, and tested from concerned product life-cycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physical model. The construction and testing of a virtual prototype is called virtual prototyping (VP)".

Furthermore, virtual environments and virtual reality applications as an interface to virtual prototypes are at the focus of this research. In other words, in this research virtual prototyping is a methodology and process perspective, a virtual prototype is a model of the design object, virtual environments are the way of experiencing and interacting with the model, and virtual reality represents the technology utilized in virtual prototyping activity. These concepts are related to concepts such as simulations, computer-aided engineering, etc. In this research virtual prototyping refers to the evolving concept of virtual environments based virtual prototyping. At this point it is also reasonable to introduce the term "Intermediary virtual prototyping" which refers to a concept that is a result of this research. Furthermore, in this way the focus of the research can be defined, and the reader may be guided to build a mind-set that helps orientation to the topic of the thesis.

Intermediary virtual prototyping (IVP) is a new concept resulting from this research. It underscores the many layers and dimensions of virtual prototyping from technical advantages (immersion, interaction) of virtual reality to the expanded mediating object of product development activity system.

IVP has an interface to virtual prototype (experience) and interface of virtual environment which benefits users in the form of interaction and perception that are directly connected to the virtual reality technology. Beyond this technology layer, the study of value of virtual environments based virtual prototyping expanded it conceptually towards dimensions of engineering design (object and process), social aspects (individual and organisation), and business and management. In other words, value of virtual prototyping can be explained conceptually when it is understood as a combination of people, processes, management and technology. Elaboration of the IVP concept will be explained by reflecting an industrial case study with scientific theories in these value dimensions.

Figure 1. Utilizing virtual prototyping and virtual environments in designing and evaluating user interfaces of a passenger car (source: Mercedes Benz).

Figure 1 aims to illustrate what virtual environments-based virtual prototyping means through an understandable example. Car manufacturers use virtual prototypes, for instance, in designing and evaluating drivers' interfaces in virtual environments. In a similar way, other aspects of a product life such as manufacture and service could be planned and evaluated with the means of virtual prototyping and virtual environments.

Virtual prototyping paradox

This research investigates virtual environments-based virtual prototyping (VP) approaches in an industrial context. The long-term mission of the research is to support the implementation of VP, and the improving utilization of it in industry as an enabler of improved product processes and business. According to the literature, virtual environments and virtual reality applications have been present for quite a long time, but only now is its potential being appreciated in many fields of industry (Amditis et al., 2008). Actually, many manufacturing companies have recognized some benefits of using virtual environments-based virtual prototyping in product design and development within several pilot studies. However, according summary of (Amditis et al., 2008), virtual testing and prototyping can be considered already as systematic parts of product engineering mainly in the automotive industry. Genuine developments of VR/VE applications in manufacturing and design in real use have been relatively few, although reports in 2006 indicated that real breakthroughs are not far away, with a number of descriptions of general industrial use (Wilson & D'Cruz, 2006).

Nevertheless, VP could be utilized more efficiently and systematically, but according to our experiences companies are today lacking an understanding and knowledge of the real value and significance of VP (see e.g. (Aromaa et al., 2012). There is a "paradox" of common statements of the high utility of VP and simultaneously a relatively low level of real adoption in industry. One reason is that companies do not have enough evidence about the impact and value of VP on a larger scale, which is needed as a basis for investment decisions. A restricted understanding of the value creation and capture of VP investments seems to be real bottleneck in industry. Hence, modelling the value creation and capture would have significant implications in practice. Therefore, the real benefits of VR as an enabler of fast, cost-effective, and valid product management should be proven and made clearly visible (Amditis et al., 2008). Furthermore, companies lack knowledge of implementation premises and enablers in order to gain the assumed benefits. Apparently, the barriers to adopting virtual prototyping, especially virtual environments, are not only related to the total costs of VR equipment but also to knowledge of how to work with it (Ottosson, 2002).

Typically, the framing of hype about a new technology (like virtual reality) is very positive, but vague when emphasizing potential positive outcomes, while other factors are under-emphasized, and potential negative outcomes are excluded (Fox, 2013a). This stance is quite common among the technology developers. Nonetheless, knowledge about value, and methods for estimating advantages and value, even returns on investment, were one of the major topics that was demanded in a workshop where several Finnish companies discussed the future of virtual prototyping ("Future Virtual Design Environment – Cofex Project Workshop," 2013). Most of those companies had already had some experience utilizing some sort of virtual prototyping in their product development, and many of them had experience of virtual environments in product development. The hype of virtual environments and virtual reality applications emerged already decades ago

because they have been given lot of publicity in the press and media. However, speculations may overstate what can be delivered with the existing technology (Kalawsky, 1993).

The associated cost and time-scale benefits of virtual environments will probably more than justify its use, but the user of the technology should establish the type of virtual environments that will satisfy their requirements. Additionally, business decision makers must be made to understand the wider issues of virtual environments by thorough business analysis. Therefore, it is recommended that a careful analysis of the application domain should be undertaken because it is difficult to predict exactly where the greatest benefits will occur and in which field, since there are so many potential applications for virtual environments. (Kalawsky, 1993)

According to the experience of our research group, one root cause of the unclear benefits of virtual prototyping is the restricted understanding a) objects and concepts of virtual prototyping, b) objects and concepts of reality in manufacturing and product development, and the links and relationships between a) and b). Additionally, the concepts and terminology is confusing in this relatively new field. Often companies have their own slang, but researchers also use perplexing locution. If there is no clear idea of what is meant by each term, nor of how these technologies can match the potential needs of end-users and user companies, the push of the new technologies may exceed the readiness to usefully employ them (Wilson & D'Cruz, 2006). Furthermore, this leads to a situation where it is difficult to proceed from pilot studies towards systematic and large-scale utilization of VP within product design and development and other business processes. This knowledge is largely lacking in the scientific literature as well. Literature often focuses on usability of technology which is different from usefulness. On the other hand discussions on virtual prototyping and virtual environments are dominated by software developers and not so much by application aspects in product design and development (Weber & Husung, 2011). However, when the scope is expanded from usability to useful systems there is demand for finding out what would be useful (Nardi, 1996).
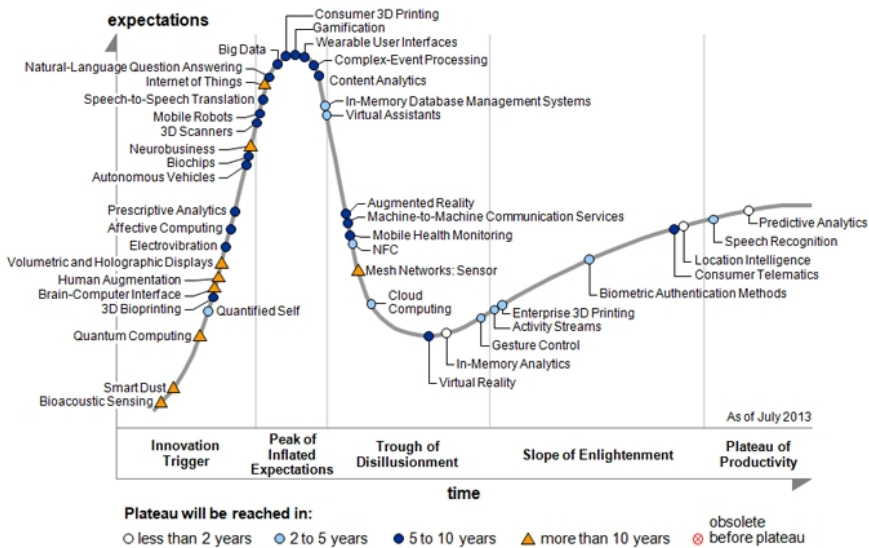
Figure 2. Gartner's 2013 Hype Cycle for Emerging Technologies (www.gartner.com)

Cycles of hype and disappointment are frequently observed in relation to new technologies (Fox, 2013b). Figure 2 by Gartner, Inc. illustrates one hype cycle, where virtual reality technology is at the bottom of a trough of disillusionment after the peak of inflated expectations. It is predicted that virtual reality will reach a plateau of productivity in five to ten years. However, proponents of a new technology promote positive forecasts about the technology's potential effects, leading to increasingly widespread and enthusiastic expectations of the technology (Fox, 2013b). With his fifteen year retrospective, the author of the thesis agrees that overoptimistic expectations and hype were associated with virtual reality as a tool and methodology for manufacturing industry. In the early days of VR companies invested into VR technology just for the hype of it, but today every new VR project needs to go through a systematic return on investment (ROI) analysis (Rehfeld, 2010).

Probably, there are many reasons for coming down to the trough, including at least insufficient technological maturity and restricted understanding of the utility of virtual reality technology. On the other hand new technology generations are introduced typically every 3–5 years but the period of adoption them into the business processes is usually longer (Ovtcharova, 2010). VR has gone through a rapid evolution in the past three decades and has become a mature technology, but it has also gone through an intense diversification as well (Keenaghan & Horváth, 2014). However, now when the technology is more mature and research has progressed it may be agreed that virtual reality is beginning the climb towards the plateau of productivity. This research aims also to contribute to this journey.

Gaps in the literature concerning the value of virtual prototyping

"Value" is a confusing concept because so many definitions of it exist, and they are strongly context- and phenomena-dependent. Generally speaking, value theories aim to understand how, why and to what degree people value things. In other words, the value of a thing is a measure of how much it is worth. In the context of products and services generally, value can be defined as equal to the cost of the product plus a subjective part of the value (Neap & Celik, 1999). The concept of value in the context of design research corresponds to the above-described value definitions. The Theory of Technical Systems (Hubka & Eder, 1988) includes the following statements:

- By means of the value of a technical system, someone's needs will be satisfied or a comfort or pleasure aroused.
- The total value can be regarded as the vector resultant of all values (technical, economic, ergonomic, aesthetic, esteem, usage value), or of the measures of all classes of properties for a given product.
- The basic value realization factors include the abilities of the design team, design time, and the number of improvements. Value is related to concepts of efficiency (doing things right) and effectiveness (doing the right things). Effectiveness can be defined as the benefits of a process divided by expenditure for the process.

Universal Virtues (Olesen, 1992); costs, through-put-time, quality, efficiency, flexibility, risk, and environmental effects are general measurable quantities for assessing company's value creation and realization for all functional areas. Hence, virtual prototyping should contribute to these areas in creating value.

Many manufacturing companies have recognized at least some of the above mentioned benefits of using VP in product design and development within several pilot studies. However, mainly partial VP case studies have been published, and they are mostly very technically oriented and lacking the business value approach (Leino & Riitahuhta, 2012). Cobb et al. already in 1995 reported demonstrations of the potential use of virtual reality and virtual environments for manufacturing industry. They recognized the potential benefits of these methods and technology in a large survey, but concluded that research on actual benefits to industry is required. In 1999 (Brooks, 1999) concluded that as usual with infant technologies, realizing the early dreams for virtual reality and harnessing it to real work has taken longer than the initial wild hype predicted. Nevertheless, the results of a survey in the same year of 1999 by Gomes de Sá & Zachmann indicated that the use of VR for virtual prototyping should play an important role in industry in the near future. In 2005, empirical evidence on benefits in real industrial projects was demanded by Söderman (1995), and it is still very scarce in the literature. Liu and Boyle discovered in 2009 that research and publications on virtual reality and virtual environments are increasing (Liu & Boyle, 2009), but there has not been evidence of the actual benefits for industry. Investigations should be made of what

the attributes of virtual environments are that bring added value (Cobb et al., 1995).

Figure 3 illustrates the dimensions of the gap in literature and in practice. It also points out the areas of science where this research aims to contribute. Additionally, the figure explains the approach to how the research was conducted. All these layers and dimensions will be further elaborated in the chapters of the book that follow. The three viewpoints to the research in Figure 3 are:

- THEORY: theories in this research are mainly used as "cognitive tools" for explaining observations and phenomena of empirical studies and building bridges between concepts of the four dimensions. The selection of theories was extended from theory of virtual environments and virtual reality to engineering design theories, social theories and management theories. The main contribution is targeted to the area of engineering design theory.
- METHODOLOGY: Virtual prototyping was extended from a VR based technology object to a methodology that creates value when it is embedded into product design and development processes, information technology, organisations and business models
- EMPIRIA: The research problem emerged from the insufficient knowledge and justification of value of VE-based virtual prototyping in a manufacturing industry context. This problem was approached from the science base by formulating a theoretical framework for value evaluation, and from the problem base by an empirical case study in one manufacturing company

Based on a literature review, the knowledge gap can be summarized using Figure 3. Firstly, a majority of the research in virtual environments is very technically oriented and experimental, concentrating on the technical features of VR/VE. Thus, research into VE-based virtual prototyping in a real industrial context is scarce. Secondly, the connection between VE-based virtual prototyping and engineering design science seems to be weak in the literature. The propagated terminology of virtual prototyping and virtual reality besides other such terminology come mostly from computer science and their use is still confused (Weber & Husung, 2011). Thirdly, the issue of the relevance of engineering design research for practice in industry has been addressed in several Design Society conferences[2] in recent years. Also literature indicates that there is a significant gap between theory and practice in the field of product design and development (Krishnan & Ulrich, 2001).

The layers and dimensions of the figure can be approached adopting a systems thinking approach, which can be defined (Moser, 2014) as adopting a "broad overview" or "big picture" way of thinking. Generally speaking, a system is composed of interrelated components organized so as to achieve one or more stated purposes[3]. Systems can be categorized in many ways: natural or artificial (Simon, 1996) including physical, biological, social, and symbolic/conceptual systems.

---

[2] ICED, DESIGN, TMCE
[3] Definition by INCOSE – International Council on Systems Engineering

Technical systems and societal (e.g. business organisations) systems belong to artificial systems (Hubka & Eder, 1988), meaning that they are designed by humans. Additionally, systems can be categorized (Amaral & Uzzi, 2007) as simple (e.g. pendulum), complicated (e.g. aeroplane) or complex (organisations, populations) systems which have many autonomously interacting components. In the context of manufacturing, a business organisation can be defined as a decision making system (Simon, 1964), problem solving and transformation process including technology, facilities, formal and informal organization, workers, and managers (Edwards & Jensen, 2014).

This research is an expansive progress (Figure 3) from a concise technical system boundary (VR/VE) to a more holistic system including the social and management system of virtual prototyping as well (METHODOLOGY). This expansion is resonating between THEORY and EMPIRIA, taking the VE/VR technology as an interventionist starting point and expanding it (extension) together with the other dimensions (frame). When the self-understanding of the dimensions of the practical real world business system increases, and the object of investigation expands from technical system (product) towards activity and social dimension, an expanded theoretical frame is required as well (abduction). On the other hand, taking the concept of value as a viewing angle, a wide business approach is needed because it is the frame within which value is ultimately debated (PRAXIS[4]). The business approach means taking into account largely the activity that is carried out in order to provide goods or services in exchange for money. The virtual prototyping methodology is studied in respect of how it creates value in an industrial context (case studies), and respectively case studies in the industrial context contributes to explaining the value of virtual prototyping by reflecting empirical data with the selected theory framework.

The value of virtual environments based virtual prototyping as an applied methodology in the context of practical industrial use is the starting point for the research. Virtual environments-based virtual prototyping, can be seen as a subclass of virtual prototyping where virtual environments refer to the means of representation of product models, while virtual reality (VR) is the applied technology that enables the use of the virtual environment. Because the practical context is manufacturing industry and product design and development, engineering design science is a natural theoretical basis with which to begin. Thus, the value of VP will firstly be studied based on engineering design theory in an empirical case.

However, besides the gap in the practical knowledge of VP benefits and value, there is also gap between concepts of virtual prototyping and concepts of engineering design theory. This gap has been visible in engineering design literature, virtual reality and virtual environments literature, and scientific conferences in the field. Though, for instance (Weber & Husung, 2011) have started a discussion about the terms "virtual prototyping", "virtual engineering", "virtual reality", and "virtual product development" from the perspective of design theory and method-

---

[4] Praxis in classical philosophy means the process by which a theory or idea is embodied or realised

ology. Additionally, there is also an ongoing discussion in the literature and at scientific conferences about the relevance of science and theory in practice i.e. in business reality. So this research aims to contribute in the following ways:

1. Increase knowledge of VP value in practice by studying it within the framework of engineering design theory

2. Extend engineering design theory by abductive conceptualization of virtual prototyping and the value of virtual environments

3. Improve the relevance of engineering design science by a practical case study
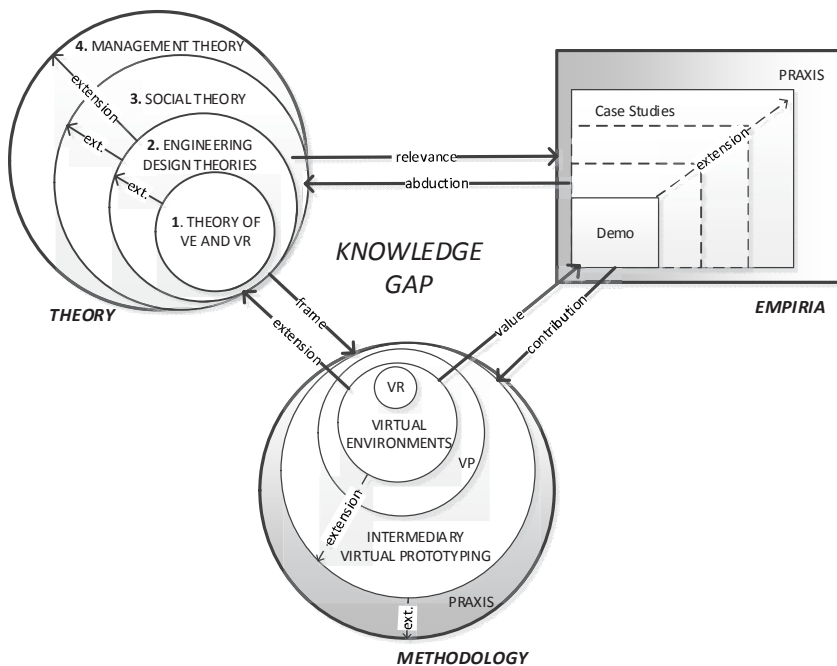
Figure 3. The extension of research in the three dimensions of theory, empiria and virtual prototyping methodology. The starting point was in demonstration of virtual environments as a technical means in the case company. During the case studies, as the understanding increased, it was extended as a methodology. This also required extension of the theoretical frame for explaining the value of virtual proto-typing.

1.1   Research problem and objective

The above described lack of practical evidence in industry and the knowledge gap in the literature concerning the benefits and value of VP was formulated as a practical research problem:

How can the adoption of intermediary virtual prototyping be propagated in manufacturing industry by justifying its value and usefulness in complex business environments?

The recognized gap between the concepts of virtual prototyping and the concepts of engineering design theory was formulated as a scientific research problem:

How should research on virtual prototyping and virtual environments be integrated with design science research?

The research objectives are derived from the above described research problems and practical industrial goals. This research aims to:

- Clarify the unclear links between concepts and objects of virtual prototyping, and product design and development of socio-technical systems in industry;
- Construct a theoretical framework as a scientific foundation for the value assessment of virtual prototyping in a business and product development context;
- Gather evidence about whether (how and by what means) real added value and advantages of virtual prototyping exist, especially utilizing virtual environments in an industrial context and socio-technical systems. This goal includes reasoning and justification of logical paths from technical features of virtual prototyping to business benefits and holistic value for many stakeholders of a product lifecycle.

The practical aim is to produce knowledge about the business and organizational value of VP, and thereby remove the bottlenecks in VP investment decisions and support implementation and improvement of utilizing VP in industry. Therefore, it is also essential to get evidence and justify the value of VP as basis for economic decision making about investment to the new technology. Anticipated industrial advantages related to the implementation of VP were the reduced amount of unnecessary rework in designing and production, decreased time-to-market in a new product development, reduced costs and improved profitability of companies.

1.2   Research scope

Scientifically speaking, an important research objective of this research is to propose new insights and contributions to Design Science. Figure 4 illustrates the main categories of Design Science. This research is positioned mainly to area of working means knowledge with links to the upper hemisphere of the circle as well. This research is mainly about a) prescribing how the value and impact of VP can be estimated, and b) describing what the findings are about the real value and impact in an industrial setting. On the other hand, a virtual prototype is a model of the design object. This model itself, as well as modelling methods and techniques, is closely linked to design process knowledge and methodology. One sub-goal of this research is to contribute integration of virtual prototyping as a discipline and methodology into the Design Science family. Nevertheless, the aim is not to increase diversity of the Design Science.

PRACTICE (BRANCH, DOMAIN) KNOWLEDGE
Prescriptive statements

Design knowledge about objects (systems)

Design process knowledge (e.g. design methodology)

OBJECT KNOWLEDGE
Statements about technical objects (systems, artifacts)

Working Means Knowledge

PROCESS KNOWLEDGE
Statements about the design process

Theory of Technical Systems

Theory of Design Processes

Descriptive statements
THEORIES

Figure 4. Main categories of Design Science Statements. Adapted from Hubka & Eder (1988).

Research is scoped from several viewpoints in order to acquire enough scientific contribution and simultaneously to avoid ending up with too wide a research area. Firstly, the research scope was characterized from industrial aspects:

- The research was specifically scoped on manufacturing industry, where products are partially configurable variants.

- The observed products in focus were large and complicated mechatronic systems for the mining and construction business.
- The observed process was new product development (NPD) in an incremental innovation setting, more specifically a) embodiment design and productisation (i.e. preparation for serial production); b) concept design evaluation.
- Another specific scope was design for manual work, because of the nature of production which contains a lot of manual assembly tasks.
- From a methodological and system point of view, the focus is on socio-technical system (i.e. human-machine system interfaces), human factors requirements, and design for manual work in manufacturing and assembly.

The specific industrial case company was Metso Mining and Construction (MAC). Metso MAC is a global supplier of equipment, service and process solutions to industries including quarrying and aggregates production, mining and minerals processing, construction and civil engineering, and recycling and waste management. In the Figure 5 is an example of a typical product of Metso MAC.

Figure 5. A typical product of the case company. LT106 Lokotrack is a mobile rock crushing unit. Source: Metso MAC

Secondly, the research scope is related to aspects of Design Science. From the design object (product) viewpoint, internal properties (e.g. product structure) and external properties (e.g. ergonomics) were in focus. From design process view-

point, the practical knowledge of virtual prototyping within designing and product development was interesting. The research unit of analysis was the impact of VP within the process, product and business level. The aspects of Design research can also be described using the Faceted Classification approach of (McMahon, 2012), see Table 1.

Table 1. Characterization of the research based on the Faceted Classification approach by (McMahon, 2012)

Facet	Explanation of the facet	The facet in question in this research
The time of the episode under study	• From very short episodes to developments taking many months	The research was conducted during several years
The part of the product life cycle of interest in the research	• That a technique applies to, that designers were undertaking, etc. • From requirements formulation to end of life	The research was related to product development and productisation, communication and collaboration between designers and product stakeholders
Human performance targets of the research	• Individuals • Teams or communities • Size of teams	The target was on the level of teams and organizational functions, team size was couple of individuals
The dimension of the activities/ issues of concern	• From single activities/issues to large number of issues	Large number of issues
The nature of the artefact focus	• Features of parts, single parts, • Assemblies, • Complex interconnected systems	The artefact in focus was assemblies; complexity was manifested by organizational and activity aspects
The degree of originality of the design application	• Variant design • Adaptive design • Original design • Radical innovation	Original and adaptive design Concept and embodiment design
The degree of abstraction	• In design • In research representations	The models used were concrete, related to structures, forms and dimensions of parts
The research approach	• Action research • Observation • Participant observation • Survey and interview • Modelling and simulation • Experimental application of a method/tool, etc.	The research approach included action research, observations, participant observations, surveys and interviews, modelling and simulations, experimental application of method and tool

McMahon (2012) proposed that areas of focus in design research could be mapped to three main categories: management of innovation, engineering design, and industrial design. The first category includes e.g. product development management, creative innovation, etc. The category of engineering design encompasses the wide areas of engineering and engineering design, mechanical engineering, manufacture and production engineering, computer-aided design, etc.

The group of industrial design includes topics such as co-design and applied arts. This research can mainly be put into the first two categories since it deals with engineering design and management of product development.

Thirdly, from a technological viewpoint of virtual prototyping, this research is scoped on real-time, interactive virtual environment simulation models that support the industrial activity mentioned. This scoping is important because the concept of virtual prototyping can also be linked, for instance, to non-real time multi-body dynamics simulations or FEM analyses. In brief, virtual environments are defined as "synthetic sensory experiences that communicate physical and abstract components to a human operator or participant" (Kalawsky, 1993). Virtual Environments systems can be considered as a bundle of technologies, or as more abstract components and features of the system. This research is focused on the latter aspect and does not go into technological details. The component level, and especially its connection to possible benefits and value for design and business, is interesting here.

1.3 Research approach

In this research, the aim was to ascertain the value and impact of VP from an organisational and business viewpoint. The purpose was to evaluate existing design support (Blessing & Chakrabarti, 2009), i.e. VP, which has been partly adopted by an industrial company in several real product development pilot studies. The constructive and exploratory research approach was based firstly on synthesizing a theoretical framework where empirical data from industrial case studies were mapped to in order to expand the theory towards the dimensions needed. The research approach is interdisciplinary.

The research approach was simultaneously a) formative (Blessing & Chakrabarti, 2009) because it aimed to improve the adoption and precondition of virtual prototyping in the company, b) summative (Blessing & Chakrabarti, 2009) because it investigated the value and impact of VP. Additionally, the design support evaluation was qualitative, because the complex nature of research unit could not be experimented quantitatively. The approach was also naturalistic (Blessing & Chakrabarti, 2009) and abductive (Harnesk & Thapa, 2013), i.e. it aimed to understand in depth the situation and context the field, compared to the classical approach which normally includes experimental and hypothetical-deductive approaches.

Characterization of the design research. The overall research approach can be characterized by using the Design Research Methodology (DRM) described by Blessing and Chakrabarti (2009). The DRM methodology basically consists of four iterative main stages (see Figure 6): research clarification, descriptive study I (DS I), prescriptive study (PS), and descriptive study II (DS II).
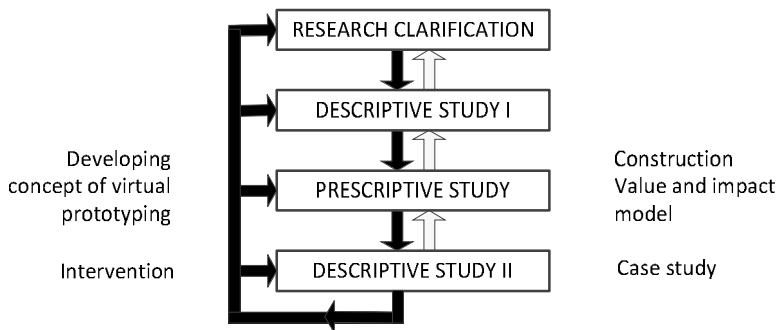
Figure 6. DRM Framework (Blessing & Chakrabarti, 2009) combined with empirical and constructive approach.

The research clarification stage aims to identify and refine a research problem that is both academically and practically worthwhile and realistic, involving an overview of the available understanding of the area of interest. Descriptive study I is required in order to obtain sufficient understanding of the current situation. This stage may include a literature review and/or empirical studies depending on the research goal, which can be descriptive, prescriptive or evaluative. The prescriptive study stage discusses how one can proceed to develop a design support (i.e., knowledge, guidelines, checklist, methods, tools, etc.) in order to enhance, eliminate or reduce the influence of some of the critical factors found in prior stages. The descriptive study II stage discusses how empirical studies can be used in order to evaluate the application and impact of the design support. (Blessing & Chakrabarti, 2009)

According to Blessing & Chakrabarti (2009), it is not assumed that a specific research project includes each of those stages, or undertakes each stage in equal depth. The types of studies in a specific stage can be categorized as a review-based study (based only on a review of the literature), a comprehensive study (includes a literature review, as well as a study in which the results are produced by the researcher by means of an empirical study, developing a design support, or evaluating a design support), and an initial study which closes a project and aims to show the consequences of the result. Based on their wide experience on supervising doctoral studies, Blessing and Chakrabarti concluded that PhD projects should focus only on one stage in-depth connected with one or several stages as comprehensive and/or initial studies due to limited time and resources. (Blessing & Chakrabarti, 2009)

The results of the research clarification stage of this research are described in this introductory section. The first descriptive stage included a literature review and the first empirical analysis in one case-company. One essential aim of the literature review was to clarification of the concept of value, and concepts of virtual prototyping and virtual environments in the context of this research. Present problems within product design and productisation, related to design for manual work (manual assembly, maintenance, corrective engineering changes), were analysed

using questionnaires and interviews. Sources for analysis included also literature, and experience from the researcher's previous research projects. Additionally, root causes for the problems were studied. The first descriptive analysis also includes analysis of the present understanding of the benefits of VP, costs, drawbacks and premises based on pilot case studies and literature.

Based on empirical data that were gathered in the previous descriptive study and the relevant theories and models of the literature, the factor elements were constructed as a prescriptive model, i.e. a hypothetical theoretical framework onto which data from the following case study (descriptive stage II) was mapped. The hypothetical "Phenomena model" linked the Theory of Technical Systems and theory of virtual reality and virtual environments. The model enabled putting structures to the data by categorization and mapping between causes and effects. In descriptive stage II, the prescriptive model was expanded towards a theory of socio-technical systems, human factors and ergonomics, and business and management theory constructing links between the concepts of the theories. The constructed model enables the explanation of causal links from technical features of virtual reality to advantages in product design and development as well as value for organisation and business.

Constructive Approach

The constructive research approach was selected as the primary philosophy in this research, because constructive research methods are fundamental (Crnkovic, 2010) for knowledge production in all engineering and sciences when it comes to concept formation, modelling and the use of artefacts. The constructive research approach (CRA) as a scientific activity is linked to the synthesis or construction of a new artefact in order to solve a problem (Piirainen & Gonzalez, 2013). In this research approach context, the term "artefact" refers to an engineering design support (tool and method, i.e. virtual prototyping) introduced and conceptualized inside the product development processes in the case company. The key idea of constructive research (or the constructivist knowledge production), is the construction, based on the existing knowledge used in novel ways, possibly adding a few missing links filling conceptual and other knowledge gaps by purposefully tailored building blocks to support the whole construction (Crnkovic, 2010). According to Crnkovic, constructive research has the following characteristics:

- Knowledge is created through interaction between the observer and the observed, and in networks of interacting agents.
- Scientific knowledge is constructed by scientists with the help of cognitive tools. Therefore, it is the opposite of the positivist epistemology which sees scientific knowledge as discovered in the world.
- Constructivism entails that there is no single valid methodology for the construction of scientific knowledge, so no unique prescription to establish "the facts" or provide the data, and no guarantee of a consensus.
- The constructive research method implies building an artefact (practical, theoretical or both) that solves a domain-specific problem in order to create

knowledge of how the problem can be solved (or understood, explained or modelled) in principle.

- Constructive research gives results which can have both practical and theoretical relevance.

CRA also has a clear-cut process (Phase I – Phase VII in Figure 7) which is elaborated by (Lukka, 2006). The figure condenses the main activities in the process. The constructive process of this research was described by supplementing Lukka's figure with the blue boxes that illustrate how the case study and action research were conducted. The research process is detailed in the research strategy chapter.
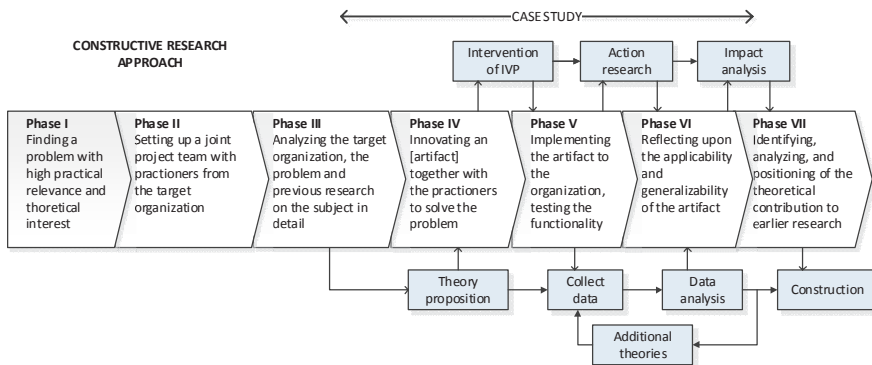
Figure 7. Exploratory (Yin, 2009) case study in the context of a constructive research approach (Lukka, 2006), (Piirainen & Gonzalez, 2013). The unit of analysis was changing from technological advantages to organizational aspects.

In CRA, the solution is based on a deep knowledge of the problem and of existing theory and is found through a heuristic process (Lukka, 2006). Lukka (2006) proposed that the researcher should reflect upon the solution and seek general inferences revealed by the artefact's implementation, which seems to fit the description of inductive logic in which the scientist observes a particular aspect of the world and inducts general inferences or explanations from the observations. However, this approach can also be characterized as abductive logic (see e.g. Harnesk & Thapa, 2013) since the theory base is expanded in order to find the best possible understanding about an ill-structured research problem.

Constructive research includes systematics and interventions based on theoretical considerations. During this process, the researcher is refining the methodological tools while collecting, analysing, and presenting data on an ongoing basis, and simultaneously getting concerned people involved in the research. The research takes place in real-world situations, and aims to solve real-world problems, so it has a social dimension too. Action researchers do not try to remain objective, but recognize their bias to the other participants. (Crnkovic, 2010)

The next chapter describes the research process used in practice including the formulation of research questions and selection of research methods. The structure of the dissertation is explained as well.

1.4   Research process

A generic scientific research process starts from recognizing relevant research problems, which will be formulated as research questions. In order to answer those questions, a research strategy should be established including the selection of suitable research methods. The methods are used for gathering and analysing data which will lead to drawing conclusions, and finally making contributions to science and practical implications. (Niiniluoto, 1980)

One aim of a PhD project is to show that the researcher is capable of carrying out research studies in a scientific manner. Therefore, it is essential to reveal the applied research methods and research process. The constructive method and process of this PhD thesis is based on the general method adapted from Jørgensen (1992) and Olesen (1992) that emphasizes the interplay between theory and practice. The method suits the situation where an industrial problem is analysed and solved by reflecting on scientific theories. The method results both in practical solutions for industry and new scientific knowledge. This approach is further elaborated in Figure 8 and Figure 9 below.

Figure 8 illustrates the interplay between theory and practice in this research. On the left hand side the case company provides the practical problem base and context where intervention of VP was made within the case study. The problem and intervention were analysed based on a constructed theory framework, which was expanded during the research. As a result, new scientific and practical knowledge was produced. The application of the general research method will be explained in the next chapter.
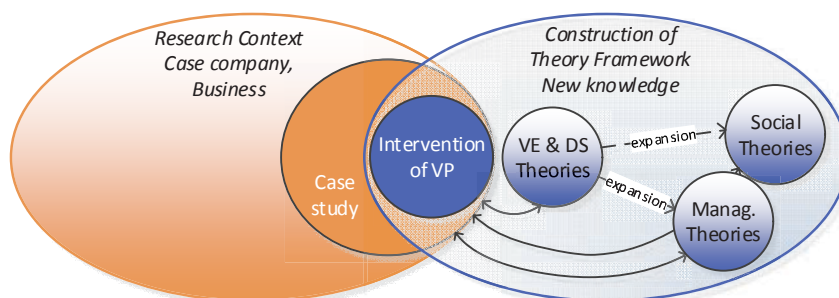
Figure 8. The relation between empirical study, intervention, existing theories, and construction of new knowledge

Formulation of research questions and research strategy

Based on the research objectives, the formulation and elaboration of the research questions will be explained in this chapter, including reasoning and justifications for why the questions were set, why these questions are important, and why the researcher wants to ask these questions.

The research questions were formulated in order to study the research problem from three different aspects: 1) prescribing a theory foundation for value modelling, 2) describing empirical value, and 3) describing the empirical impact of VP. From these aspects, the following research questions were formulated:

1. **How can the value of virtual environment-based virtual prototyping be framed, conceptualised, evaluated, and justified?**
    This question recognised the need for a means for value evaluation, and the missing link between virtual prototyping and engineering design. Therefore, it aimed to construct the theory framework for value evaluation and justification.

2. **How can the empirical value of virtual prototyping be observed, concretised, and described?**
    This question aimed to reveal empirical evidence on virtual prototyping value, and to test and iterate the constructed theory framework. Thus, answering this question should also produce practical knowledge of virtual prototyping value.

3. **How and by what means does the intervention of virtual prototyping affect the case company?**
    This question studied the possible positive and/or negative empirical impacts of virtual prototyping. Thus, answering this question should also produce practical influences of virtual prototyping in industry.

The research strategy was formulated in order to answer the research questions, and to create new scientific knowledge. This task required selection of relevant scientific theories and models. This was done iteratively during the progress of the research, and gained understanding of the problem. The research was scoped (see Chapter 1.2) from several viewpoints in order to acquire enough scientific contribution, but avoiding too wide a research area. Suitable methods were selected in order to gather data, analyse data, and draw results and conclusions from the data. Figure 9 below illustrates the logical progress of the research, and the dialogue (Jørgensen, 1992) between theories and empirical research. The strategy for answering the research questions and constructing new knowledge is discussed below. The selection of a theory basis and research methods is explained in detail later.

   The research was focused on the context of product design and development in manufacturing industry, and particularly on design for product lifecycle including

manual work i.e. human-machine and socio-technical system aspects. Therefore, theories, concepts and models from Design Science were chosen as scientific foundations. Another key concept of the research is virtual prototyping, aided by virtual environments and virtual reality, which guided the selection of a theoretical basis for that area. The third focal concept is value, which is a very wide and context-dependent concept. The research problem in hand focused the study of value concept to business and management related theory. A literature review also aimed to find out what has already been published about possible problems, advantages and the value of VP, and what kind of models and methods there exist for value evaluation.

The practical problem, i.e. justification of value of VP for industry, naturally lead to a research strategy which conducts studies in the field. The scientific approach formulated this practical problem for establishing a conceptual framework for solving this problem. Case study research was selected as a suitable method for the field study, which first required the synthesizing of a theoretical hypothesis that structures case data gathering and analysis. The material was gathered in case studies with the use of several methods including observations, workshops, simulation games, interviews and questionnaires. The existing literature points out that, generally speaking, benefits and value propositions are at least partially justified by decreasing problems in processes such as product development. Consequently, as part of the case study-typical problems in product design and development, therefore, opportunities of VP were studied by means of interviews and questionnaires as well. This conceptualization aimed to answer the first research question: *How can the value of virtual environments-based virtual prototyping be framed, conceptualized, evaluated and justified?*

Socio-technical aspects such as manual work were emphasized because of the nature of the case company's product lifecycle, where manual work is a remarkable factor for instance in assembly and maintenance functions. Analysis and categorization of the gathered material lead to a conclusion, that one major root cause of problems is related to poor communication and collaboration within the product development and lifecycle. Therefore, the literature was studied in order to find theories that support modelling value at a level of organizations and processes. A resource-based view of the firm was recognized as a starting point for theory expansion.

In order to reduce existing problems in product development, VP was introduced in the case company during two research projects. Both projects aimed to improve product development with an emphasis on manual work during the product lifecycle. Virtual prototyping was presumed to support reaching the aimed goal. VP was utilized in several true product development projects. The success of VP intervention was studied with the following research question: *How can the empirical value of intermediary virtual prototyping be observed, concretized, and described?*

The case study material gathered was analysed by means of conceptual model-ling[5] and categorization reflecting the hypothetical model and categorization of the benefits, problems and premises of VP that were found. The analysis revealed that the hypothetical model only partially explains the observed advantages of VP. Nevertheless, the conclusion of this part included factors that guided a further literature review and expansion of the theory framework. Based on the analysis and categorization, there were advantages that should be studied further in the dimensions of engineering design (design object and process), social aspects (individuals and organisation), and business and management.

The expanded theory framework was again reflected with the empirical material gathered from the case study and discussed with the literature. This enabled the establishment of solid links between concepts of the different value dimensions, better justifying the advantages and value elements of VP. Furthermore, the case results were discussed in order to answer the third research question: *How and by what means does the intervention of VP impact the case company?*

This strategy of answering the research questions can be considered to be suf-ficient in order to find solutions to the research problems. Answering the first ques-tion creates knowledge about how value VP can be evaluated based on the theo-retical framework. Furthermore, answering the other two questions creates new knowledge on value manifestations in the case company as well as impacts on the case company. The validity and generalizability of the results will be discussed at the end of this thesis.

---

[5] "Conceptual modelling is the activity of formally describing some aspects of the physical and social world around us for the purposes of understanding and communication." (My-lopoulos, 2008)
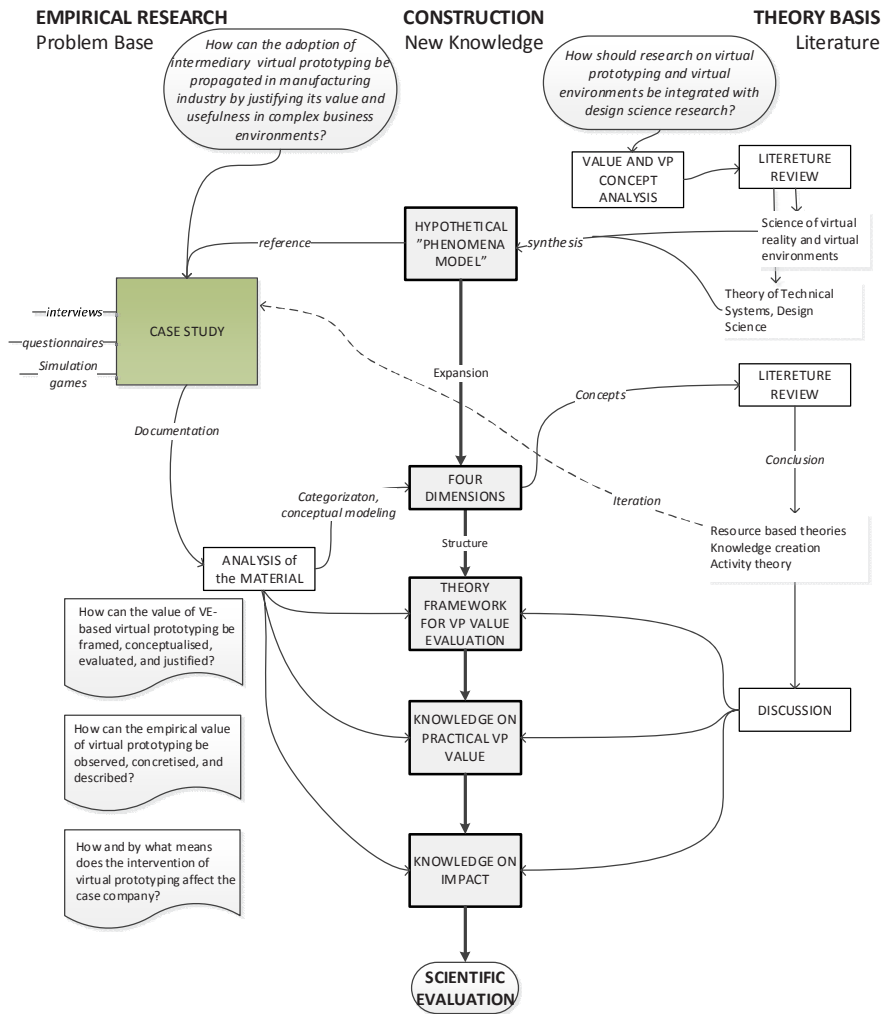
Figure 9. The practical research approach, beginning from the practical and theoretical problem base. The process is an iterative and expansive dialogue between the empirical case study, and literature. The first iteration was based on the "Phenomena model" reflecting the case data, which led to the four dimensions of value. This guided to further consultation of literature, and new iterations. Finally, the research questions were answered by producing the theoretical framework, knowledge on VP value, and knowledge on practical impacts to the case company.

Scientific theories and models

This chapter briefly introduces the theories and models that are the basis for the work, and what the relation is to the research problem. Engineering design theory is the starting frame, but it is not sufficient for modelling the value of virtual prototyping. Based on the experience of the author, and based on the empirical case findings, value of virtual prototyping cannot be modelled solely with a mechanistic engineering approach. The business and organisational value dimensions also require soft approach.

This research investigates the value of VP from several viewpoints: virtual environments-based virtual prototyping technology, product design and development, organizational and management, while the main contribution is on design science. The selected theories cover a wide and multi-disciplinary approach. The selection of the theoretical basis followed the research process introduced in the previous chapter and in Figure 9. Engineering design theory was a natural basis, because VP was studied in the context of product design and development. The essential theoretical basis of this research includes engineering design theories described by Vladimir Hubka and W. Ernst Eder in their books Design Science (Hubka & Eder, 1996) and Theory of Technical Systems (Hubka & Eder, 1988). The intention of these theories is to describe knowledge of what the object of designing is on at an abstract level, how the object (i.e. product, machine, etc.) can be spelled or modelled, and what design is as a research subject or development target. Hubka defined the Theory of Technical Systems as a sub-theory derived from general system theories. Other key theories consulted that are related to Design Science and Theory of Technical Systems are Domain Theory of Andreasen (1980), and Theory of Dispositions of Olesen (1992).

Virtual environments and virtual reality were the particular technologies used in virtual prototyping. Therefore, theory of virtual environments was a self-evident choice. The theory selected was adopted from the book "Science of Virtual Reality and Virtual Environments" by Kalawsky (1993). Value and management theories were consulted as part of this research as a basis for constructing valuing models for VP. The theories aimed firstly to define the meaning and concept of value, and its several aspects including objective and subjective, exact and abstract, quantitative and qualitative value. When the concept of "value[6]" was clarified, value configuration (Stabell & Fjeldstad, 1998) and value network analysis (Allee, 2008) turned out to be appropriate theories, because in the end value is created and captured in the business of companies. Those theories also refer to the resource-based view (Wernerfelt, 1984) and knowledge-based view (Sveiby, 2001), (Nona-

---

[6] Oxford Dictionaries defines the concept of value as: A. the worth, desirability, or utility of a thing, or the qualities on which these depend; B. worth as estimated, valuation; C. the equivalent of a thing; what represents or is represented by or may be substituted for a thing; D. something well worth the money spent; E. the ability of a thing to serve a purpose or cause an effect.

ka, 1994) to the firm, which explain the empirical findings of the research study well, and construct them as knowledge about value from organizational and management point of view. Theory of Expansive Learning (Engeström, 2001) built on the Activity Theory (Vygotsky, 1978) and theory of human factors and ergonomics, see e.g. Eason (2013) contribute to the research by providing a social and sociotechnical scientific aspect that supports the other theories.

Perspectives of the author's worldview

The researcher's background is strongest in the fields of engineering design, product development, virtual prototyping and virtual environments with an emphasis more on design than on engineering disciplines. The work of the researcher has been mostly related to research projects which include a strong emphasis on human factors. He has been involved in numerous research projects aimed to developing, for instance, manual assembly and maintenance work. The research projects enabled observations and experience of the virtual prototyping-aided development of human-machine systems.

The researcher has a relatively long history (over fifteen years) with virtual prototyping, first on technical system modelling and later more on process and methodology development. Today, the researcher's emphasis is mostly on the real utilization of this methodology in industry, questioning why it is not more widely adopted. The benefits and value of VP has been a research problem for a very long time, and a comprehensive method of value estimation is lacking. According to the author's long experience of VP, the interest and challenges have been shifting from technical issues towards industrial processes and value thinking, because VP technology has become mature enough.

Selection of research methods

Here the researcher will describe the justifications for selecting certain research methods in order to answer the research questions. The set of methods will be elaborated as the research progresses.

Selected research methods for the constructive approach. The formulated set of research questions and selected constructive approach determined the boundary of relevant research methods for gathering and analysing data and concluding results. Constructive research typically includes empirical investigations where quantitative (e.g. controlled experiments or surveys) or qualitative (e.g. case studies) methods are used (Crnkovic, 2010). Thus, a major question was the choice between quantitative and qualitative methods. The nature of design research is such that mostly qualitative methods are suitable. That was the case in this research as well, where a case study in an industrial context was selected as an appropriate method. The case studies had an action research and formative approach (Blessing & Chakrabarti, 2009) in the sense that the researcher was not just an observer, but participated in the development of VP himself.

Case study research. Design is carried out in a social and managerial context and therefore design research should draw on social science (Hubka & Eder, 1988). The case study is but one of several ways of doing social science research (knowledge of individual, group, organizational, social, political and related phenomena), while others include experiments, surveys, histories, and economic and epidemiologic research (Yin, 2009). According to Yin, each of these methods has particular advantages and disadvantages depending upon three conditions: the type of research question, the control an investigator has over actual behavioural events, and the focus on contemporary as opposed to historical phenomena. In general case studies the preferred method is when: a) "How" or "why" questions are being posed, b) The investigator has little control over events, and c) The focus is on a contemporary phenomenon within a real life context.

Typically, case studies include direct observations of the events, and interviews of the persons involved in the events (Yin, 2009). Yin has defined case study research as follows:

- An empirical inquiry that: a) investigates a contemporary phenomenon in depth and within its real-life context, especially when b) the boundaries between phenomenon and its context are not clearly evident
- The case study inquiry a) copes with the technically distinctive situation in which there will be many more variables of interest than data points, b) relies on multiple sources of evidence with a triangulating fashion, and c) benefits from the prior development of theoretical propositions to guide data collection and analysis

The most important application is to explain the presumed causal links in real-life interventions that are too complex for the survey or experimental strategies. A second application is to describe an intervention and the real-life context in which it occurred. Thirdly, case studies can illustrate certain topics within an evaluation, again in a descriptive mode. Fourthly, the case study strategy may be used to enlighten those situations (Yin, 2009).

1.5   Data collection, analysis and results of the research

Each case study and unit of analysis should either be similar to those previously studied by others or should innovate in clear, operationally defined ways. In this manner, the previous literature can also become a guide for defining the case and unit of analysis (Yin, 2009). Study of the literature was conducted firstly in the research clarification phase in order to clarify the concepts and gather understanding of the field. Later, when the research progressed and the theoretical framework expanded, the literature was included intermittently when new aspects were identified studied inter-disciplinarily. Relevant theories and state-of-the-art were searched from scientific databases.

The data gathering methods in the case study of this research included interviews, questionnaires, observations, workshops, design review meetings, simula-

tion games, and discussions with experts and other researchers. The empirical data was gathered in the case study within two large research projects in one manufacturing company during 2006–2014. In this research, qualitative data was analysed mainly by logical concept mapping models and categorization.

The research results were derived from the literature, theoretical basis and the analysis of the empirical case studies. The results include three main types of knowledge: 1) proposed theoretical framework model as a scientific foundation for evaluating value of VP in the case company in a manufacturing industry context; 2) knowledge of the benefits and value as well as drawbacks of VP in practice; 3) knowledge of impacts of adopting VP in industry. These results are discussed and reflected on with the literature in one section of this thesis, and the quality of the results is then discussed. Some results of the research projects and case studies were published during the projects, and the articles were one source of material for this research. The researcher was one of the authors of many of those papers.

1.6   Scientific contribution and novelty of this thesis

The scientifically novel contribution of this thesis is as follows:

1. Construction of a theoretical framework for modelling the value of real-time and interactive virtual environments-based virtual prototyping was proposed and discussed. The proposed framework enables structured and qualitative analysis of virtual prototyping value in industry. The novelty of the framework emerges from the ability to justify how technical elements of virtual prototyping logically contribute to value creation in the dimensions of engineering design, social aspects, and business management.
2. Contribution to engineering design theory by integrating virtual prototyping, human factors, and business management. The thesis discusses unifying theoretical concepts between the disciplines of engineering design, virtual prototyping, social science and business management. The discussion resulted in the proposed new concept of intermediary virtual prototyping (IVP) which integrates the dimensions of the four disciplines. The IVP as an intermediary object enables shared mental models and expands the product development activity system.
3. Reflecting empirical case data with the proposed theoretical framework producing new practical knowledge on the value and impact of VP, and contributing to theory in the four dimensions by validating the utility of theories as a means for analysing and explaining empirical data in the four dimensions.
4. The empirical evidence is discussed with the anticipated benefits described in the literature. The discussion was carried on from the perspective of a partially configurable products and manual work-intensive variant production mode. This perspective is novel compared to the majority of virtual prototyping and virtual environments literature. It is proposed that IVP is particularly beneficial in this context, where human skills and knowledge contribute to the flexibility of production system.

1.7   Structure of the thesis

The thesis is divided into nine sections (Figure 10), including this introduction. Each section treats one phase of the research process. At the beginning of each section, the purpose of the section is clarified. At the end of the section is a short conclusion to the section as well as a link to the next section. The sections are:

Introduction of the research and state of the art	1. Introduction	WHY and HOW the research is performed?
	2. Literature review	
Introduction of the applied theories and prescriptive theory framework	3. Theoretical basis of the research	WHAT theories are used and WHY?
	4. Phenomena model of virtual prototyping	
Description of case study and analysis of empirical data	5. Case study	WHAT is studied and HOW it is analysed?
	6. Construction of the extended value framework	
Extension of the theory framework and discussion of the empirical findings	7. Discussion on the constructed value dimensions	HOW the findings can be explained?
Discussion on research results and success of the research	8. Discussion on the research process	WHAT are the contributions and propositions? HOW validity of research can be justified? WHAT are the main implications?
	9. Summary and Conclusion	

Figure 10. Outline of the research.

The next section describes the results of literature review and concludes what is known already in literature, how virtual prototyping is defined and where are the most significant gaps of knowledge. The literature review also guided the selection of theoretical basis of the research and gave hints about an appropriate approach for value modelling. The literature review is followed by the introduction of the most significant theories that were selected as basis for establishment of a theory frame for VP value. Theories are mainly used as means for explaining scientifically the empirical case study findings, and to establish links between the notions and concepts between theories of the value dimensions. The fourth section introduces a hypothetical theory frame that integrates theory of engineering design and theory of virtual environments and virtual reality. It is used as a starting point for analysis of the empirical data. The fifth section introduces the industrial case study and the main findings. The section number 6 describes how the empirical data is analysed and concludes the necessity of expanding the theory frame towards the dimensions of product design and development, social dimension and the dimension of business management. The concept of virtual environments based virtual prototyping is evolving, and in the section number 7, the new concept of "Intermediary virtual prototyping" (IVP) is introduced in order to emphasize the necessary dimensions of VP value. The section number 8 discusses the quality and validity

of the research process and research results. The last section number 9 gives a summary of the research and answers to the research questions. The section includes also a quite extensive conclusion on the value and impact of VP in the case company, as well as general implications and recommendations for future research.

2. LITERATURE REVIEW

First this section introduces the general challenges and trends in industry, and specifically in the context of product design and development activity. The situation concerning human factors is introduced based on literature, because human factors were an essential element in the case study. These perspectives can be considered as drivers for adoption of virtual prototyping in companies. After that, the state-of-the art and definitions of virtual prototyping are introduced. Value models and theories in literature were studied in order to find out how value can be described and modelled. Finally, it is concluded where the gap in scientific knowledge is, and what can be used as starting point in this research.

Purpose and approach to the literature study

General challenges in the business environment and especially in product development were presented in the Introduction. Below are listed a summary of the main challenges related to the context of this work:

- Trends such as globalization, environmental awareness, shortening product lifecycle, variety of more complicated products and complex supply chains (Ameri & Dutta, 2005), (Kropsu-Vehkapera et al., 2009), (Stark 2006), (Durmusoglu, 2009), (Ovtcharova, 2010);
- Faster, more flexible, effective and profitable product development (Ameri & Dutta, 2005), (Durmusoglu, 2009), (Horváth et al., 2010), (Kropsu-Vehkapera et al., 2009), (Stark 2006);
- The majority of companies lack the capability to effectively generate new products and sustain them over their lifecycles which is paradoxical because innovation is seen as an essential source of growth in industry (Koudal & Coleman, 2005);
- A limited holistic system lifecycle approach and cooperation across disciplines is prejudicial to success (Gerritsen et al., 2011), (Zhang et al., 2008);
- Inadequate effectivity due to a lack of an efficient knowledge management (Ameri & Dutta, 2005);
- Insufficient collaboration and information sharing within networked product development and manufacture (Ameri & Dutta, 2005);

- Lack of technologies necessary to run the innovation and production lifecycle process effectively (Koudal & Coleman, 2005).
- The current demand to reduce the time and cost involved in taking a product from conceptualisation to production has forced companies to turn to new and emerging technologies in the area of manufacturing (Mujber et al., 2004).
- Business process re-engineering is becoming a main focus in today's efforts to overcome problems in industry (e.g., globalization, product complexity, increasing number of product variants, reduction in product development time and cost) (Gomes de Sá & Zachmann, 1999).

The concept of virtual prototyping has been proposed as a means for coping with the above-mentioned challenges especially in the product design and development as well as product lifecycle context, e.g. (Gomes de Sá & Zachmann, 1999). The idea of virtual prototyping is, at least partly, to replace physical prototypes with virtual product models (Gomes de Sá & Zachmann, 1999), (Mujber et al., 2004) with the aim of reducing time-to-market and product cost. Virtual environments is one medium for virtual prototyping particularly when human and social aspects matter. The literature concerning these domains and concepts will be reviewed in the chapters following. One objective especially is to find out how the benefits and value of VP have been modelled and described in the literature, and whether there is a research gap which should be filled.

Approach to the literature study

Purpose of this section is to; based on literature study:
- To clarify the research context and focal concepts of the research; coherent concept definition
- To report the status (problems) of product design and development of human-machine systems including manual work
- What are the recognized benefits, opportunities, enablers and problems within virtual prototyping of human-machine systems?
- To ascertain existing knowledge on value of VP and value modelling. How is the value of virtual prototyping defined in the literature?
- To reveal and clarify gaps in the scientific literature concerning value and value modelling of VP
- To find and select theories and published knowledge as a basis for formulating a foundation for value modelling and the evaluation of VP.

The approach of the review was very multi-disciplinary, combining areas of engineering design, product development, human factors and ergonomics, management and economics. The literature review followed the research process described in the Introduction. Accordingly, the process and the concepts of the research were clarified first, and the research was scoped from practical and scientific viewpoints. The first review aimed to describe knowledge of the benefits and

development targets of VP combined with supporting methodology and technological platforms. When the research proceeded and some empirical data was gathered and analysed, the literature review was scoped and expanded more towards publications that are related to economic and organizational theories. The purpose was to discover potential value theories and models as a basis for a prescriptive model of VP value analysis.

The scope of this research also determines the scope of the literature review. The research was scoped on manufacturing industry, where typical products are partially configurable heavy machines. The focus there is in integrated new product development, which engages product design, productisation, production, and stakeholders during the product life. The stakeholders include a large number of manual workers, which makes human factors and knowledge management essential approaches in the design.

Structure of this section

The content of this section is structured in the chapters following so that, firstly the paradigms and trends of product design and development as a context of this research, as well as bottlenecks and challenge that virtual prototyping are proposed to decrease. After that, the literature on human factors and socio-technical aspects and VP is summarized in order to conceptualize the fields and report the gap in the literature and state of the art. Furthermore, a summary is given of published knowledge on VP value. Finally, the literature on value concept and value evaluation in this research context is summarized in order to provide a foundation for constructing the framework for VP value modelling.

2.1 Product design and development – trends and challenges

This chapter explains the context of the research, and challenges in industry related to product design and development.

Product development processes (PDPs) are the procedures and methods that companies use so as to design new products and bring them to market, and well-designed product development processes are necessary in order to reduce development time, manage risks, and create better products (Unger & Eppinger, 2011). The product development process is the central planning task in industry, containing everything that is important from the very beginning of a new product until start-of-production or life cycle (Zimmermann, 2008). Many studies are being undertaken in the field of PDP, because it is one of the main ways to gain a competitive advantage for a company (Ibusuki & Kaminski, 2007). There is a need for improving the efficiency and even more the effectivity of product development and realization, engineering methods of complex products and systems, collaborative engineering, and organizational knowledge management during the whole product

lifecycle. According to Hines et al. (2006), the problems within product development form two groups: firstly, development process effectiveness (doing the right things) from a market success point of view, which includes, for instance, problems of the lack of understanding of customer requirements, and secondly problems with efficiency (doing things right) of the development process itself, including problems, for instance, with the lack of a formal or standardised process, ineffective control of high volume development environments, poor internal communications and a lack of common focus. They also include an inability to improve or learn from mistakes. Lack of learning capability, feedback system failure, communication barriers and poor organizational memory are causes of failure in the product development process (Ameri & Dutta, 2005). Coping with these problems can also be categorised as strategic or operative objective (Gomes de Sá & Zachmann, 1999). Strategic objectives are global and involve the complete business process including a reduction in development costs, development time, and time-to-market; an increase in product innovation, product quality, flexibility, and maturity at series start. Operative objectives are more local, related to only one or a few key processes (Gomes de Sá & Zachmann, 1999).

Several methodologies exist, including practices and tools intended to cope with challenges mentioned in the Introduction. Suitable methodology depends on the type of product development in companies. Product development can be categorized as revolutionary development projects, and incremental evolutionary innovation projects (Hines et al., 2006), (Oja, 2010). New product development (NPD) can be defined as the creation of a new product from the generation of an initial concept or idea through to the decision to commercialize the product (Hines et al., 2006), or more specifically as a sequence of steps or activities that an enterprise employs to conceive, design, and commercialise a product (Ulrich & Eppinger, 2004). Design ideas as they progress will normally go through iterative development, when mock-ups and simulation of the system are necessary to support this iterative design (Maguire, 2001). For instance, systems engineering, (see e.g. Kossiakoff & Sweet, 2003) has been proposed as a holistic approach which should enable the development of large and complex multi-disciplinary products and human-machine systems. The roots of systems engineering are mainly in revolutionary development projects in the military and aerospace sector during the Second World War, and typically they utilize modelling and simulations during product development. The management of system's requirements, coming initially from different stake-holders, such as end-users, are an essential part of systems engineering. Nevertheless, systems engineering seems to be focused on technical system requirements with a limited treatment of human demands. However, based on initial requirements, there is a systematic way to define the functional, logical and physical structure of a system, and finally validate the solution against the original requirements. Nevertheless, systems engineering processes do not generally incorporate methods for systematic generation of alternative design solutions. Additionally, the traditional linear one-way (water-fall) systems engineering process does not fit today's dynamic and iterative NPD processes.

Yet there are dedicated paradigms and models, e.g. Integrated Product Development (Andreasen & Hein, 1987), Product Design and Development (Ulrich & Eppinger, 2004), Engineering Design – A Systematic Approach (Pahl et al., 2007) for producing solutions for the requirements. Anyway, the relationship between systems engineering and engineering design methods should be better defined (Bergsjö, 2009).

Other important engineering design paradigms and models to support systems engineering include concurrent engineering (CE), collaborative engineering (CE II) and product lifecycle management (Zhang et al., 2008). Concurrent engineering is a systematic approach to the integrated development of products and their related processes (Backhouse & Brookes, 1996). According to Gerritsen et al. (2011), the introduction of CE (and similar type concepts above) made the traditional staged waterfall model-based product development and realization obsolete and replaced it by asynchronous online collaboration environments. In their recent literature review (2011), Unger and Eppinger concluded that the traditional staged PDP process model (waterfall processes) is not sufficient for developing current complex products, because they are sometimes too inflexible for companies in dynamic markets (Unger & Eppinger, 2011). Therefore, methods such as concurrent function deployment, concurrent engineering, value-engineering (Ibusuki & Kaminski, 2007) and spiral process models adapted from software development (Cooper & Edgett, 2008) have been adopted in product development, enabling more flexible processes and anticipated feedback with reduced cost and risk related to technical, market, budget, and project schedule aspects. In between the two extremes (staged waterfall and spiral processes) is evolutionary prototyping, which focuses on gaining rapid feedback from early prototypes (Unger & Eppinger, 2011). Nonaka (1994) explained the rapid product development capability of Japanese firms by "rugby-style" (Takeuchi & Nonaka, 1986), which is flexible and integral, assisted by information redundancy. Later in this thesis it will be discussed how intermediary virtual prototyping can support the flexibility, efficiency and effectivity of product development in manufacturing companies. Table 2 summarises some of product development models of literature.

Table 2. Summary of product development model types and their advantages and challenges. It is essential to understand that this set of product development process types are models, i.e. prescriptive descriptions of how industrial product development can be organized in principle.

Process type	Advantages	Challenges
Staged (waterfall); e.g. (Kossiakoff & Sweet, 2003)	Controlled, stable Sharp and early frozen specifications	One way nature Rigid, inflexible
Concurrent and collaborative engineering; (Backhouse & Brookes, 1996), (Sriram, 2002)	Parallel, integrated process steps Systematic Lifecycle view	Changing requirement Knowledge management
Spiral; (Cooper & Edgett, 2008)	Flexible Early feedback Iterative	Complex Requires significant management Possible delays
Evolutionary prototyping; (Unger & Eppinger, 2011)	Fast feedback Experimental	Process not clearly defined
Rugby; (Takeuchi & Nonaka, 1986)	Parallel, integral, flexible Information redundancy Knowledge creation	Risk of confusion Lack of strict specifications

The concurrent engineering model includes a process rather than technological emphasis, customer focus and the parallel processing of activity steps (Hines et al., 2006). In turn, CE creates a new problem in that projects need to take account of changes in user requirements, context of use and base technology during design and development (Earthy et al., 2001), which in dispersed environments, knowledge management becomes even more difficult because sources of knowledge are not co-located. Even though in the customer and user requirements knowledge is dispersed and sometimes fuzzy, it should be seen as a major competitive edge for a company. The collaborative engineering design model (Sriram, 2002) fundamentally addresses control over lifecycle costs, product quality and time to market, as well as the important roles of suppliers and IT (Willaert et al., 1998). Nevertheless, any PDP model should methodically be customised to different companies (Unger & Eppinger, 2011), and in practice every PDP process is different in reality.

Product lifecycle management (PLM) is a strategic approach to creating and managing a company's product-related intellectual capital from cradle to grave, integrating organizations, processes, methods, models, IT tools and product related information (Ameri & Dutta, 2005), (Grieves, 2005), (Stark, 2006). PLM is one of the key enablers for the effective management of product development and product creation processes (Abramovici, 2007). Even though PLM should not be seen just as an IT solution (it also includes people and processes), IT is the backbone of PLM, and a good IT infrastructure capability enables efficient product process by reducing the cycle time, improving communication and collaboration as well as improving the process quality (Durmusoglu, 2009), (Eppinger & Chitkara, 2009). Important IT applications for networking engineering include communication infrastructures, computer-aided engineering tools, virtualisation or simulation

tools, engineering data management/product data management, integrated product development systems, etc. (Zhang et al., 2008). The research on PLM is still at a very early stage (Abramovici, 2007), and PLM itself is still in its growth phase (Ameri & Dutta, 2005). So far, only a few organizations exploit the true benefits of PLM because of a lack of clear understanding of what PLM is, its core features and functions, and its relationship to the many software tools (Ameri & Dutta, 2005). Companies are not sure whether and to what degree the integration of processes is reasonable (Abramovici & Schindler, 2010). In all, there is a lot of business potential which can be reached by implementing a PLM landscape more widely beyond the product design phase. This requires defining the necessary processes, practices, information models, system architectures and integrations. PLM systems extensions should include support for an information content-based product model, modelling procedures, data exchange with non-integrated modelling systems, group work management, and Internet portal communication (Horváth & Rudas, 2009).

2.2 Human factors and socio-technical aspects in product development

This chapter introduces human factors and socio-technical aspects as a discipline. Furthermore, the challenges of this discipline in respect to integration with product design and development is summarized based on the literature survey. This chapter also introduces human knowledge as the essential contribution to product design and development.

Improving efficiency and effectivity, i.e. productivity, is today an important strategy in companies for surviving in the market place, as reported in previous chapters. The Scientific Management theory (Taylor, 1911) focused on analysing and synthesising work flows in order to improve labour productivity. This emphasis on efficiency and productivity was later in the 20th century supplemented by a need to ensure that humans and technology could work well together (Hollnagel, 2014). According to Hollnagel, ergonomics or human factors (different terms for the same concept – ergonomics in Europe and human factors in America) became a scientific discipline in the late 1940s. The fundamental objective of human factors/ergonomics (HF/E) is to contribute to human performance and well-being by establishing and implementing integral system design (Grote, 2014). Human factors/ergonomics (HF/E) are important because humans are part of every product´s life at some stage. Humans may be the end-users of a machine, or they are part of manufacturing, logistics or maintenance processes. Humans' requirements are increasingly important for successful business. Therefore, end users and other lifecycle stakeholders should be a primary source of requirements. However, more cost-efficient practices are needed for gathering users' needs and requirements in real product development contexts (Kujala, 2003). There is still a lack of focus on the human aspects of product development and a lack of focus on real world envi-

ronments (Hines et al., 2006). Therefore, there are many poorly designed and unusable systems which users find difficult to learn and complicated to operate (Maguire, 2001).

According to Norros (2013), there are three established characteristics of high-quality HF/E: 1) HF/E takes a systems approach, 2) HF/E is design-driven, and 3) HF/E focuses on two closely related outcomes, performance and well-being. The area of HF/E is structured based on these three dimensions in the chapters following.

Performance and well-being. A product and a production system that is building the product (e.g. in this thesis assembly and maintenance of mining and construction machines) should be treated as a whole including human actors. The ergonomic profession aims to ensure that design or redesign of production systems considers both productivity and employee well-being, but there are many approaches to how to achieve this (Edwards & Jensen, 2014). On the other hand, Hollnagel (2014) saw that the 'mechanisms' that produce performance improvements are relatively well known, resulting in an insignificant delay and limited uncertainty, while the same is not the case for well-being. Well-being is both a mental and physiological state, and there are many things that can affect this, but the relation is often indirect and delayed (Hollnagel, 2014).

Systems approach. HF/E is a systems discipline and profession, applying a systems philosophy and systems approaches (Wilson, 2014). The term system ergonomics refers to the theory and application of human behavioural and biomechanical science to the analysis and design of complex technical systems involving both people and machines (Sheridan, 2014). According to Dul et al. (2012), HF/E defines a system: "*Ergonomics (or human factors) is the scientific discipline concerned with the understanding of the interactions among humans and other elements of a system, and the profession that applies theoretical principles, data and methods to design in order to optimize well-being and overall performance*". Systems approaches in ergonomics recognize that people at work often engage in tasks as part of a complex system and that this has profound effects on them and their task performance (Eason, 2013).

Human factors are also discussed in the Theory of Technical Systems (Hubka & Eder, 1988) as part of socio-technical systems and transformation systems. In TTS, the concept of ergonomics was defined as the study of relationships between humans and technical systems, especially direct interactions between them. The term ergonomic also refers to a property of a technical system. The designers' task is to allocate appropriate tasks for the human being and for the technical system, as well as creating decent ergonomic properties for the technical system. In TTS, Hubka and Eder referred to general systems theory, but also to cybernetics theory.

Cybernetics theory (Wiener, 1954) was developed firstly in order to analyse the potential of machines to amplify human capabilities, and thereby release them from the monotony of manual labour. Nevertheless, while the cybernetic objective of amplifying human capabilities is quite similar to what HF/E aims to do, the similarity of the objectives obscures a fundamental difference in the approaches

(Hollnagel, 2014): "*Where the ambition of HF/E is to design artefacts and work situations, the ambition of cybernetics is that we modify ourselves in the sense of understanding how the environments that we create affect what we can do, and vice versa*". However, according to Wilson (2014), systems ergonomics aims to design a system as whole rather than concentrating on an individual part of it. Designing and developing a rock crusher with its assembly, maintenance and whole lifecycle including the needs of human stakeholders is an example of such a system ergonomics approach.

Concerning socio-technical systems, there is also a distinction between so-called hard systems (the systems engineering approach) that are outside ourselves and that can be engineered to work better, and soft systems where the world is taken to be very complex and mysterious (Checkland, 2000). Sociotechnical systems are heterogeneous systems constituted of components (artefacts and people) with very different characteristics (Eason, 2013), and very different concepts and terminology (Sheridan, 2014). People are learning and adapting organisms, not just resource components of the system. Therefore, people should also be seen as designers of their work system (Eason, 2013). Additionally, a socio-technical system should be treated as an open system, meaning that the boundaries of the system are difficult to define, and the environment has impacts on the system (Eason, 2013). The increased complexity of socio-technical systems induces dynamic changes and loads the systems with unexpected phenomena (Norros, 2013).

Design-driven. Currently, HF/E seeks to improve performance and well-being through analyses and assessments of systems resulting in recommendations for systems design (Dul et al., 2012). However, from its earliest manifestations, the sociotechnical systems theory used to analyse existing systems, it is a short step to trying to influence design so that a more effective sociotechnical system can result (Eason, 2013). HF/E is shifting from evaluation towards design, and the shift is driven by following factors (Edwards & Jensen, 2014): In the early design phase, there are more options, the cost of changes is much lower than in the phase of physical manifestation of the plan, and such shift would have a significant positive effect on the overall effectiveness of the system. Nevertheless, Norros (2013) has concluded that becoming design-driven is needed, but it appears to be the most difficult quality target for HF/E to reach. In order to become design-driven HF/E experts and scientists must adopt a creative mind-set and become designers themselves.

Socio-technical systems, such as products and production systems (e.g. mining machines) cannot be designed without the engagement of the people who will use them, so participative and user-centred methods for new systems design have been developed (Eason, 2013). User-Centred Design (UCD) and Human-Centred Design (HCD) are design approaches based on the active involvement of users in improving the understanding of user and task requirements, and the iteration of design and evaluation (Mao et al., 2005), (Vredenburg et al., 2002), (Maguire, 2001). Most literature considers UCD and HCD as synonyms, but some sources distinguish that HCD emphasizes more the needs of different stakeholders in

broader contexts (Zhang & Dong, 2009). They are described in several standards. ISO 13407 and ISO TR 18529 summarize good practice for each human-centred design process in the lifecycle (Earthy et al., 2001). On the other hand, ergonomic standards often focus on the physiological aspects of human performance, while subjective factors such as knowledge and competences are not well represented in the guidelines (Darses & Wolff, 2006). Participatory design is the bottom rung for the user involvement philosophy. It introduced the idea of bringing end users and other stakeholders into direct contact with designers (Kujala, 2003). Participatory design has been promoted as an approach to secure optimization of both the economic and ergonomic aspects of work (Vink et al., 2008).

Engineering design reviews are fundamental elements for the evaluation and control of engineering design activities, and opportunities for all the parties to share information about the product and related processes (Huet et al., 2007). Ideally, formative evaluations of sociotechnical systems are carried out by implementing pilots, demonstrations, scenarios or trial versions of new technical systems, making the implications of the new system evident to everybody (Eason, 2013). Although traditional tools are still used in industry (Aromaa et al., 2012), several studies of the use of virtual environments in the review meetings have been reported, e.g. (Bordegoni et al., 2009), (Kremer, 1998), (Aromaa et al., 2012), (Leino et al., 2010), (Heikkilä et al., 2011), (Becker et al., 2011). The use of the VEs addresses the natural feel of the task and illustrative presentation of the model (Aromaa et al., 2012), which is particularly beneficial when combined with a participatory approach and human-centred design method.

Although virtual environments and participatory approaches have been seen as beneficial for the review meetings, unfortunately their potential in product design is still not fully taken in to practice in industry. Based on a literature review (Leino & Riitahuhta, 2012), the main gaps are related to lack of practical and adapted implementations of HF/E in product design and development, integration of virtual prototyping and virtual environments to product processes, data flow between virtual engineering applications and data management systems.

User- and human-centred design methods and participatory design approaches have been accepted as a means for improving human-machine system development in industry (Mao et al., 2005). Nevertheless, there is an urge for more practical and adapted implementations of the user- (or human-) centred design approach for a specific product development context in manufacturing companies. UCD/HCD should be implemented within product development processes so that many stakeholders, including end users, internal customers and designers, could participate and experience product models, i.e. virtual prototypes, through virtual environments.

Gaps and challenges. According to Wilson (2014), acceptance of the need for and value of the systems orientation of ergonomics and humans factors is increasing. However, Dul et al. (2012) asked why knowledge in human factors and ergonomics has not yet found wide-spread acceptance and application, and answers to this question: because relevant stakeholders are not aware of this knowledge, and the knowledge is multi-faceted and ambiguous. This problem should be ad-

dressed by positioning socio-technical system design as a strategic task based on a conceptual framework that practically links business and HF/E concerns (Grote, 2014). People who design technical systems and managers who create social systems do not speak a shared language (Eason, 2013). Norros (2013) added that the underexploited potential of HF/E is related to the stakeholders in the design and management of organisations who typically focus on performance outcome. According to Norros, insufficient awareness of the value of HF/E, lack of high-quality, limited scope, small size with vague identity of discipline may be the reasons for this. Evidence of the impacts of HF/E criteria in production system design is limited, and it is not clear how to integrate HF/E in the design of production and service systems (Edwards & Jensen, 2014). On the other hand, socio-technical systems are the product of many different design processes spread out in time and space resulting in a situation where no one designs the whole system (Eason, 2013).

The user/human-centred design method is gaining industry acceptance, but its current practice needs fine-tuning (Mao et al., 2005), because contextualized process statements written as generic methodologies are difficult to adapt to a particular project or business context (Earthy et al., 2001). Common characteristics of an ideal UCD/HCD process were not found in practice (Mao et al., 2005). However, the benefits of UCD/HCD include increased productivity, reduced errors, reduced training and support, improved acceptance, and enhanced reputation (Maguire, 2001). A multidisciplinary approach to UCD/HCD appears to be closely related to perceived effectiveness (Mao et al., 2005). In practice designers do not often have many direct inputs concerning the real needs of the end users. Nevertheless, physical and virtual prototyping and user trials can bridge the gap between designers and users (Darses & Wolff, 2006).

Capitalizing on knowledge. Development of socio-technical systems, such as design and production of mining machines in compliance with decent HF/E practice is a very knowledge-intensive task. Knowledge of such system users should be captured in the product development process. Knowledge is a multifaceted concept with multi-layered meanings (Nonaka, 1994). In this context the definition of Ameri and Dutta (2005) is valid: "*Knowledge is evaluated and organized information that can be used purposefully in a problem-solving process*". On the other hand, (Nonaka, 1994) emphasized the dimensions of absolute, static and non-human nature of knowledge, and the dimension of dynamic human process of justifying personal beliefs. Nonaka (1994) continued about information as pieces which may change, restructure or contribute to knowledge. Ameri and Dutta added that, compared to knowledge, data and information are much easier to store, describe and manipulate. Therefore, systematic management of organizational knowledge is a demanding task (Ameri & Dutta, 2005). Because of its tacit nature, HF/E knowledge is typically difficult to communicate, capture and manage. In a typical organization, only 4% of organizational knowledge is available in a structured and reusable format, while the rest is either unstructured or in peoples' minds (Ameri & Dutta, 2005). Today's industry recognizes the potential of knowledge management. However, the challenges of a successful adaptation and

implementation of product lifecycle knowledge management are tremendous (Gerritsen et al., 2011), because knowledge captured in one context must be made usable in a different application and context, in closed loops back and forth (Kiritsis, 2011). Additionally, there is lack of understanding as to what product knowledge management actually means. Challenges are related to knowledge capturing, transferring and sharing. We are lacking methods, tools, procedures and infrastructure are lacking for efficient knowledge management.

Nonaka (1994) argued that the organisations should be studied from the viewpoint of how they create information and knowledge, rather than how they process these entities. Nonaka (1994) proposed a paradigm for managing the dynamic aspects of organizational knowledge creating processes. Its central theme is that organizational knowledge is created through a continuous dialogue between tacit and explicit knowledge. In their later article, Nonaka and von Krogh (2009) systematically and comparatively analyse the on-going debate on organizational knowledge creation theory. Nonaka's paradigm of organizational knowledge creation theory includes two main premises: Firstly, tacit and explicit knowledge can be conceptually distinguished along a continuum, and secondly, knowledge conversion explains, theoretically and empirically, the interaction between tacit and explicit knowledge. Nonaka's theory includes four different "modes" of knowledge conversion.

2.3   Virtual prototyping with virtual environments

This chapter first discusses the terminology related to virtual prototyping, and then establishes the definition that is adopted in this research. After that, the state-of-the art of virtual prototyping within the scope of this research is summarized. Finally, the expected benefits and the real evidence of benefits of virtual prototyping in literature are summarized.

There exist many tools, methods and frameworks proposed as a means for coping with the challenges mentioned at the beginning of this section, such as systematic product design and development methods, human factors and ergonomics, and knowledge management. Their efficacy has been proved in many case studies and publications (Leino & Riitahuhta, 2012). Virtual prototyping and virtual environments have been proposed as an additional tool and methodology for improving the efficiency and effectivity of product processes. Nevertheless, holistic business and organizational value of virtual prototyping is vague in industry. The literature survey of Leino and Riitahuhta (2012) revealed that mainly limited case studies of virtual prototyping have been published, and they are mostly very technically oriented and lack the business value approach.

There are a number of computer aided engineering (CAE/CAx) tools and methods developed in order to streamline product processes and collaboration within value networks of product processes. They can be named in many ways, for in-

stance "virtual engineering", "virtual prototyping", "virtual reality", "virtual environments", "simulation based engineering", and "digital mock-ups". Terminology in this area is still scattered in the literature, and even more so in industry. However, those examples of terms mentioned are conceptually different, but they are often used as synonyms. In the first place, in this context the word "virtual" can be understood in two degrees. In the narrow sense it indicates adopting VR technology, and in the broad sense it indicates utilizing computer simulations and digital models to carry out the product design and manufacturing activities before the physical product has been manufactured (Liu et al., 2006), (Gomes de Sa & Zachmann, 1998). Another distinction can be seen between the virtual prototype as combination of functional models of different engineering domains and the virtual prototype as multisensory and multimodal interface (Ferrise, et al., 2013), and between immersive virtual prototype and analytical prototype (Tseng et al., 1998).

One fine definition of virtual prototyping with reference to virtual engineering, virtual product development and virtual reality was provided by Weber and Husung (2011). Their definitions are mostly in line with the definitions of this thesis. However, the term "virtual engineering" is not used in this thesis because for the author the term "engineering" sounds limiting from the human factors viewpoint. In this thesis, the term virtual prototyping is used as a higher level framework where virtual environment and virtual reality-based applications belong. As stated in the Introduction, one objective of this thesis is to conceptualize the focused virtual prototyping sub-set and to clarify the terminology in this area.

After the establishment of CAx technology, there was a necessity to extend virtual development by enhancing visualization quality and real-time intuitive applications by means of VR (Zimmermann, 2008). On the other hand, this subset of virtual prototyping, namely virtual reality and virtual environments, includes a whole family of technologies used in various circumstances (Wilson & D'Cruz, 2006). Besides visualization, other human modalities such as hearing and touch may also be supported with those technologies. The virtual reality configuration needed depends on the purpose of the system, for instance which product properties are evaluated with a virtual prototype.

Definitions of virtual prototyping. In the product development process, prototyping is an essential step (Ulrich & Eppinger, 2004). Prototypes represent the important features of a product which are to be investigated, evaluated, and improved (Mujber et al., 2004). In their book, Ulrich and Eppinger (2004) define the term 'prototype' as "an approximation of the product along one or more dimensions of interest". This definition includes such diverse forms of prototypes as concept sketches, mathematical models, and fully functional preproduction versions of the product. Virtual prototypes must support the same purposes and even more as a physical prototype (Wang, 2002). It is essential also to understand that, in this respect, virtual prototype is not a single monolithic computer model, but is configured in different ways for different engineering design purposes (Ferrise et al., 2013). Wang (2002) has proposed a definition and components for virtual prototyping (VP) terminology, as well as providing a review of the area of VP in engineering design: "*Virtual prototype, or digital mock-up, is a computer simulation*

of a physical product that can be presented, analysed, and tested from concerned product life-cycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physical model. The construction and testing of a virtual prototype is called virtual prototyping (VP)". The definition of (Weber & Husung, 2011) is quite well in line with Wang's definition, but it builds a link to design theory. According to Weber and Husung, virtual prototyping means "constructing computer-based representations of an artefact that may physically not yet exist", while the term virtual prototype as a result consists of characteristics of the artefact and dependencies between characteristics. In the terminology of Weber and Husung, "virtual engineering" means applying analytical methods/tools to virtual prototypes in order to predict the relevant properties of the artefact, while virtual reality is a means for more immersive and intuitive assessment of the properties. This is the point where the definitions of Weber and Husung (2011) and Wang (2002) differ from each other. Weber and Husung (2011) defined virtual prototyping similar to physical prototyping which in their view does not include testing the prototype. However, definition of virtual prototyping in this thesis is closer to Wang (2002), because, according to e.g. Hubka and Eder (1988), prototypes are built for testing and evaluation purposes.

According to Wang (2002), a complete virtual prototype should essentially include three types of models: a 3D solid model, a human-product interaction model, and a perspective test related models, whereas (Cecil & Kanchanapiboon, 2007) have defined a virtual prototype as a three-dimensional virtual reality (VR)-based model which seeks to "mimic" a target (or "real-world") object, system, or environment. Harrison et al. (2011) see that virtual reality refers to computer-generated 3D real-time environment where users interact with the simulated environment. Ferrise et al. (2013) introduced a concept of interactive Virtual Prototype (iVP) which means the result of the conversion of net of interconnected functional, multiphysics and multi domain virtual prototype models into multisensory functional models. Accordingly, VR technology combines multiple human–computer interfaces so as to provide various sensations (visual, haptic, auditory, etc.), which give the user a sense of presence in the virtual world (Seth et al., 2011). VR technology usually refers to the hardware, software, and the related peripherals needed to create a virtual environment, such as sensors, motion trackers, 3-D eye wear, etc. (Cecil & Kanchanapiboon, 2007). These slightly different definitions use different concepts and terminology, but the fundamental philosophies are similar.

In this book, the following definition is used:

- Virtual prototyping is a model-based methodology that aims to support product design and development activity in companies by providing computer-based, interactive models of a not yet existing product, including relevant aspects of its behaviour
- Virtual environments are computer simulation- based environments which aim to improve users perception and interaction with the product and socio-technical system model and its behaviour
- Virtual reality refers to technology which enables building the virtual environment

Concerning the applications of virtual reality and virtual environments, two distinct approaches can be seen in adopting virtual reality and virtual environments for engineering design (Raposo et al., 2006), (Mujber et al., 2004): 1) Constructing 3D models in VE, and 2) Visualising 3D models in VE (e.g. virtual prototyping, design review). By virtual prototyping, Mujber et al. (2004) understand the application of virtual reality for prototyping product and process data. In the context of this thesis, 3D models are not constructed in VE, but they are used and analysed in virtual prototyping. VR-aided design is mostly on top of conventional CAx design, while creative designing in a virtual environment without data from previous steps is still a subject of research for universities and institutes (Zimmermann, 2008). Current VR research is either directed to extend applications to various domains or to achieve a better exploitation of present technology, such as increased computing and graphics power (Ovtcharova, 2010)

State of the Art. The book "Product Engineering – Tools and Methods based on VR" edited by Talaba and Amditis (2008) firstly summarizes recent research in Europe on virtual environments and virtual reality including barriers related to technology, interaction concepts, integration, as well as a drivers for change concerning industry requests, socio-economic factors, and technology. The book comprises research papers from both academia and industry dealing with topics such as VR-aided product design and engineering, manufacturing and assembly, and case studies in the automotive and aerospace industry sectors. (Amditis et al., 2008) summarizes state of art of virtual reality in Table 3:

Table 3. Summary of research barriers by Amiditis and Talaba (2008) (Amditis et al., 2008).

Research barrier category	Explanation
Technology	• The simulation technology (hardware and software) is still immature, unfriendly, complex and of limited usability; • Lack of adequate bandwidth, particularly for simulating the human sensory system; • Accuracy of available spatial tracking techniques is not yet sufficient; • The current application systems serve highly customized needs but is lacking in efficiency • Synchronization of multimodal and multi-sensory components is still low
Interaction concepts	• Lack of immersive 3D user interface paradigms, mainly due to an imperfect understanding of spatial interaction at a cognitive level, and computer-mediated "presence" and its impact; • There is no standard evaluation methodology for spatial interaction or presence; • It is still doubted whether VR/AR interaction techniques can assist in improving understanding and access to abstract data
Integration	• There is a vast need for interoperability among VR systems, and also among relevant applications such as CAD, CAE, PLM, etc.;

	• The lack of standardization leads to an undesirable personalization and large amounts of non- reusable data; • Not all VR/AR systems can be integrated into existing workflows, thus raising the cost of the VR/AR investments tremendously
Socio-economic issues	• VR systems are still very expensive both in terms of hardware and software applications; • There is no valid general ROI evaluation; • Concerning the social issues, humans do not easily quit learned habits; therefore they become reluctant in using new interfaces

Virtual environments as a means of virtual prototyping has been largely investigated and used in entertainment and military applications, and the aerospace industry (Ottosson, 2002). Recent applications of virtual prototyping include, for instance, assembly and manufacturing (Gomes de Sa & Zachmann, 1998), (Chryssolouris et al., 2000), (Choi & Guda, 2000), (Hu et al., 2010), (Seth et al., 2011), (Ottosson, 2002), (Sousa Santos et al., 2008), (Mujber et al., 2004), (Di Gironimo et al., 2014); maintainability (Hu et al., 2010), (Peng et al., 2010), (Lind et al., 2008); ergonomics (Pang et al., 2006), (Wang, 2002), (Ottosson, 2002), (Brooks, 1999); safety engineering (Määttä, 2003); design review (Sousa Santos et al., 2008), (Brooks, 1999); and verification (Mujber et al., 2004). Wilson and D'Cruz (2006) have concluded that industrial design, product testing, planning and training are applications which seem both highly feasible and potentially profitable, apart from medical and military applications.

While most commercial computer-supported tools address specific engineering issues (e.g. FEM, geometric modelling, etc.) and support the solving process of well-defined problems (Ovtcharova, 2010), we are lacking the tools to support cross-disciplinary work (Boujut & Laureillard, 2002). Furthermore, Boujut & Laureillard (2002) underscore the uselessness of the produced information itself in its transformation into knowledge and action on the product as a whole (i.e. the manufacturing process, sales, support, etc.).

Due to the fact that the origins and driver of VR are in the entertainment sector, this technology is still strongly focused on visualisation, which is the most advanced modality. However, in principle all senses of human user can and should be addressed and a great deal of research and development is targeted to haptics and acoustics. On the other hand, the required modalities (human senses) depend on what product properties need to be presented, while the available VR technology may limit the possibilities. Furthermore, geometry makes up the major part of the product defining characteristics (Weber et al., 2003) thus it is important to enable effective visualization of geometry. Some product behaviours and properties cannot be simulated in real-time, but they need to be calculated in advance. These are major bottlenecks in the utilization of VR today. (Weber & Husung, 2011)

Human factors of virtual environments. It is remarkable to acknowledge that, besides utilization of virtual reality and virtual environments for HF/E, there are also human factors for virtual reality and virtual environments. HF/E for VR/VE is

about much more than usability testing (Wilson & D'Cruz, 2006), also including aspects of people which influence, or are influenced by their participation in virtual environments. Within this there exist four classes of human factor on which we need models, methods and knowledge (Wilson & D'Cruz, 2006):

- Influence of participants on application of the technology and on the quality of the output (for instance the quality of a design produced using VR/VE).
- The characteristics of people which should inform the development process for new VR technology and VE elements and applications (for instance the range of hand sizes to develop handheld control devices).
- The user (company and individual) needs which should be met by the design, implementation and operation of VEs (for instance the requirement to lay out process plant in a more effective way than at present)
- The effects of VE participation on people, both direct effects (for instance, any problems with their health whilst in the VE) or indirect effects (for instance changes in the nature of work and society over a number of years).

There will be an increasing array of VR/VE technology with increasing sophistication and functionality available commercially. Yet this technology will be still of little value (or even harmful) if it is not implemented with a good understanding of human and organizational factors (Wilson & D'Cruz, 2006).

Expected advantages of virtual prototyping. Virtual prototyping is widely seen as an enabling technology for intensifying product processes and involving stakeholders such as product users. It has been claimed for instance that virtual prototyping enables shortened product development cycles, reduced physical prototyping costs and better quality of products (Cecil & Kanchanapiboon, 2007), (Choi & Guda, 2000), (Seth et al., 2011), (Wang, 2002). Virtual prototyping techniques could also facilitate better concurrent engineering and communication among cross-functional teams (Ovtcharova, 2010). They enable engineers to consider product lifecycle downstream issues earlier in the product design phase and to make design changes in the conceptual design stage (Cecil & Kanchanapiboon, 2007), (Seth et al., 2011). With a virtual prototype, users can obtain useful feedback to improve the design (Pang et al., 2006). One of the main benefits of this virtual engineering is flexibility of product development (Horvath & Rudas, 2007b). The opportunity to extend the virtual product design approach to cover the whole product lifecycle management and involve all stakeholders is seen as the driver for the adoption of virtual reality in industry (Amditis et al., 2008).

Several industries already gain benefit from using virtual reality technology, and virtual prototyping already pays off to some extent in companies that already have 3D models available (Amditis et al., 2008). Zimmermann (2008) made a survey of virtual reality-aided design in the automotive industry where many applications have entered the product processes. Some of the applications have been found to be very useful compared to more conventional techniques. Zimmermann considered the utilization of VR from the viewpoint of the economy of the development process simultaneously with the quality of results. His observations on the advantages of VR can be summarized as follows:

- Simultaneously shortened the time-to-market, increased quality and re-duced overall costs;
- Shorter product development time and earlier production ramp up;
- Shorter amortization delay and thus better return-of-invest;
- The most important cost factor which could be positively influenced: model and prototype costs, reduction of change costs, delay times (models, proto-types, parts), and communication.

Virtual and Augmented Reality are broadly considered to be the next-generation of man-machine interface (Amditis et al., 2008). It is tempting to believe that new technologies are solutions to any given problem. Even though virtual environments are not a new thing anymore, they are still a piece of technology that easily excites people, and they start imagining all the potential they offer. However, it is im-portant to begin from the needs where this technology would be applied and de-fine requirements for the system. The essential starting point is the task and the user interface accounting for all human factors and issues associated with com-plex human-technology interfaces (Kalawsky, 1993).

The major advantage of virtual environments has been argued to provide the most natural means of communicating with a computer that utilizes humans' 3D spatial processing capability. It provides an intuitive and immersive human-computer interface (Gomes de Sa & Zachmann, 1998) and interactive and direct manipulation of virtual objects (Cheng, 2014). Cheng (2014) argues the benefits of virtual environments in three dimensions: 1) intent (ability to operate in an enough realistic way), 2) perception (the relevant real-time representation of a virtual ob-ject), and 3) interaction (ability conduct spatio-temporal sequence of interactive manipulations). Nevertheless, the claims of benefits are hard to prove because of a lack of objective measurement (Kalawsky, 1993). In order to quantify the bene-fits of a VE system compared to other approaches, it will be necessary to provide objective evidence of the gains (Kalawsky, 1993). Anyhow, the virtual environ-ments should be perfectly suited to ergonomic studies because of the intuitive and natural human-computer interface (Gomes de Sa & Zachmann, 1998).

However, it has become clear that investing in technology is not enough. Apart from that, product data management, data acquisition, tool interfaces, and change process chains have also become important factors (Zimmermann, 2008). In the automotive industry, VR technology has been utilized as a more natural way for evaluating the styling of a car in the early product development phase. Even though such systems needed large investments, they were adopted because they enable significant cost reduction through a decreased need for physical prototypes in the early production phases. One specific area of advantage is visual represen-tations for stakeholders such as technicians and decision-makers. (Amditis et al., 2008)

Evidence on benefits. Many manufacturing companies have recognized at least some of the above-mentioned benefits of using virtual environments-aided virtual prototyping in product design and development within several pilot studies. Leino and Riitahuhta (2012) summarized the published benefits and drawbacks of

VP especially from a sociotechnical system and life-cycle perspective. They concluded that partial virtual prototyping case studies have mainly been published, and they are mostly very technically oriented and lack the business value approach (Leino & Riitahuhta, 2012). None of the works presented in the literature offer a complete evaluation of VP from both the performance and usability points of view (Toma et al., 2012). Additionally, arguments on benefits are anecdotal (Gruchalla, 2004), and concern the assumed potentials of the virtual environments rather than empirical documentation (Söderman, 2005). Practitioners show relatively few examples of VR systems in the real world, lacking measurable benefits (Bowman et al., 2007). For instance, Toma et al. (2012) presented an experimental study comparing traditional 2D user interfaces of 3D models with a VR system aiming to analyse the added value of VR in the assembly process. However, they did not show benefits beyond improved perception and interaction with the 3D model. Finally they recognized that VR technology provides some "parameters" (e.g. form, size, material, surface qualities) which improve user perception. This is a point where a link to the engineering design theory, and business value, should be better established.

Cobb et al. (1995) already in 1995 reported demonstrations of the potential use of virtual reality and virtual environments for manufacturing industry. They recognized the potential benefits of these methods and technology in a large survey, but concluded that research on the actual benefits to industry is required. In 1999 (Brooks, 1999) concluded that, as usual with infant technologies, realizing the early dreams for virtual reality and harnessing it to real work has taken longer than the initial wild hype predicted. However, the result of a survey in the same year 1999 by (Gomes de Sá & Zachmann, 1999) indicated that the use of VR for virtual prototyping should play an important role in industry in the near future. In 2005, empirical evidence on the benefits in real industrial projects was demanded by Söderman (2005), and it is still very scarce in the literature. In 2009 Liu and Boyle discovered that research and publications on virtual reality and virtual environments are increasing (Liu & Boyle, 2009), but there has not been evidence on the actual benefits to industry. Investigations should be made on those attributes of virtual environments that bring added value (Cobb et al., 1995). Barriers to VR utilization are principally related to the lack of visibility on the real benefits of VR as well as difficult implementation of technologies and systems, which still present narrow application envelopes (Amditis et al., 2008). A survey study of Engelbrektsson and Söderman (2004) for instance concluded that product developers' perception of the usefulness of different product representations is not necessarily equivalent to actual representation experience, but is influenced by expected usefulness in product development. This was explained with the tendency of focussing on the time- and cost-related efficiency of product development rather than its quality aspects. VP was considered to be an expensive methodology and difficult to use. Therefore, integration with company processes, knowledge and infrastructure is essential in order to spread the utilization of VP.

Bowman et al. (2007) also argue that VR technology is quite expensive, and it is difficult to justify the expense and development complexity for business. Never-

theless, VP could be utilized more efficiently, effectively and systematically. Apparently, the barriers to adopting virtual prototyping, especially virtual environments, are not only related to the total costs of VR equipment, but also to knowledge of how to work with it (Ottosson, 2002). Utilization of VR technology has been rather impulsive and disorganized, lacking a long-term vision depending on case-by-case scenarios (Amditis et al., 2008). It was recommended already by Kalawsky (1993) that a careful analysis of the application domain should be undertaken, because it is difficult to predict exactly where the greatest benefits will occur and in which field, since there are so many potential applications for virtual environments. Ellis (1994) stated that, as a communications medium, VE appear to be useful for practically everything, which may in fact be a source of difficulty.

2.4 Value modelling

First this chapter introduces the generic value definitions related to the scope of this research. After that it is summarized how value of information technology based assets is described and modelled in literature. Finally, theories and models that guided value modelling in this research are introduced.

There are many kinds of definitions of a concept called value, and the definitions are strongly context- and phenomena-dependent. Generally speaking, value theories aim to understand how, why and to what degree people value things. In the context of products and services generally, value can be defined as equal to the cost of the product plus a subjective part of the value (Neap & Celik, 1999). This is similar to the approach of classical economists. They made a distinction between use value and exchange value (Bowman & Ambrosini, 2000). Neap and Celik (1999) also listed different value situations: exchange value, esteem value (prestige or appearance), use value (i.e. function of an item), other value situations such as aesthetical, judicial, moral and religious. Salvatierra-Garrido and Pasquire (2011) summarized the characteristics of the value concept: objective (measurable attributes), subjective (stakeholders personal judgements), relative (opportunity to use), context dependent, and dynamic. Allee (2000) categorized value creation sources as 1) goods, services and revenue, 2) knowledge (for instance strategic information, technical know-how, collaborative design knowledge), 3) intangible benefits). The above definitions of value give a good basis for modelling the value of VP. However, a challenge to this research is that methods for holistic value modelling of VP specifically are lacking in the literature (Leino et al., 2013).

Value theories and models. Some theories found emphasize organizations as sets of resources, and when the resources are valuable, rare, imperfectly imitable and substitutable, they are competitive advantages of firms. These theories are called Resource-Based Theory (Bowman & Ambrosini, 2000), or Resource Based View of a firm (Melville et al., 2004) which combines the rationale of economics with an organization-centric management perspective. In their research (2000), Bowman and Ambrosini have used a Resource-Based Theory approach, and they

emphasize that especially the perceived use value of an asset has both an internal (enterprise) and external (customer) part. Perceived use value is the price the customer is prepared to pay (Bowman & Ambrosini, 2000). They also state that tangible and intangible resources (e.g. information) are inanimate so they need to be activated by the intervention of people in order to create new use value. Therefore, labour is the only source of new use values which can be realized as exchange value, and profit. However, not all labour is a source of exchange value and profit. Bowman and Ambrosini (2000) have categorized labour as generic, differential and unproductive. Differential labour is the most remarkable source of an organization´s uniqueness and capacity. This asset can exist in an explicit or tacit form. On the other hand, labour can even be unproductive and value decreasing. This means waste in lean thinking (see Womack and Jones 2003) terminology. The waste can manifest itself, for instance, as producing scrap, unnecessary reworking or repair work. In lean thinking, value generation is connected with waste, and defined as meeting customer requirements while minimizing waste (Salvatierra-Garrido & Pasquire, 2011). The waste means unproductive and value-decreasing activity.

Neap and Celik (1999) define how the value of a product is composed of a cost and subjective value part, and how the subjective part can be assessed using their criteria weighting method. They also highlight the difference between traditional value engineering and value management. Value engineering is based on hard-system thinking, and it assumes that value can be improved by reducing costs, whereas value management is based on soft-system thinking integrating subjective and objective value criteria, and aims to maximize the functional value of a project (Neap & Celik, 1999). Cagan and Vogel's (2002) opportunity model categorizes product opportunity factors as sociological, economic and/or technical value. According to Cagan and Vogel, product value opportunities (attributes) include emotion, aesthetics, product identity, impact (social, environmental), ergonomics (human factors, usability, comfort, and safety), core technology (enabling, reliable) and quality (fit & finish, meet customer requirements, durability). Value is not just the most features for the lowest cost.

Oliveira and Ferreira (2011) introduce a systematic qualitative method called Business Narrative Modelling Language for modelling business value creation. The method is visual and highlights both tangible and intangible assets, as well as the value chain view. Gupta et al. (2006) reviewed a number of implementable mathematical models for customer lifetime value calculation. Bowman and Ambrosini (2000) introduced an integrative model of value creation and value capture, which combines several theories. They explain finely how resource investments create new use value when using labour wisely, and how this value can be captured as exchange value from the customers.

Value modelling – analogies. One challenge is that methods for holistic value modelling of VP are specifically lacking in the literature. Instead of that, there are interesting publications about modelling and evaluation of information technology (IT) value. There has been a similar problem in the general IT domain of how to measure the value of IT and how to show the link between IT and organisational

performance or profit. This is called the "IT Value Paradox" (Thatcher & Pingry, 2007) or "Productivity Paradox" (Lee, 2001), (Gregor et al., 2006). Though VP must not be seen just as a pure IT matter, models and methods for IT value evaluation could be a helpful approach. "IT business value research examines the organizational performance impacts of information technology" (Melville et al., 2004).

A resource-based view. Melville et al. (2004) provide the firstly comprehensive literature survey in their review article, and on top of that they propose an integrative model of IT business value. The main theoretical foundation of their model is a Resource-Based View (RBV) of the firm. Melville et al. (2004) summarize: "*IT business value as the organizational performance impacts of information technology at both the intermediate process level and organization-wide level, and comprising both efficiency impacts and competitive impacts*". Additionally, they revealed two formulations of performance: efficiency (which emphasizes internal perspective, doing things right) and effectiveness (achievement of organizational objectives and manifested as competitive advantage).

According to Gregor et al. (2006), IT as a general purpose technology provides a higher than normal rate of return, than normal capital investment, because it facilitates complementary innovations. On the other hand, measuring the business benefit of intangible assets is difficult and also the direction of causality in relationships is a problem. Value realization from IT depends on time-consuming investments in organizational change, resulting in organizational assets (Gregor et al 2006). Causality was studied and modelled also by Soh and Markus (1995). They describe how IT investment leads to IT assets (IT conversion process), IT assets to IT impacts (IT use process), and IT impacts to organizational performance (competitive process).

Value-in-use. The notion of value-in-use proposes that value is not embedded in goods or services (value-in-exchange), but value is rather created when goods or services are used and the skills and knowledge of users are added in the value creation process (Grönroos, 2008). Therefore, goods and services are value propositions and foundations for value created by the consumers. Sometimes part of value can be measured in short-term financial terms, such as cost savings, but value has always also an attitudinal component such as trust, affection, comfort and easiness of use whose impact can be assessed only in the long term. (Grönroos, 2008)

The integrative model for IT business value modelling of Melville et al. (2004) which is grounded on RBV theory includes three domains: 1) focal firm (including IT resources (technological and human), complementary organizational resources, business processes, performance (business process, organizational), 2) competitive environment (including industry characteristics, trading partner resources, and business processes), and 3) macro environment, i.e. country characteristics. Thatcher and Pingry (2007) explain with their model that the directional impact of IT investment on business value depends critically on three factors: 1) the type of product development the IT supports (digital vs. traditional products), 2) the market structure in which the firm competes (monopoly vs. competition), and 3) the

type of IT in which the firm invests (design tools vs. production/distribution tools). IT design tools include, for instance, CAD/CAE tools, simulation/visualization tools, collaborative technologies, decision support systems, and prototyping tools. (Lee, 2001) modelled the business value of IT by developing an economic model based on the grounded theory approach. The model is visual and includes categorization of IT and its usage as well as other variables such as origination cost, cycle time, leanness of internal processes, use of IT technologies, with the causal relationship between IT use and variables. Lee also highlights that complementary factors must be monitored together with IT investment when estimating payoff. Nevo et al. (2011) have recognized the challenge of demonstrating the business value of Virtual Worlds to the organization. Nevo et al. (2011) explain the challenges and factors in implementing novel technologies to organisations and, on the other hand, opportunities for gaining from collaborative systems.

Nevo et al. (2011) have recognized the challenge of demonstrating to the organization the business value of Virtual Worlds. In their research, virtual worlds mean collaborative computer simulated environments in which individuals interact with one another via avatars representing their digital selves. This is not exactly same with VP or virtual environments, which are targets of our study. Nevertheless, the paper by Novo et al. could have analogies to our research area and give some hints of how to evaluate the business potential of VP as well. Nevo et al. (2011) explain the challenges and factors in implementing novel technologies in organisations and, on the other hand, the opportunities for gaining from collaborative systems.

2.5   Conclusion of the literature review

More flexible, effective, profitable, and faster product development methods are demanded. Companies are lacking the capabilities to effectively generate new products. This is partly due to insufficient collaboration and information sharing within networked product development and manufacture, as well as a lack of the suitable technologies necessary to run the innovation process. Thus, business process re-engineering and digitalization are becoming a main focus in today's efforts to overcome the challenges in industry.

The purpose of the literature section was to report published knowledge on the benefits and value of VP in an engineering design science and industry practice context, as well as to find methods and models for valuing the VP. Additionally, the literature was reviewed concerning clarification of the context (i.e. product design and development and human factors in manufacturing industry), and key concepts related to practice and scientific theories. Furthermore, drivers and barriers for adopting VP in industry were recognized. The research topic is very wide and interdisciplinary, which caused challenges for the survey. On the other hand, virtual prototyping and virtual environments are fast changing domains. Therefore, the literature must be surveyed critically concerning the technological progress.

There seems to be gap, i.e. a lack of links, between concepts and terminology in areas of engineering design theory, product development methods, human factors and ergonomics, and socio-technical systems, as well as links from virtual prototyping and especially virtual reality and virtual environments theory to both these areas. There is also a lack of understanding or at least evidence about how HF/E and virtual prototyping can support product processes in industry.

Status of designing human-machine systems. HF/E seeks to improve performance and well-being through analyses and assessments, resulting in recommendations for systems design. However, it has been recognized that HF/E should shift towards a design-driven approach, but it appears a difficult target to reach. Users and other stakeholders should be involved in designing socio-technical systems. Therefore, approaches such as participative and user-centred methods have been developed. Nevertheless, there is an urge for more practical and adapted implementations of a user- (or human)-centred design approach for a specific context in companies.

Engineering design reviews are important elements of product processes, and opportunities for stakeholders to share information about the product and related aspects. Although virtual environments and participatory approaches have been seen to be beneficial for the review meetings, unfortunately their potential in product design is still not fully taken in to practice in industry.

The development of socio-technical systems is a very knowledge-intensive task, and the knowledge of system users should be captured into the product development process. However, this is challenging because of the tacit nature of HF/E knowledge. There is a lack of methods, tools, procedures and infrastructure in this kind of knowledge management.

Knowledge in human factors and ergonomics has not yet found wide-spread acceptance and application, because the relevant stakeholders are not aware of this knowledge, and the knowledge is multi-faceted and ambiguous. This problem should be addressed by positioning socio-technical system design as a strategic task. Different stakeholders do not speak a shared language. Therefore, a common conceptual framework is demanded. Additionally, there is a lack of evidence of HF/E impacts on productivity and designing socio-technical systems.

State of the art on virtual prototyping. In the literature it a popular statement that virtual prototyping and virtual environments enable shortened product development time, earlier production ramp-up and time-to-market, shorter amortization delay, better return-of- invest, increased quality and reduced overall costs. Despite the large investment needed on VP technology, the positive influence on cost factors should include: model and prototype costs, reduction of change costs, delay times (models, prototypes, parts), and communication. From a product design and development viewpoint, virtual prototyping and virtual environments are claim to intensify product processes by facilitating better and more flexible concurrent engineering and communication among cross-functional teams, involving stakeholders such as engineering designers, internal and external customers and product users, by enabling considering product lifecycle downstream issues and getting feedback earlier in the product design phase, making engineering design

changes earlier. Especially virtual environments should be of advantage by providing the stakeholders more natural way of dealing with digital product models.

However, published knowledge on the benefits and value of VP seems to be scattered and an approach that combines areas of design methodology and VP technology is missing in the literature. In fact, just a few publications about the direct value of VP were found. Literature on the value of virtual prototyping and virtual environments particularly is either scarce or very old (1990s), or very technically oriented. Yet, the value of virtual environments has been reported in other domains such as training, learning, and psychology. Furthermore, practical industrial applications seem to be sparse. Actually, according to the literature, utilization of VR technology has been rather impulsive and disorganized, lacking in long term vision and dependent on case-by-case scenarios. Many VP applications have been created with the bottom up principle, without sufficient integration to product processes, other engineering applications (CAE), product data management, or a connection to business value. Barriers to adopting virtual environments in industry are not only related to the total costs of VR equipment, but also to knowledge of how to work with it. After all, VR technology in terms of hardware and software is considered to be quite expensive, and it is difficult to justify the expense and development complexity for business, in particularly because the valid and general return-of-invest evaluation method has not been found. Additionally, VR technology (hardware and software) is still considered to be immature, unfriendly, complex and of limited usability. Concerning the social issues, humans are reluctant to use new interfaces.

Knowledge of value modelling methods. Concept of value is tricky because it can be defined in dozens of ways, and it is very context-dependent. Hence, in this research context of value was restricted to product- and service-related value theories and models. The literature shows that measuring the business benefit of intangible assets such as virtual environment is difficult and the direction of causality in relationships is also a problem. No theories or models that truly enable the evaluation of business value of virtual prototyping and virtual environments were found. Instead of that, analogy with IT value evaluation models and methods seemed be a helpful approach. Some of those models apply a strategic resource-based view of firms as a fundamental principle for value evaluation. Those models explain how firms' resources contribute to internal business value and external customers' value. However, only part of the value can be quantified when the use value of an asset can only be described qualitatively.

3. THEORETICAL BASIS OF THE RESEARCH

This section describes in summary the relevant scientific theories that were selected as a basis for this research. The theories introduced are divided into four categories: 1) Theories related to technical systems and design, 2) theories related to virtual prototyping and virtual environments (technology), 3) theories related to organisations and human factors (social), and 4) theory of economics and management. The concluding part explains how the theories contribute to the research questions, and what the relationship is between the theories.

Engineering design theory (especially Theory of Technical Systems, Theory of Properties) and Theory of Virtual Reality and Virtual Environments were selected as starting points in building a framework for virtual prototyping value evaluation. During the empirical study and analysis, this hypothesis was expanded towards other areas of engineering design theory, as well as towards social science and management theory in order to construct a theory framework for value evaluation. The expanded theory aims to find new dimensions that enable the explanation of the value, and the constructed framework adds links between the concepts of these theories.

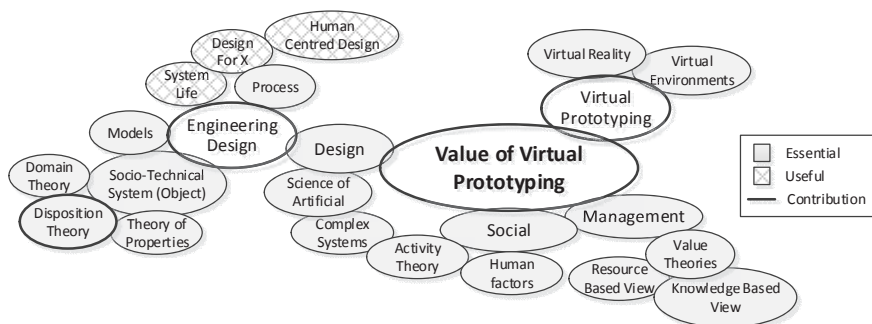Figure 11. Areas of Relevance and Contribution (ARC), adapted from Blessing and Chakrabarti (2009). This research contributes mainly to engineering design theory and virtual prototyping theory. The wide set of theories from management and social science is needed to conceptualize the value of virtual prototyping from the perspectives that engineering design theories cannot provide sufficiently.

Figure 11 illustrates the areas of relevance and contribution (ARC) of the research. The ARC-diagram approach was proposed by Blessing and Chakrabarti (2009) in their "DRM, a Design Research Methodology". The basic idea of the ARC diagram is to show what theories, methods and models are relevant for the research project. It also indicates which areas are essential and which are rather useful, and to which areas the main contribution of the research will belong.

The biggest oval includes the topic of the research, namely value of virtual prototyping. The relevant theories form three main groups. The grouping could be done in many ways. For instance, virtual prototyping could be seen as sub-group of engineering design theories. However, the theory and knowledge concerning virtual prototyping in this context is based on the science of virtual reality and virtual environments. Value is also a concept which is also addressed in engineering design theories. Apart from advantages and value of virtual prototyping related to engineering design, in this research, value creation is essentially explained by business and organization theories. The main proposed research contributions will be in the area of engineering design.

Design – designing

'Design' and 'designing' are terms whose meanings can be understood and defined in many ways depending on one's background and education. Design can be understood (Hollnagel, 2014) as a verb (process of designing) or as a noun (product of designing, artefact). It can even be understood as an attribute (the quality of a product). For some people, design means a nice look and exclusive brand, whereas others think it means engineering drawing. In this research, the terms 'design' and 'designing' have meanings that are more abstract. Nevertheless, the definition of 'design' is related to both approaches above.

Designers are agents of change in society with a goal to improve the human condition in all its aspects (Gero, 1990). Design is about understanding the demands of people and society, and the process of transforming the demands into product descriptions that enable manufacture, distribution, operation, and maintenance – the lifecycle of a product. Human factors and ergonomics are typical characters that have an abstract nature and which have to be transformed as concrete specifications. Perhaps due to the partly abstract nature of design, there are designers who claim that design is such a mysterious activity that it is not amenable to scientific examination (Gero, 1990). However, design can be based either on intuitions, or it can be replaced with a more scientific design approach (Saariluoma, 2005). There are general truths about design that can be formulated and communicated in a scientific manner (Simon, 1995).

Design is thinking, deciding and solving problems (Simon, 1996). In the context of technical systems the term 'design' can also be defined by comparing it with the term 'engineering', which is often used as a synonym of 'design'. Contrary to engineering sciences, which model known objects, design theories are frameworks to guide the elaboration of still unknown objects (Le Masson & Weil, 2012). Therefore, design sciences are languages of the unknown. Design related to engineer-

ing activity has the purpose of creating future operating artefacts and processes, to satisfy the needs of potential customers, stakeholders and users (Eder, 2008).

Norros (2013) state that (in human factors and ergonomics) the challenge in shifting towards a design-driven approach is the dilemma of maintaining scientific orientation in development study because the problems are specific and the solutions created are local and particular. In other words, explicitness and generalizability are questionable in design science. However, this is exactly the goal of engineering design science (Hubka & Eder, 1988), namely developing abstract concepts that are valid for all kind of socio-technical systems and their development. Norros continue that, therefore, it would be important for human factors and ergonomics research to collaborate more closely with the design research community that has a considerable tradition in conceptualising design activity (Norros, 2013).

Early design thinkers started to articulate design as a process already in the nineteenth century, but not until the 1960s were major design research programmes initiated (Gero, 1990). Then Herbert Simon was one of the pioneers developing formal models of design as an activity (Gero, 1990). The Sciences of the Artificial (Simon, 1969/1996) describes objects and phenomena – artefacts – that result from human intervention in the natural world, whereas the Natural Sciences describe "natural" objects and phenomena. Aimed at satisfying human purposes, artefacts are not exempt from natural laws, but are deliberately adapted to the environments in which they operate.

Design goals are often poorly defined and simultaneously there may be many possible solutions that are difficult to evaluate. Therefore, extensive systemic goals are often over simplified which lead to inadequate detail design (Hubka & Eder, 1988). Engineering design has been relying on the laws of nature when design object is the technical system, but the human element has been designed with an intuitive stance (Saariluoma, 2005). Question is (Hollnagel, 2014), how far the design should extend. Should it be limited to technical system elements, or should it consider the system as a whole including for instance cognitive task design (Hollnagel, 2003). However, real-world situations are complex so that every designed and built artefact has direct consequences for how it is used, but also indirect consequences for the other parts of the system (Hollnagel, 2014).

3.1 Engineering design science

This chapter aims to give a brief introduction into the field of engineering design science, and the roots of the theories and models used in this thesis. The engineering design theory is still evolving, and there are several schools in the area. A recent and comprehensive review to engineering theories and models can be found in the book "An Anthology of Theories and Models of Design – Philosophy, Approaches and Empirical Explorations" edited by (Chakrabarti & Blessing, 2014)

Generally speaking, design means synthesis, conceiving objects, processes and ideas for accomplishing goals and showing how they can be realized to satisfy

someone's needs (Simon, 1995). Design research aims to better understand design as an activity in order to develop tools that support human designers, but may also automate some design tasks (Gero, 1990). These statements of generic design are also valid for the subset of engineering design. Contrariwise, it could also be helpful to see engineering design more widely as a profession for satisfying human needs.

The core nature of design in the context of engineering design and technical products is captured in Gero's 'Function-Behaviour-Structure-Model' (Gero, 1990) which describes how designers reason from required product function to expected behaviour, and synthesise structures or solutions (Andreasen, 2011). In the Design Science of Hubka and Eder (1996) design is defined as "*the transformation of information from the condition of needs, demands, requirements and constraints (including the demanded functions) into the description of a structure which is capable of fulfilling these demands. The demands must include the wishes of the customers, but also all stages and requirements of the life cycle and all intermediate states that the product must pass through*". Figure 12 shows the relation between engineering design and other actors and entities in the business context. Therefore, design science draws also from knowledge about culture, societal organizations, economics, market development, and other areas (Eder, 2008).

Goals of Enterprise:
Revenue (Profit)
Products
Customers (Satisfaction)
Employees
Owners / Investors
Suppliers
Society

Information In State 1

Needs, Requirements, Constraints

Planning of Product, Product Development, and Designing Design Process (DesP)
Transformation of Information

Information In State 2

Description of The Technical System (TS)
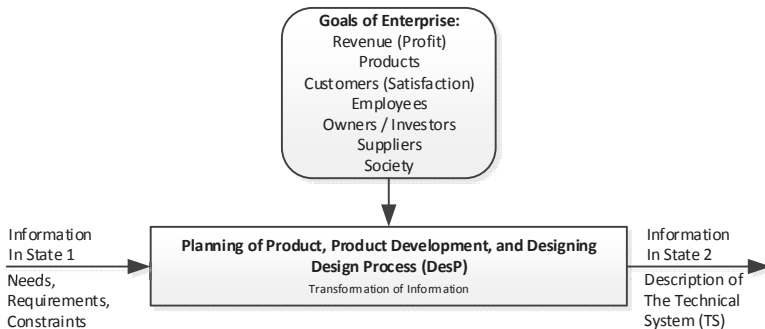
Figure 12. This model offers an orientation about breadth of design, where engineering design interacts with integrated product development as a management function (Hubka & Eder, 1996).

The definition of engineering design forms a bridge between the theory of technical systems and the theory of design processes or design science (Hubka & Eder, 1988). These theories are described in the chapters following. Design Science (DS) is to be understood as a system of logically related knowledge, which should contain and organize the complete knowledge about and for design (Hubka & Eder, 1996). The DS aims to a general and comprehensive design theory. De-

sign science can be developed in two ways which are not mutually exclusive (Hubka & Eder, 1988):

- By the conventional empirical way of observing, describing, abstracting, generalizing, formulating guidelines, modelling, refining
- By postulation a set of hypotheses, formulating a theory, modelling, refining, and only subsequently testing.

The purpose of the theory is to support expedient thinking, holistic understanding of systems, and identifying analogies and dependencies between things (Hubka & Eder, 1988). The Theory of Technical Systems and theory of engineering design processes constitute the main pillars of Design Science (Eder, 2008). Design Science has four (Figure 4) main categories (Hubka & Eder, 1996):

- *Theory of technical systems:* descriptive statements about technical systems: describe, explain, establish and substantiate the structures, their elements, properties, modes of action, functions of technical system
- *Design object knowledge:* The branch-related design knowledge contains the know-how regarding ways of satisfying the functions in a realized technical system, i.e. the knowledge about ways and means in which technical products can and must be laid out and detailed in concrete forms to fulfil the required functions.
- *Theory of design processes:* Descriptive statements about the design process: describes, explains, establishes and substantiates the elements, properties, sequences, and effects (actions, results, successes) of actually observed design and possible processes in their socio-technical context, including all company-related, operational, organizational and leadership aspects
- *Design process knowledge:* Prescriptive statements about the design process: design process knowledge contains indications about all operators of the design process. Of particular importance is the 'methodology of designing' (design methodology) which shows ways (methods, procedures, strategies, tactics) for successfully performing and managing design processes in an industrial context.

An additional class of working means knowledge can be defined besides the four main categories: descriptive and prescriptive statements about working means, particularly about the application of computers. This category combines practical knowledge about design processes, and the theory of design process. The application of computers is naturally the focus of this thesis.

3.2 Theory of Technical Systems

This chapter introduces the main base theory of this thesis in the dimension of engineering design and product development. The main models and concepts are briefly explained here, including the model of transformation system, Theory of

Properties, complete model of the origination and operation phases of technical systems, utilisation of models and prototypes in product design and development. Domain Theory and Theory of Dispositions are off-springs of theory of technical systems. They are also key theories of this thesis. These theories and models are utilised in Section 7.

The Theory of Technical Systems (TTS) is a comprehensive and unifying theory to promote the understanding of technical systems, and building a foundation for a rational approach to the engineering design process (Hubka & Eder, 1988). The abstract forms of modelling of transformation systems, a generalized life cycle and classes of properties of systems constitute the major parts of TTS (Eder, 2008).

Transformation system is the fundamental model in the TTS. In Figure 55 is an application of the transformation system to the design process. The transformation system model incorporates elements of system theory. It explains the role of technology in society, and the elements of a socio-technical system model. All transformation systems have a certain purpose, i.e. fulfilling stated needs by transformation of an operand (materials, energy, and information). The elements of a transformation system are connected by suitable relationships, and the properties of the whole system result from the sum of the elements, whereas the system's behaviour includes the synergistic effect of the relationships. The structure of the system is formed by the arrangements and relationships of the elements. The system is connected to its environment by means of inputs and outputs. The major elements of the total transformation system are divided into a process, an operand, and the operators that drive and guide the process. The operand may be affected by modifying its structure, form, location, and time. The Theory of Technical Systems originates in the late 1960s. The base model in Figure 55, published in (Hubka & Eder, 1988) has been further developed over the decades so that, for instance, assisting inputs and outputs have been added to the model (Eder 2008).

One of the purposes of engineering design is to provide information about suitable real transformation systems that are capable of fulfilling needs, i.e. changing an operand from starting state to final state. On the other hand, in our case, we can look at the design process itself as a transformation process. In this view, the object to be designed is the operand of the design process. Designers are the human operators with their characteristics, working methods, and use of information. Working means (tools) are the technical systems of a design process. Operations of the process have a certain sequence and structure, components and relationships, systematic and procedural aspects (methods), creativity and intuitive factors. The information system and management and goal system are the context in which engineering design takes place. The social, moral and political context is the environment of designing, producing and using the resulting technical system. Design is the transformation from a more abstract form of model of a technical system or process to a more concrete form. Each step or stage of this transformation may be performed with the help of suitable methods, and individual designers may prefer a different set of methods. Some new computer-based methods and tools, such as virtual environments, have penetrated into

engineering practice to only a limited extent. The sum of actions in designing, and the sum of recommendations for methods that can be used, is termed Design Methodology, a heuristic prescription (and model) of "how to proceed". The development of Design Methodology aims at general methods and methodologies that are not product-specific, and that are also suitable for new product development. (Hubka & Eder, 1988)

Theory of Properties. In this research, the Theory of Properties (Hubka & Eder, 1988) is an essential sub-theory of the TTS. Every technical system, its elements and relationships have certain properties that describe the system. Many of these properties are objectively measurable, while others can only be assessed by subjective means. The state of the technical system (TS) at any one time is defined by the totality of all its properties and their state of embodiment. The most important property of any TS is its function reflected in the system behaviour. Customers or users determine the desired properties for TS in the form of a requirements specification, which is then transformed into a design specification that guides the design of the system. The properties can be categorized (Figure 13) by way of observing them:

- *External properties* interest the users, operators, and customers. The external properties are the relationships of the technical system to its environment. For instance, ergonomic properties deal with direct relationships between humans and technical systems
- *Internal properties* deal with relationships between the elements of the system and the properties of those elements.
- *Design properties* serve as a means for the designer to create the desired external properties. These properties are usually hidden from the system users.
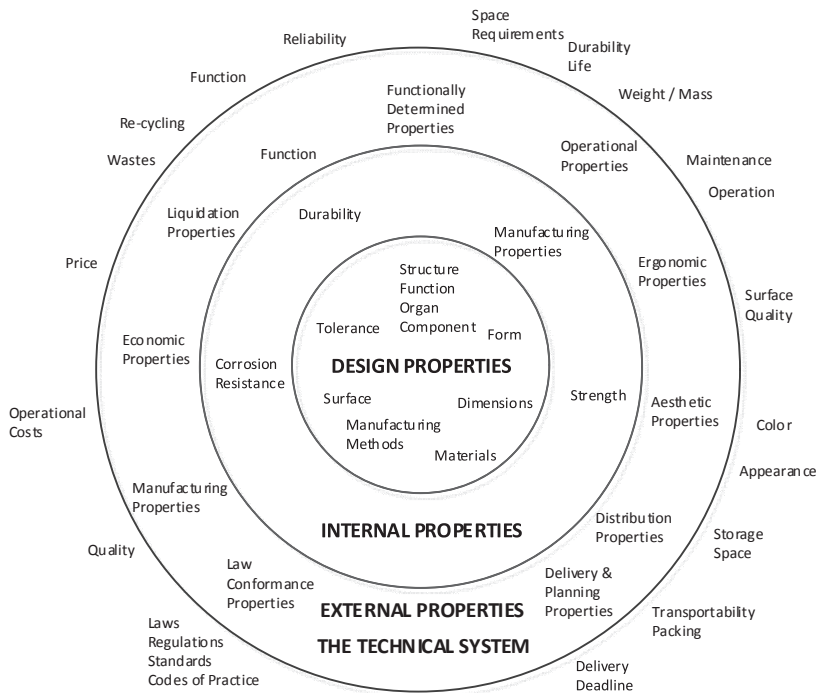
Figure 13. Relationships between classes of product properties (Hubka & Eder, 1988).

Complete model of the origination and operation phases of technical systems. Technical systems are generally very complicated, as is the progress from the first idea to the finally realized system. In order to design the system properly, it is important to recognize all the phases that a technical system must pass through during its origination and operation, and all the factors that will influence the TS. The complete model of the whole TS lifecycle can be divided into four major phases, including a number of partial processes: origination, distribution, operation and liquidation (Hubka & Eder, 1988). The complete applied model of the origination and operation phases of technical systems can be seen in Figure 56. The model is an early representation of product lifecycle thinking.

   Each technical system attains a series of typical states of existence and composition of the transformation system during its lifecycle. The design engineer should be capable of using mental models, i.e. imaging a proposed system in all of these states in order to examine the suitability of the system for the requirements in each state. This activity could be supported by modelling and testing (Hubka & Eder, 1988). Mental models by individual designers seldom cover all aspects of the lifecycle, and they are difficult to communicate for other people.

Utilization of models in the Theory of Technical Systems. The properties of proposed TS must be determined in order to evaluate against the requirements. Different methods for evaluation can be applied depending on the life phase of the system. In a conceptual phase, modelling and simulation are often the most suitable means of evaluation. A model is a representation of the real technical system, the process, or the idea by suitable means (Figure 14). Laws of similarity deal with the relationships between a model and the original system (Hubka & Eder, 1988). They emphasize the purpose of the model, and which properties are, therefore, to be expressed in the model. Apart from determining the properties of the system, models can be used for e.g. verifying, communicating, or instructing. Typically, a prototype of a TS permits the determination of most of the properties relevant to the final system, whereas a model often only permits the determination of certain properties, such as behaviour, structure or form. Aspects of the models can be summarized (Hubka & Eder, 1988):

- *Context* ranges from abstract to concrete, from material to conceptual, from general to specific
- *Function and purpose* can be one or a combination of the following: describing, predicting, exploring, planning, prescribing
- *Medium*: can be one or a combination of: verbal, mathematical/symbolic, imaginal/graphical
- *Model of usage*: can be iconic, similitic or analogue, metaphoric
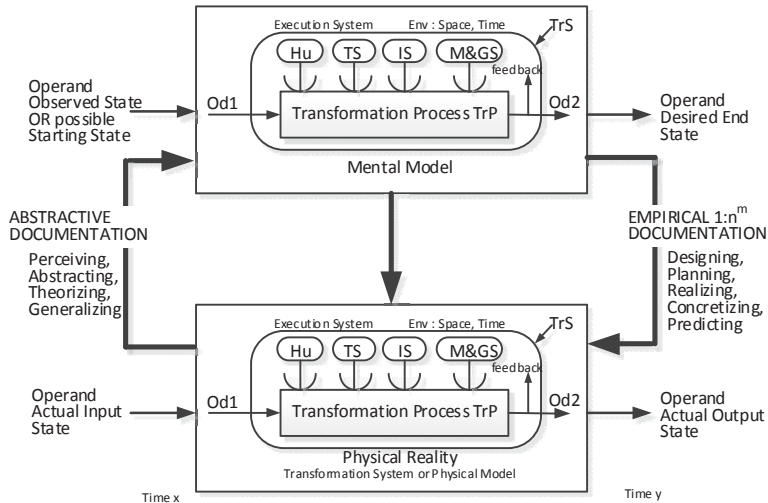
Figure 14. Formation and use of models. Mental models are formed by abstractive documentation, by perceiving and abstracting from physical reality, and their properties are elaborated by generalizing and theorizing. The relationships of similarity between two systems are investigated by the laws of similarity. (Hubka & Eder, 1988)

A model is a way of representing knowledge for the purpose of thinking, communication, decision making, system design or analysis and operation ranging from mental images to highly refined mathematical equations (Sheridan, 2014). Therefore, something can be modelled to the extent that it can be understood by humans. In science, a distinction must be made between denotative and connotative models (Sheridan, 2014). Denotation refers to the explicit literal meaning of the words, symbols or signs used to represent the model, while connotation refers to the implied or suggested meaning – a metaphor.

Prototyping and virtual prototyping. In their book Product Design and Development, (Ulrich & Eppinger, 2004) define the term 'prototype' as "an approximation of the product along one or more dimensions of interest". Therefore, any entity exhibiting at least one aspect (i.e. product property in the terminology of Hubka and Eder) of the product that is of interest to the development team can be viewed as a prototype. This definition includes such diverse forms of prototypes as concept sketches, mathematical models and fully functional preproduction versions of the product. Prototyping is the process of developing such an approximation of the product (Ulrich & Eppinger, 2004) including the dimensions: a) Physical vs. analytical, b) Comprehensive vs. focused. Within a product development project, prototypes are used for four purposes: learning, communication, integration, and as milestones (Ulrich & Eppinger, 2004). Product development is a process consisting of cycles that include the steps of synthesis, analysis, determining individual deviations, overall evaluation (Weber & Husung, 2011).

Figure 15 shows where prototyping belongs in the Theory of Technical Systems of Hubka and Eder (1988). A concept of design review is related to prototyping, and this phase of system originations as well. The design review should be conducted by a group of experts when most properties of the system have been specified, before the detailing and manufacture of a prototype. For a quantity-produced system, the prototype is usually the first physical realization.
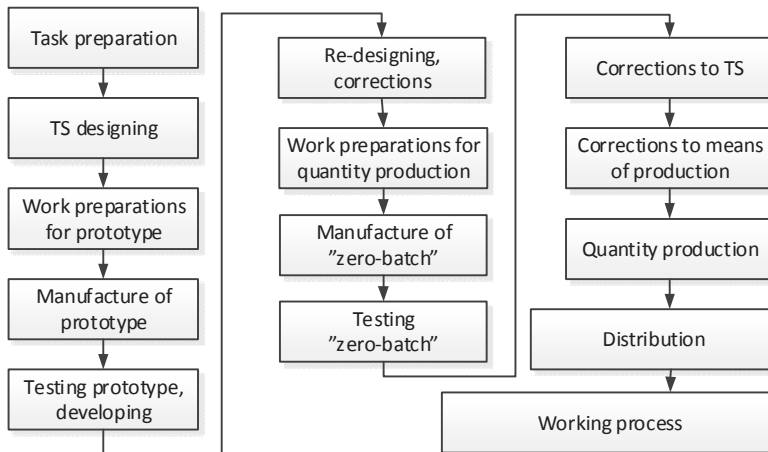
Figure 15. Simplified block diagram of the origination and operation phases of TS in quantity manufacture (Hubka & Eder, 1988). Not all feedback loops are shown in the diagram.

By building and testing the prototype, all manufacturing properties including assembly should be evaluated and verified. All errors and difficulties found should be fed back to the designers in order to develop the systems and correct the manufacturing documents. Without careful prior design work, this phase can lead to a costly re-design mode. After the prototyping phase, a "zero-batch" is manufactured. This phase incorporates all the preparations for actual production, including manual work and organizational aspects. Virtual prototyping should naturally be related to the above-described 'conventional' prototyping process.

The theory of Dispositions. The Theory of Dispositions of Olesen (1992) deals with relationships between the parameters of a product and the parameters of the systems which are realising the product and which the product meets during its life. The theory was proposed to be used during the design process in order to anticipate those parameter relationships and to choose the optimal parameters of the product during its production and product life. The dispositional mechanism of the theory describes an important type of integration between the various functional departments of a company (Figure 16). A disposition is the type of effect which arises when the product and, for example, assembly system are affected at the same time. Dispositions can be measured in terms of their effects on the so-called universal virtues: cost, throughput time, quality, efficiency, flexibility, risk, and environment.
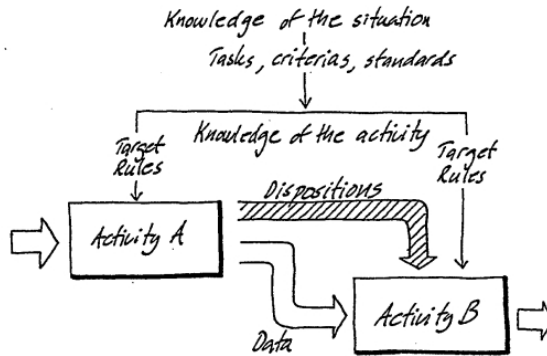
Figure 16. General model of disposition between two functional areas (Olesen, 1992). In disposition a decision taken in one functional area, i.e. product design, consists of two parts: a data part describing the task (typically represented by drawings), and a dispositional part describing the conditions affecting activities in other functional areas, such as product assembly.

Olesen (1992) proposed so-called Design for X (DFX) tools as one possible means for "revealing dispositional effects by exposing the solutions' characteristics, and the relationships between design characteristics for the product and the X-system". The DFX tool can be used either for analysing an existing product and X-system in order to identify dispositions, or for choosing design characteristics in order to achieve desired dispositional effects. Matrix-based product modelling methods (the product modelling Design Structure Matrix, P-DSM) can support the development of complex products by, for example, visualizing, structuring and analysing them (Malmqvist, 2002). Matrix-based methods can be classified according to scope and content, e.g. as inter-domain or intra-domain matrices.

Domain Theory. The Domain Theory was introduced in the doctoral dissertation (in Danish) of Andreasen (1980). It approaches the product synthesis from the viewpoint of four domains: transformation, function, organ, part. In each domain, design synthesis progresses through detailing and concretization. Each domain is a system in which the structural characteristics which define or specify the system, and its behavioural properties must be distinguished. Later, the "function domain" was abandoned. It was reasoned that each domain should contain a synthesis dimension, and in each domain it should be possible to reason backwards from demanded behaviour to structure (Andreasen, 2011). Thus, in the organ domain, the products effects, i.e. functions, are defined as structural characteristics. However, in this thesis, the original Domain Theory with four domains is referred to because the Disposition Theory is based on that. Thus, we can avoid mismatch and confusion between these theories. The terminology of Andreasen in respect to distinguishing concepts of property and characteristics was adopted by Weber; see e.g. (Weber et al., 2003), (Weber & Husung, 2011) and putting it to a centre of his CPM/PDD (Characteristics-Properties Modelling, Property-Driven Development/Design) theory. This distinction reduced the external, internal and design

properties of Hubka's Theory of Properties to two classes (Andreasen, 2011), while its "characteristics" are very similar to "internal properties" of (Hubka & Eder, 1988). The CPM/PDD theory has been used as basis for the development of computer-aided tools and methods as well as PDM/PLM systems (Weber et al., 2003), (Weber & Husung, 2011).

The paper by Andreasen (2011) gives a nice and comprehensive review of the elaboration of the "Copenhagen School" in the area of design theory and methodology and product development that was based on the basic theory of Hubka and Eder.

3.3 Science of virtual reality and virtual environments

This chapter clarifies the main theory, concepts and components related to virtual environments that are rooted in computer science and electronics. However, in the Section number 4 the conceptual links between the engineering design theory and theory of virtual environments are established. This conceptual model was used as a hypothetical theory frame for analysis of the empirical case study data, and explanation of value of virtual prototyping in product design and development.

A major theoretical contribution related to virtual reality (VR) and virtual environments (VE) is based on the book of Professor Roy S. Kalawsky titled "The Science of Virtual Reality and Virtual Environments" (1993). The book deals in depth with both scientific and engineering viewpoints, including human factors and technological aspects. In the book professor Kalawsky asks the question "*Are we dealing with a science?*", and answers the question himself by saying that the field of virtual environments is a multidisciplinary science that combines, among other things, physics, mathematics, engineering, and ergonomics.
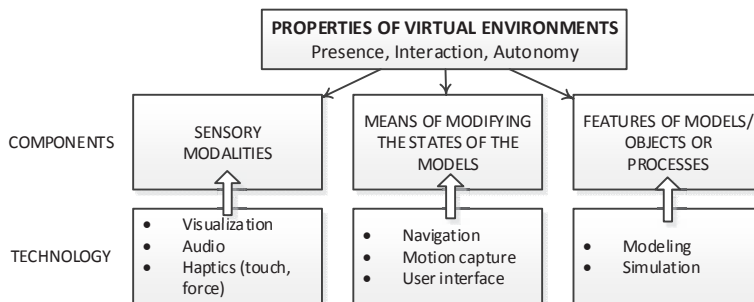

Figure 17. Virtual environments; properties, components and technology.

Virtual Environments can be considered as a bundle of technologies, or as more abstract components and features of the system (Figure 17). *This research is focused on the latter aspect, and does not go into technological details. The com-*

ponent level, and especially its connection to possible benefits and value for designing and business, are interesting here.

Let us define the concepts and terminology of virtual reality and virtual environments that are used in this research. In common usage 'virtual reality' is a popular term, used for instance in the entertainment business. According to Oxford Dictionaries, the word 'virtual' means something that is "*almost or nearly as described, but not completely or according to strict definition*". The word is correct (Kalawsky, 1993) in the sense that the optical images (and other sense perceptions) are virtual, but the simulated environment is ordinarily not close to true 'reality'. On the other hand, in the context of engineering design and product development, it is essential to understand that the term 'virtual' should be contrasted with 'physical' and not 'real', because in product design and development 'virtual methods and tools' mainly try to challenge conventional 'physical methods' (such as physical prototyping) (Weber & Husung, 2011), (Zorriassatine et al., 2003).

The roots of virtual environments can be traced back as far as to the 1950s virtual displays and immersive visually coupled tele-operated environments in the aerospace industry (Kalawsky, 1993). The origins of virtual reality can also be traced to "The Ultimate Display" by (Sutherland, 1965) who introduced in his seminal paper the key concepts that are the basis of current virtual reality research (Mujber et al., 2004). Naturally, the evolution of virtual environments has proceeded hand in hand with the general development in electronics and software technology. During the first decades of VE, development was mainly directed by the aerospace and military industry. Today, the entertainment business is also a major factor bringing more inexpensive devices and software onto the market.

Scientifically, the term 'virtual environment' (VE) is preferred by the pioneers Kalawsky (1993) and Ellis (1994), and is used also in this paper. This is because the term is linguistically conservative, relating to well-established terms such as virtual image (Ellis, 1994). The term 'virtual reality' (VR) refers to technology system elements, and it can be seen as an ideal goal where scientific and technological evolution is targeted (Ellis, 1994), (Kalawsky, 1993). Also for instance Cobb et al. (1995) made a similar distinction between the terms virtual reality and virtual environment. Other terms that have been used in publications apart from virtual reality and virtual environments are, for instance: artificial reality and cyberspace (Ellis, 1994), (Kalawsky, 1993).

According to Wilson and D'Cruz (2006), "*the virtual environment is the computer-generated experience of a participant, obtained by and through an interface which engages one or more of our senses but almost always includes the visual sense*". This VR/VE experience can have some or all of the following attributes (Wilson, 1997):

- Sense of being within a three-dimensional space, interacting with three-dimensional objects.
- Sense of involvement (or presence), in that VE and a feeling of transportation to somewhere that is not the actual setting in which we are participating.

- Ability to carry out direct interaction via a number of channels with the computer generated display, either by it updating through our movements and actions or by us moving and manipulating, i.e. working with the presented virtual objects within it.
- Responses from the environment to the participant's control actions and movements are perceived as immediate or close-to-immediate.

Some VR technologies will provide all of these attributes at least in the visual and (usually) auditory senses (Wilson & D'Cruz, 2006). Today we are far away the original meaning of virtual reality as a real-time human-machine interface which should work perfectly with all human senses (Zimmermann, 2008).

Components of the virtual environment. Zeltzer (1992) proposed that any virtual environment has three components: 1) a set of models/objects or processes (autonomy), 2) a means of modifying the states of these models (interaction, e.g. moving objects in a virtual environment), 3) a range of sensory modalities to allow the participant to experience the virtual environment (presence). They can be put on the three axes of the cube model (Figure 18).
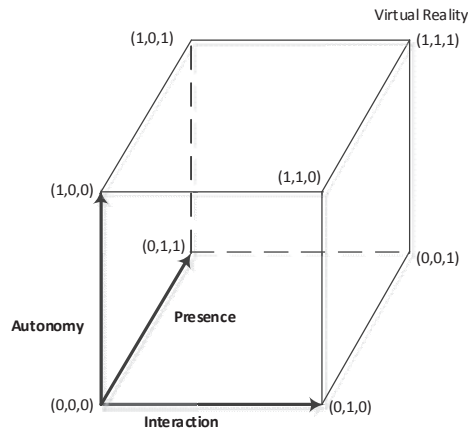
Figure 18. Zeltzer's Cube (Zeltzer, 1992).

In the case of genuine virtual reality (1,1,1), sensory simulation would be so complete that one would not be able to distinguish the virtual environment from the real world (Kalawsky, 1993). The conventional CAD would be in the (0,1,0) since it is very interactive, but the presence and autonomy are lacking (Ottosson, 2002). Söderman (2005) stated similarly from a technological viewpoint that any virtual reality system should include a computer-generated object or environment (VE), a sense of presence in the VE, the possibility to navigate in the VE, and possibility to control the view of the virtual object according to the viewer's position and motions. Mujber et al. (2004) emphasized the functionality of the models in a virtual

environment as part of virtual prototyping. From a presence point of view, the four determinants of virtual environment are (Kalawsky, 1993):

- Extent of sensory information
- Ability of the observer to modify their viewpoint for visual parallax or visual field.
- The ability to modify the spatial relationships of objects in a VE
- The closed loop performance due to an operator-induced motor movement. This also includes the dynamic behaviour of movable objects in the VE

The above determinants distinguish VE for instance from conventional CAD tools. In brief, virtual environments are "*synthetic sensory experiences that communicate physical and abstract components to a human operator or participant*" (Kalawsky, 1993). This definition is predominantly in line with Brooks (1999), Toma et al. (2012), and Ellis (1994). By coupling the position and orientation of the human head with computer graphics, it is possible to create a computer-synthesized view of a virtual environment. Besides visualization, audio and haptics are usually simulated in a VE (Figure 19). However, visualization is highlighted in VE research and applications, because the human visual sense is dominant, though other senses may be important in many areas. On the other hand, other senses such as auditory and haptic senses require more complicated simulation models, hardware and real-time computing power, which are not necessarily available yet.
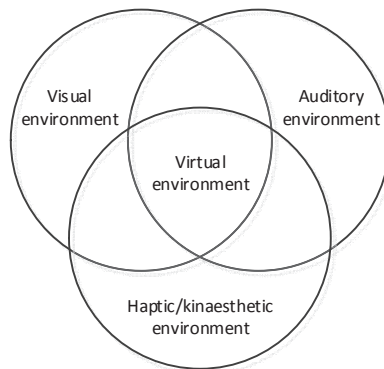
Figure 19. Interrelationships between a partitioned virtual environment (Kalawsky, 1993).

When defining the concept of virtual environments, it is essential to understand the relevant human factors, such as physiology and perception besides the technology issues as well. Compatibility with the human being is the most fundamental requirement for a virtual environment system. The human-technology interface of virtual environments can be partitioned into the visual, auditory and kinaesthetic (haptic and tactile) worlds. The technologies used in each of these worlds are described in terms of theory of operation, physics and implementation (Kalawsky,

1993). Normally, the visual sense is the most important in a virtual environment, having simultaneously the widest bandwidth channel. Human senses are very sensitive to anomalies which make the computing of simulations very challenging. Stereo graphics and real-time motion of the camera (viewpoint) make even a basic system complicated. Apart from the visual channel, accurate dynamic simulation auditory and haptic channels also demand massive computing power.

'Presence' and 'immersion' are distinct key concepts of virtual environments (Kalawsky, 1993), (Bowman et al., 2007). Degree of presence depends on the subjective psychological feel of being part of a synthetic experience, while immersion refers to the objective level of sensory fidelity (Bowman et al., 2007). To be immersed in the experience means that the person feels part of the actual environment (Kalawsky, 1993). Sense of presence in a virtual environment can be improved by visual and other cues. For the virtual environment scientist, the basic question is: does a sense of presence or immersion actually improve the performance of an operator? (Kalawsky, 1993). On the other hand, Sheridan (1992) has noted that presence is a subjective sensation which is not a totally objective physiological definition and measurement. However, the needed level of presence depends on the task to be performed. There is often a temptation towards simulating reality as closely as possible, which is seldom a cost-effective way.

Classification of virtual environments. In order to clarify the concept of virtual environment, it will be classified and categorized from different theoretical and technological aspects in the following. Firstly, VEs can be divided into virtual environments where phenomena obey the laws of physics (reality), and to a class of entirely virtual worlds (Kalawsky, 1993). From a technological viewpoint, VE can be split into immersive (e.g. head-mounted) and non-immersive (e.g. desktop or large) displays which have emerged from animated CAD (Kalawsky, 1993), or to three main categories (Mujber et al., 2004) with ranking by level of immersion: 1) Desktop systems, 2) Semi-immersive projection systems, and 3) Fully immersive systems. However, the level of presence needed depends on the task to be performed. The level of virtual presence depends on many factors, including for instance field of view, display resolution, level of interaction. It is not self-evident that immersive VE always delivers a better virtual presence. Nevertheless, there is no doubt that seeing parts of one's own body reinforces the feeling of presence (Kalawsky, 1993). There is often a temptation to simulate reality as closely as possible, which is seldom the cost-effective way (Kalawsky, 1993).

Content of virtual environments. Objects in a virtual environment must have a range of attributes such as (Kalawsky, 1993): A) Static: position, orientation, visual characteristics (for example, material appearance); B) Dynamic: motion, behaviour, constraints (for example, collision, force). These attributes can be called state vectors. An actor is a special type of object who has the ability to interact with other objects in the environment. The actor holds the point of view where the system provides the constructed virtual environment. Real-time interactivity between objects and actors makes the system challenging from a software and hardware point of view.

3.4   Value and organization theories

First definitions of the concept of value are introduced. After that, the main models and theories, that enabled the extension of the theoretical frame, and explanation of value of prototyping in the dimensions of organisations and business management.

Value definitions. The definition of value concept is strongly context- and phenomena-dependent. In general, value theories aim to describe how, why and to what degree people value things. Consequently, the value of a thing is a measure of how much it is worth. Speaking about products and services, value can be defined as equal to the cost of the product or service plus a subjective part of the value (Neap & Celik, 1999). This is in line with the approach of classical economists who made the distinction between use value and exchange value (Bowman & Ambrosini, 2000). The concept of value in design science corresponds to the above-described value definitions. The Theory of Technical Systems (Hubka & Eder, 1988) includes the following statements:

- By means of value of a technical system, someone's needs will be satisfied or their comfort or pleasure aroused.
- The total value can be regarded as the vector resultant of all values (technical, economic, ergonomic, aesthetic, esteem, usage value), or of the measures of all classes of properties for a given product.
- The basic value realization factors include the abilities of the design team, required design time, and the number of improvements of the given product. Value is related to concepts of efficiency (doing things right) and effectiveness (doing right things). Effectiveness can be defined as benefits of a process divided by expenditure for the process.

Universal Virtues (Olesen, 1992); costs, through-put-time, quality, efficiency, flexibility, risk, and environmental effects are general measurable quantities for assessing a company's value creation and realization for all functional areas.

Value chain. Porter (1985) pioneered conceptualizing and modelling business as a value chain, where the primary activities deal with concrete (physical) products. The primary value chain activities are directly involved in creating and bringing value to the customer, whereas so-called support activities enable and improve the performance of the primary activities (Stabell & Fjeldstad, 1998). The generic support activity categories of the value chain are: procurement, technology development, human resource management, and firm infrastructure. The generic activity categories of the value chain are not the same as organizational functions, but can span several organizational functions from a competitive advantage perspective (Stabell & Fjeldstad, 1998).

Value configurations. Although Porter's Value Chain model is versatile and widely accepted, Stabell and Fjeldstad (1998) propose three alternative value configurations (value chain, value shop, value network) as a foundation for a theory of value configuring for competitive advantage. The theory extends Porter's

value chain using a typology of technologies (Thompson, 1967), and identifies critical value activities, the distinction between primary and support activities, and the analysis of cost and value in common with the configurations. Besides the sequential value chain model, business organizations can be modelled as value shops where value is created by mobilizing resources and activities to resolve a particular and unique customer problem, and the value network models that create value by facilitating a network relationship between their customers using a mediating technology (Stabell & Fjeldstad, 1998).

Value networks. The article by Allee (2008) describes a detailed framework with a system view that reasonably combines theory and practice for a value network analysis that addresses the conversion and utilization of intangible assets. The framework provides a dynamic approach to intangible value capture (turning a tangible or intangible value input into real benefits that contribute to the success of the participants and their organizations), interconvertability, conversion (the act of converting or transforming financial to non-financial value or transforming an intangible input or asset into a financial value or asset), and value creation (converting intangible assets into negotiable value). Allee's (2009) value network analysis combines business management practices where human interactions and relationships reside in one world of models and practices and business processes and transactions reside in another.

Resource-based view of the firm. The theory of Resource Based View (RBV) of the Firm was first introduced and named by Birger Wernerfelt in his article (1984). It builds on Penrose (1959), which provides a theory of effective management of the firm's resources, productive opportunities, and diversification strategy (Kor & Mahoney, 2004). In the RBV theory, a firm's resource can be defined as tangible and intangible assets (such as brand names, knowledge of technology, skilled personnel, machinery, efficient procedures, etc.), and they mean anything which could be thought of a as a strength or weakness of a given firm. The RBV theory looks at firms in terms of their portfolio of resources rather than in terms of their portfolio of products, and gives a different perspective on strategic options.

Value-in-use. The notion of value-in-use proposes that value is not embedded in goods or services (value-in-exchange), but value is rather created when goods or services are used and the skills and knowledge of the users are added in the value creating process (Grönroos, 2008). Therefore, goods and services are value propositions and foundations for value created by the consumers. Sometimes part of the value can be measured in short-term financial terms, such as cost savings, but value has always also an attitudinal component such as trust, affection, comfort and easiness of use, whose impact can be assessed only in the long term. (Grönroos, 2008)

Knowledge-based theory. The Knowledge-Based Theory builds on the Resource-based View of the Firm, and considers knowledge as the most strategically important resource, because knowledge resources are difficult to imitate. The competence of people and efficient knowledge transfer and conversion should be seen as the foundation for enterprise strategy formulation, because people are the only true agents in business (Sveiby, 2001).

Dynamic Theory of Organizational Knowledge Creation by Nonaka (1994) states that organizations should be studied from the viewpoint of how they create information and knowledge, rather than how they process these entities. The theory emphasizes the joint creation of knowledge by individuals and organizations, taking a humanistic knowledge society beyond the limitations of economic rationality. The main concepts and elements of the theory include the epistemological and ontological dimensions of knowledge creation, modes of knowledge creation, and the spiral of organizational knowledge creation. Epistemological knowledge dimensions vary between tacit and explicit knowledge (Figure 20), and the ontological dimension includes social interaction between individuals, departments, and organisational boundaries. The word explicit refers to codified knowledge that can be transmitted by formal and systematic language. Tacit knowledge has a personal quality and a cognitive mental model which makes it difficult to formalize and communicate. The concept of spiral of organizational knowledge creation means interactive amplification of tacit and explicit knowledge held by individuals, organizations, and societies.

	Tacit kowledge	**TO**	Explicit knowledge
Tacit knowledge	SOCIALIZATION		EXTERNALIZATION
FROM			
Explicit knowledge	INTERNALIZATION		COMBINATION
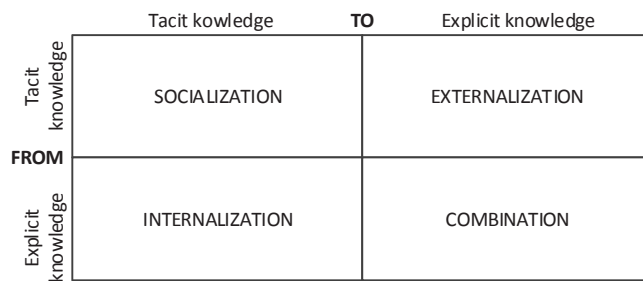
Figure 20. Modes of the knowledge creation processes (Nonaka 1994), also called "SECI" (Nonaka & von Krogh, 2009).

The Theory of Expansive Learning (Engeström, 1987) founded on the Cultural Historical Activity Theory (Vygotsky, 1978) provide for explaining perspectives of individual person or group, and the community where he/she or they are performing. In these theories, activity is the key concept. Vygotsky's idea of mediation is commonly illustrated as a triad of subject, object of activity, and mediating artefact (Engeström, 2001). An application of the triad model is found for instance in Figure 58. The mediating artefact (Allen et al., 2011) may be physical (e.g. tools), or abstract (e.g. skills, experience, competence). Engeström (1987) expanded the first generation activity system of Vygotsky to include elements of community, division of labour, and rules or norms (Allen et al., 2011). Five central principles of the Theory of Expansive Learning are a) activity system as unit of analysis, b) multi-voicedness of activity, c) historicity of activity, d) contradictions as driving force of change in activity, and e) expansive cycles as possible form of transformation in activity.

4. PHENOMENA MODEL OF VIRTUAL PROTOTYPING

This section studies the relationship between phenomena of the real world in the context of engineering design and product development and the characteristics of virtual environments as means of virtual prototyping. This study aims to construct a hypothetical theory frame – "Phenomena Model" – as a starting point for valuing virtual prototyping in the empirical case study. The model will be synthesized and based on theories and concepts that were introduced in the literature review and theoretical basis sections concerning engineering design and virtual environments. Theory of Technical Systems (Hubka & Eder, 1988) and Theory of Virtual Reality and Virtual Environments (Kalawsky, 1993) were selected as the fundamental theories. This section will study how links between the theories can be constructed. Development of the Phenomena Model was also discussed in Leino and Riitahuhta (2014).

Reality and virtuality

Oxford Dictionaries[7] defines the term 'virtual' in the context of computing as "*not physically existing as such but made by software to appear to do so*", and the concept of 'virtual reality' as "*the computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors*". In the theory section of this thesis, it was stated that, concerning virtual reality, optical images are virtual but the simulated environment is ordinarily not close to true reality. Therefore, 'virtual environments' was preferred as a term that better characterizes the methodology used. The virtual environments are defined by Professor Kalawsky (1993) as "*synthetic sensory experiences that communicate physical and abstract components to a human operator or participant*". In this research, the term 'virtual reality' (VR) refers to the technology (devices) utilized within virtual environments and virtual prototyping.

---

[7] www.oxforddictionaries.com

In the theory section, the concepts of 'virtual prototype' and 'virtual prototyping' were defined as follows: "Virtual prototype, or digital mock-up, is a computer simulation of a physical product that can be presented, analysed, and tested from concerned product life-cycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physical model. The construction and testing of a virtual prototype is called virtual prototyping". Therefore, in this context, virtuality aims to mimic phenomena of reality that are important for a particular purpose in design. Thus, virtuality is based on models of reality. On the other hand, the models are always restricted descriptions of reality made for a purpose (Crnkovic, 2010). Therefore, it is essential to discuss what the significant purpose and phenomena are. The properties of a target system itself must be clearly distinguished from the properties of its models (Crnkovic, 2010).
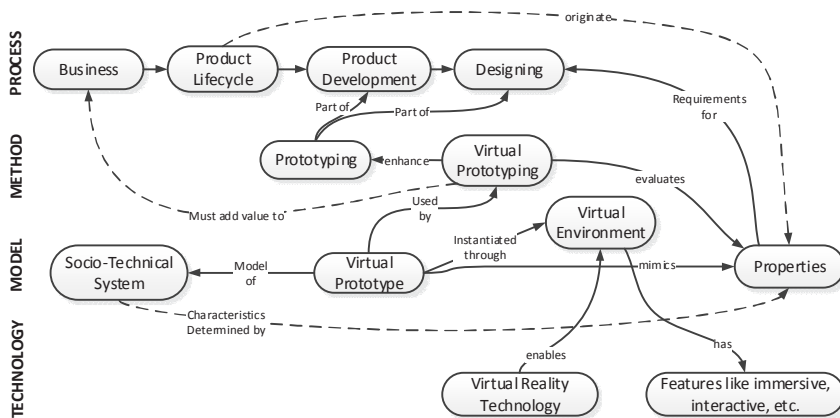
Figure 21. Map of the main concepts related to virtual prototyping in the context of industrial business and designing. The concepts are classified into four categories; process, method, model, and technology.

Figure 21 (Leino & Riitahuhta, 2014) aims to clarify the relationship between the main concepts of virtual prototyping in the context of this research, namely design and business in manufacturing industry. The concepts are classified into four categories; process, method, model, technology. This classification is not universal, but it is intended to emphasize the meaning and position of the concepts within the research.

On the process level, design is considered to be a transformation process (Hubka & Eder, 1988) from the abstract needs and requirements of stakeholders towards a concretized and realized product specification that fulfils the needs and requirements. The design process is managed by product development, which is rather a project and quality management process. Furthermore, design and product development are phases of the product lifecycle. Simultaneously, product

lifecycle management is an essential business approach, where other phases and stakeholders of a product life set the requirements for design. The product requirements are manifested in the form of properties of the product. Properties (Hubka & Eder, 1988) include external properties (such as ergonomics and economics) and internal properties which refer, for instance, to the structure and function of the product. All these properties are determined by design properties which are manipulated by the engineering designers.

Design methods. Prototyping and virtual prototyping are in this context considered as product design and development methods. The purpose is to define or evaluate certain properties of the design in a certain phase of the transformation process, e.g. assembly properties in the internal productisation phase. The purpose of virtual prototyping is similar to prototyping (Wang, 2002) with a physical prototype, but it is aimed to enhance and benefit the prototyping phase by means of e.g. a decreased need for physical prototypes and their re-design and re-manufacture.

Models in design. In the context of design, models are defined as restricted representations of reality on different abstraction levels (Hubka & Eder, 1988), made for a purpose and ignoring aspects that are irrelevant to its purpose (Crnkovic, 2010). Andreasen (1990[8]) recognized three interactive concepts: 1) design language, i.e. a vocabulary for thinking, reasoning, conceptualising and specifying solutions in three domains (activities, organs and parts), 2) design models, i.e. models for structures of activities, organs and parts, carrying the specifications of these structures and allowing a more or less formalised specification of relations inside and between the domains and of property statements of the entities, and 3) design operations, i.e. methodologies for synthesising, composing, evaluating, modelling, simulating etc. for a gradual synthesis in all domains. Therefore, models in design can be seen as a medium for transformation from more abstract design thinking-driven demands towards more concretized requirements and product descriptions, and the means for analysing the outcome of designers. Thus, this dual approach of utilising models is the interplay between external, internal and design properties (Hubka & Eder, 1988) or the establishment of product characteristics (synthesis) and assessment (analysis) of the product properties (Weber & Husung, 2011) and customer satisfaction. Product development is a cyclical process (Weber, 2014) of synthesis, analysis, determining individual deviations (comparing as-is properties to required properties), and overall evaluation (deciding how to proceed) where more and more characteristics are established. Different kinds of models can be utilized in all steps of the product development process.

Models can be used for many purposes from defining customer demands to sketching a concept on squared paper so as to complete manufacturing specification and drawings or 3D models of a product that fulfils the customer demand. Altogether, models in design are representations of a socio-technical system, and

---

[8] Andreasen, M.M., 1990. Designing on a designer's workbench. Unpublished notes from the WDKWorkshop Rigi.

virtual prototypes are limited subset models of the socio-technical system. In a wide meaning of the system model, also the stakeholder and activities (such as manufacture, operation, service, maintenance) during system life should be included in addition to the technical system model. The virtual prototypes are "used" by the virtual prototyping method in order to study and evaluate certain properties and phenomena of the system. Thus, virtual prototypes aim to "mimic" properties of socio-technical systems. Virtual environments are in a sense both models and methods (or tools), so that they are a kind of 'user interfaces' of virtual prototype models, and a way to manage the virtual prototyping method as part of designing. Additionally, virtual environments have typically technological features (such as immersion, interactivity) of virtual reality, which should in some way provide an advantage to virtual prototyping. These fundamental features are one research target related to the value of virtual prototyping. The virtual reality also refers to the technological user interface of virtual environments. So, there are two levels of user interfaces concerning the virtual prototype: 1) Virtual Environments (experience) as an interface to models of socio-technical systems, and 2) Virtual Reality (devices) as an interface to Virtual Environments, see Figure 22 below.
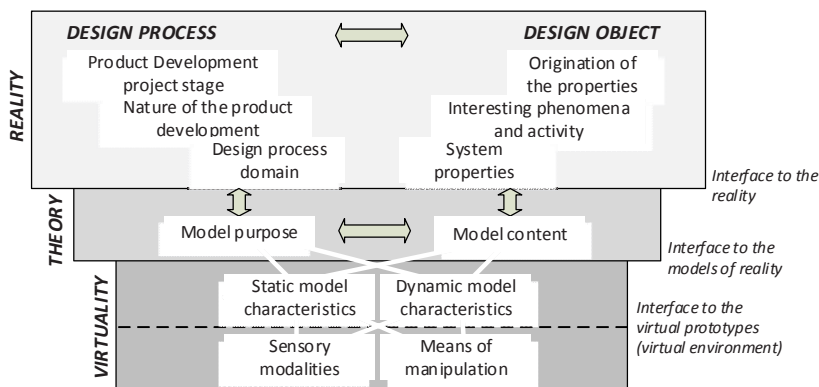
Figure 22. The recognized three interfaces between reality and virtuality. The first interface is the interaction and presence of virtual environments created by the VR technology. The second interface is the representation of the models of products in virtual prototyping. The third interface is between the models, and the reality of design process, and design object.

Phenomena of reality

The system life i.e. origination of system properties, design. i.e. transformation from needs to system specification and the socio-technical system i.e. design object represent the different dimensions (Hubka & Eder, 1988) of reality models (Figure 23). The model of the technical system refers to the design object and design to the design process of design theory. The system life is the origination of

system properties, i.e. the design requirements including the demands of manual work. The properties of technical systems can be categorized by the way of observing them (Hubka & Eder, 1988): A) external properties interest the users, operators, and customers (socio-technical view), B) internal properties deal with relationships between the elements of the system, and the properties of those elements, and C) design properties serve as a means for the designer to create the desired external properties.
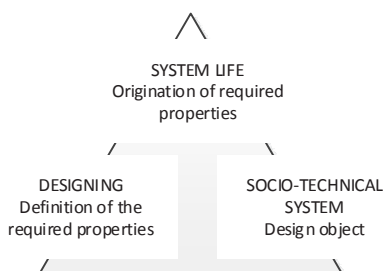
Figure 23. The three important phenomena areas of reality

Phenomena of system life. Aspects of manual assembly and maintenance work are at the focus of this research. According to the good HF/E principles (Norros, 2013), the characteristics of manual work should be studied and designed together with production and maintenance performance in order to optimize the total socio-technical system. Characteristics of manual assembly and maintenance include, for instance: how workers are performing their work tasks; what kind of difficulties may exist; the safety and comfort of the workers: how the design of the system could be improved: how the work tasks and activity could be modelled; and how the total system could be optimized?

    Phenomena of the socio-technical system. The phenomena of the socio-technical system are the origination of system properties. External properties (manufacturing, economic, function, operational, ergonomic, aesthetic, delivery, distribution, etc.) of the technical system determine how the socio-technical system performs during its life-cycle. The external properties are determined by design properties which need to be studied in virtual prototyping: form, dimensions, function, (organ), structure, material, surface, tolerances, and manufacturing methods. The focus of the study depends on what phenomena are interesting. Ergonomics is an important external property besides manufacturing, operational and economic properties when manual work tasks are studied. In the case of productisation, form, dimensions, structure, tolerances and manufacturing methods are the most interesting design properties. Therefore, VP should be an in advantage investigating these properties.

    Phenomena of design. Naturally engineering design is a particularly interesting life-cycle aspect in this research. The phenomena of design and engineering

(the virtual phase of the product life) include developing the specification of the product, and verification and validation of the specification by utilization of virtual prototyping. Other (physical) product life-cycle aspects include manufacturing and service set requirements for the external properties of the socio-technical system. The specification of a product is actually a model of a technical system. The model describes internal and external properties that are defined by design properties. Therefore, virtuality should ultimately be capable of simulating certain phenomena on the level of technical system characteristics (such as structure) and properties (like easiness of assembly work). The benefits of virtual prototyping are manifested by capabilities of simulating phenomena of product properties and life-cycle aspects so that phenomena of designing are supported.

This case study scoped the research to include two design process phases: 1) concept design, where the main principles of a new product module are assessed, and 2) productisation, where a new product or module is prepared for standard production. Conventionally, physical prototypes have been used in order to investigate how the product or module can be manually assembled. Simultaneously, aspects of product life, i.e. maintenance and operations as well as their safety and ergonomics, have been considered as well. The physical prototypes are utilized for other purposes such as investigating the function and durability of the machine as well. The introduction of VP can be seen as a step towards integrated product development (Andreasen & Hein, 1987), where the product and its manufacture system are developed in parallel. Design for assembly contains three different views (Andreasen & McAloone, 2008): the assembly process described as a system of activities, the assembly equipment system described by its functionalities and characteristics important for assembly, and the product as a system of parts and their characteristics and relations important for assembly.

Because assembly and maintenance are to a great extent conducted manually, design for ergonomics is a significant area. The posture, reach, visibility, physical and mental stress of a worker as well as convenience and overall occupational conditions are features that should be taken into account when designing the product and its assembly and maintenance.

Design review meetings have been used for assessing or even verifying design specifications from different stakeholder aspects. For instance, manual assembly and maintenance workers have participated in assessing design from their viewpoint. Traditionally, design reviews have been organized using 2D-drawings and 3D-CAD models and video projectors in a meeting room environment, or on the factory floor around the physical prototype.

Phenomena of virtuality

This chapter aims to describe how virtual prototyping technology could improve investigating the phenomena of the socio-technical system and its life-cycle, and how design could benefit.

In this research, virtual environments (VE) are a means of virtual prototyping activity and virtuality, whereas virtual reality is a technology for creating virtual environments. As described in the theoretical section, the capability of mimicking reality depends on capability of:

1. Sensory modalities (visualization, audio, haptics),
2. Means of modifying states of models (navigation, user interface, motion capture), and
3. Features of object, models and processes.

Sensory modalities refer to the extent of user perception and experience in a virtual environment. The means of modifying the states of models together with sensory modalities are strongly related to VE technology devices, while features of objects, models and processes refer to the content and phenomena of the virtual prototyping (static: position, orientation, visual characteristics; dynamic: motion, behaviour, constraints, force). The features of objects, models and processes should meet the relevant phenomena of product design and lifecycle as well as the external, internal and design properties of socio-technical systems. How well these features are supported in virtual prototyping depends on the capabilities of sensory modalities and the means of modifying states of models. Because design in this research is closely related to the characteristics of manual assembly and maintenance phenomena of manual work tasks should be supported by the VE capabilities:

- The features of objects, models and processes should support product the properties of form, dimensions, structure, tolerances and manufacturing methods by the features of static object position, orientation and visual characteristics, as well as dynamic motion, behaviour, constraint and force (haptics)
- The means of modifying the above mentioned features and properties
- The sensory modalities that support and advantage both above mentioned categories

Besides the above-mentioned essential capabilities, audio may be important in some cases, e.g. when a diagnosis is made by acoustic analysis as part of maintenance task. The basic properties (autonomy, interactivity, immersion, fidelity, and deterministic) of virtual environments are determined by the level of these capabilities. In the end these properties and capabilities of virtual prototyping depend in practice on the implementation level of virtual environments technology: visualization, audio, haptics, navigation, user interface devices and motion capture.
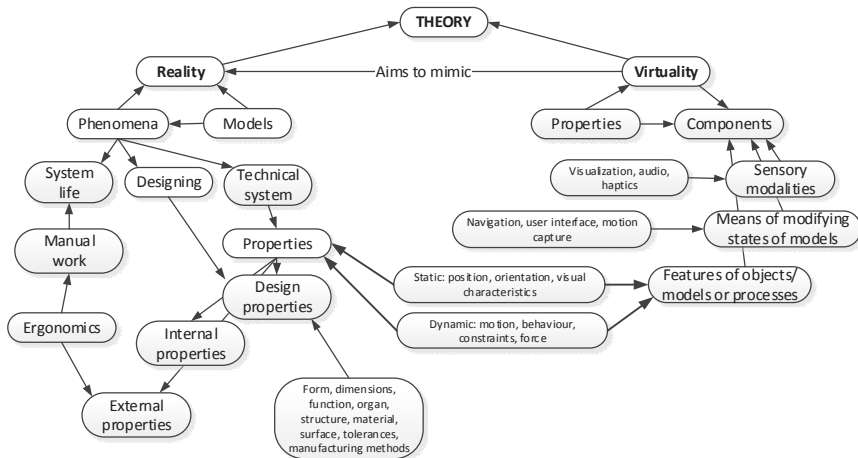
Figure 24. Theoretical phenomena of reality and virtuality in the context of engineering design – a synthesis of the theory of technical systems and theory of virtual environments

Figure 24 illustrates the synthetic reality-virtuality model that combines elements of the Theory of Technical Systems (Hubka & Eder, 1988) and the theory of virtual environments (Kalawsky, 1993). It recognizes the features of objects/models or processes of virtual environments as a link to models of reality via the properties of a technical system (TS) model. The static features (position, orientation, visual characteristics) have their counterparts in the static properties of TS like dimensions, structure, form and material. Similarly, the dynamic features of VE object/models or processes have their counterparts in TS properties such as function. The other components of virtual environments (sensory modalities and means of modifying states of models) refer to the capabilities of utilising virtual environments in virtual prototyping and design in general. Thus, they should deliver some added value compared to other virtual prototyping methods or conventional CAD tools.

4.1 Conclusion

There has been lot of cogitation, for instance in our research group, about relationships between the concepts of virtual environments, virtual reality, virtual prototypes, virtual prototyping, and designing. This section aims firstly to clarify the concepts and terminology as well as their relationships related to virtual prototyping in the context of product development and engineering design. These concepts are then classified in to four categories, namely processes, methods, models, and technology. The distinction between phenomena of reality and phenome-

na of virtuality is recognized. Furthermore, it is remarkable that there exist two levels of user interfaces, namely the user interface of virtual prototype (virtual environment experience), and the user interface of virtual environment (VR technology) which refers to devices and software.

All our knowledge of systems is mediated by models (Crnkovic, 2010). The theoretical reality-virtuality phenomena model created explains how the phenomena (system life, socio-technical system, design) of reality relates to the phenomena of virtual environments. The three groups of phenomena refer to the origination of system properties, designing the system, and the design object of design theory. The constructed "Phenomena model" clarifies how the phenomena of reality of engineering design relate theoretically to phenomena of virtual environments. This clarification was proposed in order to improve the understanding of the potential benefits of virtual prototyping and virtual environments in the industrial context.

The constructed model is intended to be a framework where the data of case studies can be mapped to in order to explain the benefits of virtual environments compared to more conventional methods. Based on the theoretical model, the main benefits can be derived from a more natural interface with product models and other information. This aspect will be elaborated in the section where empirical case study data will be discussed.

5. CASE STUDY

This section introduces how the empirical research was carried out in industry. It is described how the virtual environments based virtual prototyping was used and developed in three research projects, and in several true product development projects of the case company, during years 2006-2014. The hypothetical theory model "Phenomena model" was introduced in the previous section number 4. The model was a used as a preliminary theoretical framework in the empirical case study. Analysis of the case study will be discussed in Sections 6–7.

Case study is an empirical research method that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and its context are not clearly evident (Yin, 2009). This case study was conducted in one manufacturing company, but it consisted of six sub-cases over a nine-year period. Figure 25 below illustrates the relationships between the sub-cases and three large research projects.
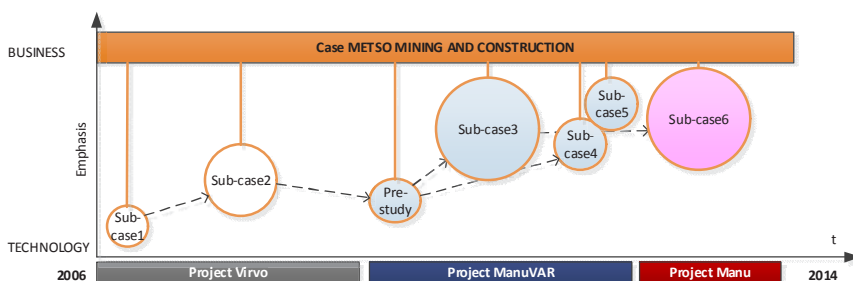
Figure 25. The case study was conducted in three relatively large research projects over nine years.

The emphasis and focus of the sub-cases shifted from the first technology studies in 2006 to the business processes and product data management later. The size

of the sub-case "ball" in Figure 25 refers to the volume of the sub-case study. Thus, there were three larger sub-cases, and three minor sub-cases. Additionally, there was a pre-study that was carried out before beginning of the actual sub-case 3. Furthermore, sub-case 6 was started in 2013, and it will continue approximately until 2017, but some preliminary material of that study has been utilized in this thesis as well. A summary of the sub-cases is found in the Table 4 below.

Table 4. Summary of the sub-cases of the research

Sub-case	Scope	Purpose	Results
Sub-case 1 2006–2007	Engine main-tainability Maintenance training	Technology study, Introduction of VE and VP for the case company	Experience and feedback from user candidates, Knowledge of technology maturi-ty, problems and development targets, Experience of the process from CAD models to VE system, Basis for developing systematic virtual prototyping process
Sub-case 2 2008–2009	Maintainability of new gener-ation rock crusher	Improve ergonomics and safety, Design for manufacture, reliability and mainte-nance, Support product lifecycle management and docu-mentation	Experience of VE-based VP in a real NPD project, Understanding on how VE-based VP influences new prod-uct design and development, 3D-model and meta-data pipe-line, Experience on design reviews based on VE and VP, Method that combines VP and risk-analyses methods, Understanding of the benefits, utility, drawbacks, requirements, and maturity of VE and VP, Recognition of human tasks and activity as an essential dimen-sion of VP
Pre-study 2009	New genera-tion engine module	Introduce the new engine module for productisation and production, Assembly and maintaina-bility assessment, Testing and introduction of the present VP technology, Focusing the research project and development targets	Collected experiences through interviews and questionnaires concerning virtual design review events, the usability and ad-vantages of virtual environ-ments, level of immersion and interaction in VE , Ideas on how usage of VE-based VP and virtual product reviews could be developed, Understanding of prerequisites for using VE and VP systemati-cally in product design and development
Sub-case 3 2009–2012	New genera-tion engine module	Improve combined mass-customization and manual maintainability and easy assembly,	Knowledge of virtual product reviews as user experience, Knowledge of VP compared to conventional practices,

		Develop internal productisation and collaboration between product design, development and production, Improve ergonomics and safety, Get feedback on VE and VP	Knowledge of VE advantages compared to conventional presentation technology, Knowledge of VE capabilities in order to perceive product properties and conduct critical tasks in a virtual environment, Understanding of how virtual product reviews should be organized as a process, Understanding the benefits of virtual prototyping as a process, Development targets
Sub-case 4 2011–2012	Noise reduction module for mobile rock crushers	Modular solutions for improved noise and dust reduction, Test solution concepts, Get feedback and validate solution concepts with internal and external customers, Maintainability, assembly, safety and ergonomics	Knowledge of the benefits and challenges of VE-based VP in concept design, Knowledge of the benefits of VE-based VP in design verification and customer validation, Feedback from the end customers
Sub-case 5 2012	maintenance concept for mobile crusher units	Development of safety equipment for crusher maintenance work task, Evaluation of human performance, safety and ergonomics, Early validation of the concept	Knowledge of the benefits and challenges of VE-based VP in concept design phase
Sub-case 6 2013–2014	Internal productisation	Faster time-to-profit, Effective utilization of VP in new product development, VP-aided NPD and productisation process and product data management, Modelling quantified impact and value of virtual prototyping,	Principles for supporting VP with product data management, Preliminary quantified benefits of VP based on a comparison of past NPD projects

5.1   Case company and main products

Metso is (2014) a global stock exchange-listed technology corporation and leading manufacturer of equipment and services, for instance, for mining and construction. Metso has customers in more than a hundred countries around the globe. The company has engineering, production, procurements, services business, sales and other operations globally around the world. Over 40% of Metso's sales come from the services business. In the case projects, the focus was on the mining and construction sector.

During the research projects, the participating company's name was Metso Mining and Construction (Metso MAC) business line. The main products of Metso MAC were crushers, feeders, screens, conveyors, and mobile crushing units, i.e. Lokotracks. Lokotracks are the main products of the Metso MAC Tampere site, which is the business unit studied in the case studies. The main modules of a Lokotrack include the track frame, feeder, crusher, main conveyor, and power unit (normally a diesel-engine). The crushers can be categorized as jaw crushers, cone crushers, and impactors. Figure 26 is an illustration of a Lokotrack LT 106 mobile crushing unit.

Figure 26. Lokotrack LT 106 mobile rock crushing unit (source: Metso MAC).

The products of Metso MAC are typically partially configurable variants, which mean that in practice almost every product individual is different. This kind of variant production paradigm with relatively low production volumes requires high flexibility of the production system, hence the involvement of human actors and manual work.

5.2 Case projects

The industrial case studies were part of three large research projects and research programmes. The first project (2006–2009) was called "Virtual engineering and remote operation in design, training and completion of demanding maintenance work tasks in challenging industrial plants – VIRVO", and it was funded by Tekes – the Finnish Funding Agency for Innovation. The Virvo project aimed to create a comprehensive method for the virtual design, planning and training of critical manual and remotely operated work tasks in industry.

The name of the second project (2009–2012) was "Manual work support throughout system lifecycle by exploiting virtual and augmented reality – ManuVAR". The ManuVAR project was an EU-project in the EU FP7 NMP "Be-

yond lean manufacturing". The goal of ManuVAR was to develop a technology and methodology for designing and supporting all aspect of manual work throughout the system lifecycle. The ManuVAR consortium consisted of 18 partners from eight European countries representing industry, research and academia.

The third project "Product Knowledge Management in Global Networks – PROMAGNET" is part of the research programme of Fimecc (Finnish Metals and Engineering Competence Cluster) called "Future Digital Manufacturing Technologies and Systems – MANU" (2013–). The MANU programme is funded by Tekes and the participating organisations. One of the main research goals of MANU programme is to establish the world's fastest time-to-market with better productisation capabilities. Metso MAC was one of the case companies in all the three projects. There was one other case company in VIRVO, and several other case companies in ManuVAR and MANU, but Metso MAC was the company with which the researcher was mainly working. Moreover, the cases of the other companies had different kind of objectives.

The three projects over nine years allowed observing the progress of implementation and adoption of virtual prototyping and virtual environments technology and methodology. At the beginning of the Virvo project, the focus was mainly on testing different kind of techniques and assessing their usability and utility. Later, when the technology was developed and validated, the focus shifted towards development of methods, procedures, processes, product data management. Virtual prototyping became a method that could be used in the real product development projects of Metso MAC. Nevertheless, the use cases were still pilots which aimed to recognize the benefits and development targets of virtual prototyping. It was understood that virtual prototyping holds great potential, but it also causes major influences on the organisation and business processes as well. In the ongoing MANU programme, the goal is to develop virtual prototyping processes and infrastructure to better support business in industry.

Technology studies in Virvo project

At the beginning of the Virvo project, the first demonstrations and tests with a virtual prototype and virtual environment were made in order to become familiar with the new technology in the case company. The demonstrations were related to training manual maintenance tasks of the mobile crusher's engine module. In the maintenance task, the change of an air filter of Metso MAC C9 engine module (Figure 27) was at the focus.
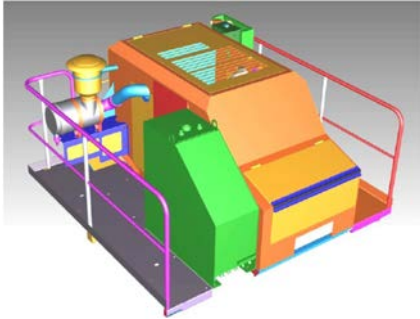
3D model of the Metso MAC C9 engine module in Deep Exploration visualization programme.

Air filter change operation in virtual environment

Figure 27. Examples about the first VR technology studies in Virvo project. Source: Martikainen (2010).

The main elements of the virtual environment configuration used consisted of 3D-shutter glasses and a four-metre- wide screen with back projection, and an electro-magnetic motion tracking (position, orientation with respect to time) system (Ascension, user's head and data gloves). Therefore, a realistic perspective of visualization could be calculated for the user in the virtual environment, and the user was able to manipulate certain parts when he/she was performing the maintenance task. Thus, it could be called a semi-immersive virtual environment.

The 3D models and structures of the C9 engine module were exported from I-DEAS CAD to STEP-standard data format, and imported to the Deep Exploration tool where the models were simplified and the module structure was modified in order to better serve the maintenance task. After this operation, the models were imported to the Virtools software tool at VTT in order to create an interactive virtual environment simulation model.

The air filter change task was demonstrated in 2007 in a workshop together with researchers and Metso MAC personnel. The main conclusions about the technology demonstrations (Martikainen, 2010) were:

- From the utilization viewpoint, it was seen as a value adding solution in maintenance task training
- From the usability point of view, the virtual environment configuration demonstrated was not very highly appreciated. In particular, an improvement in the user interface and controls (such as haptics) were demanded. Nevertheless, it was understood that new tools and systems need learning as well.
- From the design process viewpoint, the main result was the process created of CAD model conversion and import into the virtual environment sys-

tem. Also the first steps towards a systematic method for virtual prototyping aided maintainability design were made successfully.

5.3 The real product development pilot studies

At the time of the VIRVO project, Metso MAC's product process was called "Metso Innovation Process – MIP" (Figure 28) as part of their quality process manual. It consisted of six main process stages (idea management, feasibility study, research and development, solution development, launch, and review), and gates between the process stages where project steering group makes a decision about proceeding to the next process stage. According to Jokioinen (2006), the MIP process is based on the "Stage-Gate" new product development model, described for instance by Cooper and Edgett (2008). (Martikainen, 2010)
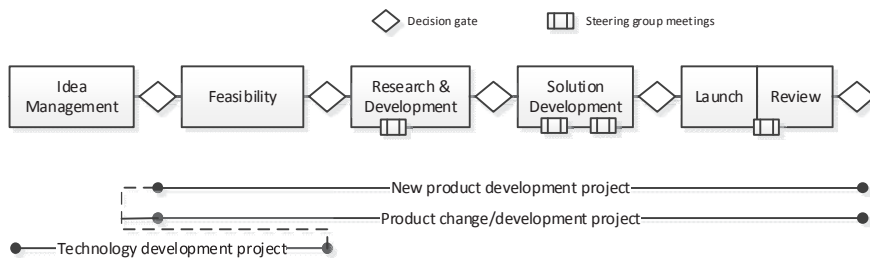
Figure 28. Metso Innovation Process (MIP). Adapted from Martikainen (2010).

The process begins from ideas followed by a feasibility study where a rough cost level and markets are studied. After that, in the research and development stage, a new product is modelled, drawings are generated and a prototype manufactured. The solution development stage includes productisation, testing 0-patch prototypes and preparation for market launch and standard production. Standard mobile crushing units are produced on the "SpeedLine" assembly line at the Tampere Factory of Metso MAC. In standard production, even small design flaws may cause serious problems and halt the production line. Therefore, design, assembly structure and assembly sequences should be carefully verified in the solution development i.e. productisation stage. Metso MAC strategy was to increase service business. Therefore, product maintainability was identified as a critical property as well. (Martikainen, 2010)

   The practical VP cases that were part of the case company's real product development projects were related to design review meetings. Product design reviews are an essential part of productisation, and their target can vary from a single welded structure to a whole Lokotrack assembly (Leikko, 2012). The purpose of design reviews is to share information and to stimulate discussion on the product design. All the design review virtual prototyping sessions were organized

at the VR laboratory on VTT premises in Tampere, Finland. Product design review / design brainstorming were related to four different product development projects. These projects can be categorized as 1) internal productisation, and 2) concept design (Table 5). Figure 29 illustrates how the research projects can be positioned in the dimensions of design maturity and product life.

Table 5. Type of new product development projects in the three research projects

Type of the new product development projects			
Internal productisation		**Concept development**	
New rock crusher maintain-ability	VIRVO	Mobile rock crusher noise reduction module	ManuVAR
New engine module as-sembly and maintainability; preparation for standard production	ManuVAR	Mobile rock crusher maintenance concept	ManuVAR
Development of productisa-tion process and product data management	MANU		
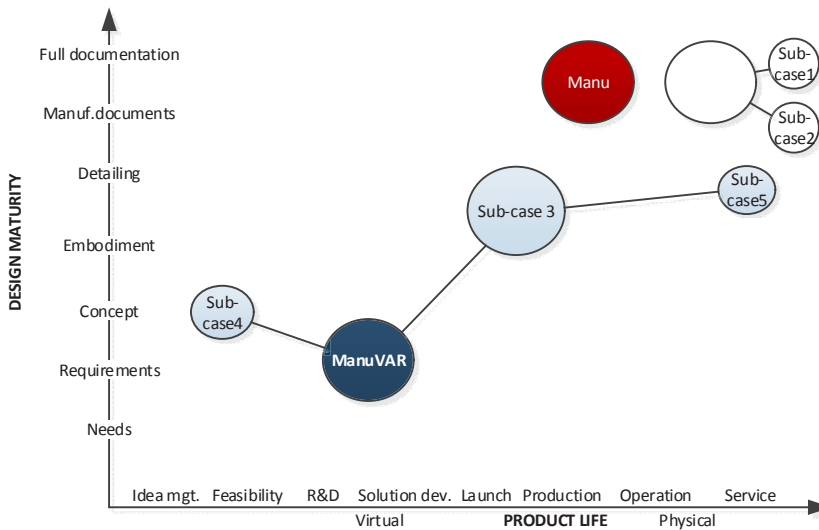
Figure 29. illustrates how the sub-cases can be characterized in the dimensions of product life stage and design maturity.

5.4   Internal productisation in new product development

Productisation at Metso MAC means the activity of preparing new products for market. It should be distinguished as internal and external productisation (Leikko,

2012). The internal productisation means the preparation and development of new products or modules for standard/serial production with a target cost level, while external productisation is related to customer interface, sales and marketing. Internal productisation can be also called "Inbound productisation – ability to make" and external productisation "Outbound productisation – ability to sell" (Simula et al., 2008). The productisation function at Metso MAC builds prototypes that are utilized in testing product functionalities and preparation for standard production.

The internal productisation is based on a prototyping process. In other words, prototypes (i.e. physical models of the end product for certain purposes) are built and used for investigating suitability for assembly, and other product properties. Testing the prototypes produces request for engineering changes as a feedback. In the end, a prototype is actually a mature product individual which may be sold or leased to a customer. In this phase, the new product or module type is ready for standard production including all manufacturing specifications and instructions. The products in productisation may be at different stages of their lifecycle. They may be totally new models with new technological solutions, or they can be mature products whose cost efficiency in production must be enhanced (Leikko, 2012). Thus, the newness of a product from production viewpoint can be also manifested by new manufacturing methods. The greatest challenges of productisation are related to tight time schedules, new product parts and assemblies, and possibly new suppliers (Leikko, 2012).

Apart from these activities, productisation at Metso MAC also refers to an organizational function. It is a function that acts as an interface between engineering design, standard production and suppliers in new product development and production ramp-up phase (Leikko, 2012). At the time productisation used to belong organizationally to the production department, and its purpose is to build the prototype and be a link between product design and standard production. Engineering designers communicate and acquire feedback mostly from workers and development engineers of the productisation department. Apart from production, the productisation activity also for instance involves maintenance workers and other stakeholders when needed. This aims to avoid optimization of one function at the cost of another. The production function creates value for the product process by fast and agile preparation of specifications for production, enabling a faster standard production ramp-up, removing non-value adding operations and reducing the need for changes and disruptions in the standard production line (Leikko, 2012).

New rock crusher maintainability

The case company's strategic goal was to improve their "engineering quality for service performance, and reliability management in product engineering process" and to move "from equipment supplier towards product lifecycle service provider". The company intended to greatly increase their service business and share of service market. It was recognized that a fundamental precondition for a good service business is efficient and reliable product data and lifecycle management, but also accounting serviceability (such as maintainability) and lifecycle cost in

design and development as well as in producing high quality documentation and instructions for the product life. Another identified challenge was a great variety of products, increased complication of products combined with an increased volume of sales. The increased complication was the result of e.g. packaging more product functionalities into a smaller space inside the product. Apart from the complication of products, also global manufacturability and serviceability was an increasing issue. The capability for manufacturing and maintaining the same product configurations at several sites around the world was a necessity. These challenges were drivers for the development project where new technologies and methodology for improving capability to design, produce and service were the target. Figure 30 shows an example of a product maintenance work task.

Figure 30. An example of crusher maintenance work task in the rock crushing site. (Source: Metso MAC.)

Product reliability is one of the most important properties that creates value for a customer besides the lifecycle cost. In order to guarantee overall product reliability, the products must have good maintenance process and data reliability (item data, spare catalogues, skills, instructions, availability), and maintainability (short and easy maintenance and repair operations, diagnostics, maintenance-free solutions). Product design and product development required improved methods in order to produce solutions that fulfil these requirements efficiently. However, nowadays maintainability design is underresourced in the case company, and the maintainability is assessed in the late physical prototyping phase (Vehviläinen, 2014). Improved collection and management of product design- and lifecycle-

related information and knowledge (besides pure data) was also recognized as a development target area.

3D and product data management. During the VIRVO project (2006–2009) the company was in a situation where a major transformation from conventional 2D drawings to 3D modelling (I-DEAS 3D-CAD of UGS, today Siemens PLM) had already been completed in product design and development several years previously (2001). In 2009, Metso MAC was substituting I-DEAS and implementing NX of Siemens PLM. The first global product data management (PDM) system was implemented already in 1997. In 2005, the company started to invest heavily in the utilization of 3D and engineering data management (EDM[9]). Besides 3D-CAD utilization of other kinds of 3D-models and novel technologies (called "virtual engineering" at the time) were at the focus of interest in the company as well. There was a vision that 3D and virtual engineering could support the whole product lifecycle from design and engineering to manufacture and maintenance of the product. The aim to achieve a holistic PLM was recognized as a strategic goal of the company.

A remarkable percentage of product development and design work was made in 3D-CAD. Besides design, 3D-models were also utilized in design review meetings. Nevertheless, there were neither systematic procedures nor processes for utilization of 3D, and there were significant differences between product development projects at the time. 3D was utilized in documentation only occasionally. In 2012 better and systematic utilization of 3D in productisation within couple of years was recognized as a development target (Leikko, 2012).

Goals of the Virvo research project

The VIRVO project started with a literature review and interviews with the stakeholders of the company from different functions and organizational levels, and focusing the project scope. Based on the reviews and interviews, the project was scoped to find new virtual engineering-based methods and tools for supporting product lifecycle management and to study how they could be utilized in design for manufacture, reliability and maintenance and integrated to design processes, production planning, generation of documentation and instructions and customer service and data management. It was recognized by the case company that all potential advantages of transition from 2D drawings to 3D modelling had not been captured. In fact, sometimes the quality of the documentation was even worse than before, see Figure 31.

The purpose was to carry out a number of pilot studies (2007–2008) and demonstrations, not actually the implementation and integration to the processes. It is a remarkable boundary condition that the new tools and methods must not make the product development processes more inflexible and the projects longer.

---

[9] During the case studies, at Metso MAC EDM was an IT-solution that managed CAD and other design objects before they are released to PDM. From PDM product individuals are configured to ERP system at production.

Nevertheless, it was assumed that the new tools and methods inevitably influenced the existing product development processes. An objective was to ascertain what kind of implications design for reliability and maintainability as well as design for assembly combined with the novel virtual engineering had for the product development processes, how the new tools and methods could streamline the processes. Assembly and maintenance work activity planning and training was also an important part of reliability and maintainability design. Investigation of suitable methodology and commercial tools for engineering system environment was an important sub-goal of the Virvo project.
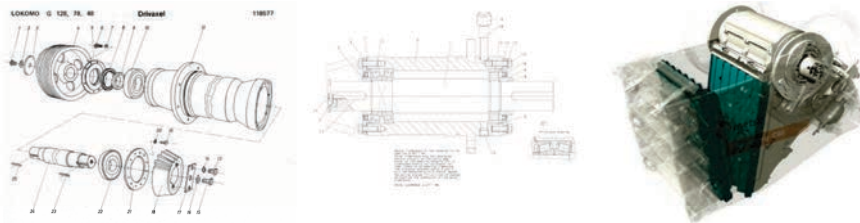
1970's. "In the 1970s it probably took at least one week to create this isometric explosion drawing manually"

2006. "Today we are proud to create spare part drawings for our eParts catalogue in two minutes by removing unnecessary dimensions from the manufacturing drawing with using Adobe tools"

Goal. "…And for marketing purposes our trainees are able to create Jaw crushers with transparent side plates directly from an existing 3D-CAD model in one hour. Can you explode it? Yes, you can! Five minutes more..."

Figure 31. Transition from handmade 2D drawings to drawings generated from 3D models aiming towards effective utilization of 3D (Heikkilä, 2006).

The practical approach of the VIRVO project was to implement and develop "virtual engineering" tools and methods at the VTT laboratory in Tampere, and utilize them in a real new product development project of Metso MAC. The tools and methods included virtual prototype models (3D geometry, product structure, kinematics), virtual environments (haptics, interaction, interfaces), and activity and context models as well. A vital task was firstly to establish a 3D-model and metadata pipeline from the company engineering systems (CAD, EDM) to VTT's virtual prototyping system. In order to guarantee effective cooperation between the company and researchers, several Metso MAC and Etteplan (engineering subcontractor of Metso MAC) staff were based at VTT's premises. Part of this cooperation is documented in Martikainen (2010).

Pilot project. As the product development pilot project a new generation cone crusher was chosen. The assembly and maintainability of the cone crusher (Figure

32) was evaluated in a design review meeting with virtual prototypes. Dismantling and reassembly sequences of the cone crusher were specific activities that were analysed in the review meetings. Inspection of a thrust bearing of the crusher is an example of a manual service work task which was simulated in detail. Apart from the maintenance sequences, the positioning of a maintenance hatch of the cone crusher was designed and analysed. Altogether, ergonomics and safety issues were at the focus of all the pilot studies as well. At the end of the pilot project, the focus was mainly on change tasks of wear parts of the cone crusher.

During the product development project, assembly and maintainability studies were also carried out with a physical prototype which enabled gathering data on the real world conditions and comparing the virtual prototyping with the real one. Researchers participated in one of the studies with the physical prototype. The study was video-recorded and analysed afterwards. The assembly and maintenance workers were interviewed in order to recognize the most demanding and possibly dangerous work tasks.

Figure 32. The developed rock crusher module on a mobile Lokotrack crusher unit is highlighted with the red colour on the left side of the figure. On the right side is a cross-section of the crusher. (Source: Metso MAC.)

Goals of the virtual prototyping. One sub-goal of the Virvo project at Metso MAC was to develop a methodology which combines virtual prototyping and risk analyses (FMEA, FMECA, FTA[10]). The results of this sub-task are detailed in a Master's Thesis by Tomi Martikainen (2010). The target module of these studies was the Metso GP550 cone crusher. These studies led to the conclusion that the virtual prototype enabled a novice to become familiar with the digital crusher module, and carry out the risk analyses without a physical machine. Nevertheless, experts and experienced maintenance workers and operators from the company participated in the risk analysis session, verified the model and validated the analysis results.

Product design reviews. During the Virvo project two major design review meetings of the new cone crusher project were arranged at VTT's virtual reality

---

[10] FMEA = Failure Mode and Effect Analysis, FMECA = Failure Mode, Effect and Criticality Analysis, FTA = Failure Tree Analysis.

laboratory (3.6.2008 and 19.2.2009). Besides the major review meetings, several minor focused reviews were arranged with smaller groups. Some of the meetings were focused on developing the virtual prototype models and the virtual environment simulations.

In the second major design review meeting (cone crusher, 19.2.2009), the virtual prototype model was verified i.e. the model and work tasks were walked through and evaluated that the product model and tasks were correct. In the review, the Lokotrack was driven to a maintenance position and prepared for maintenance. The whole maintenance activity was not modelled in detail, but it was concluded that only tasks that are considered to be most critical should be simulated and analysed precisely.

Comments and feedback from the design review meetings

As a general feedback, the usability of virtual reality system and realism of virtual environments should be improved. The comments and feedback were divided and summarized into three categories (Table 6): technology level and usability, virtual prototyping methodology and utilization, and development targets and ideas.

Table 6. Assessment of technology maturity, usability, methodology and development targets of virtual prototyping

Technology maturity level and usability	
Visualisation quality	Resolution of the VE visualization was not sufficient for detail design or analysis. In that respect, CAD and a regular computer monitor or screen was considered better. Nevertheless, the virtual environment benefits the improved perspective and sense of depth
Measure tools	Features for measuring or estimating dimensions in VE were requested. Specifically some kind of human model was demanded in order to demonstrate human-machine interactions for members of the design review board.
Data pipeline	The time taken for data conversion and constructing the virtual environments was estimated to be 1–2 working days. This process included simplification of the native CAD 3D-model, transformation to JT-model (light 3D), import to VIRTOOLS VR-software, and programming the scene and functionalities of virtual environment and virtual prototype
Interaction	Haptics was found to be useful in principle, but in the typical work task forces are too big to be simulated with cost-efficient equipment. Data gloves were found to be useful in interacting with the virtual prototype, especially in dismantling and assembling a machine in a virtual environment. Tasks which need careful actions could in particular benefit from using data gloves and haptics.
Methodology and utilization	
Human participation	In principle, the virtual environment was found to be a promising system for design review, especially in cases where human participation is essential.
Application areas	Apart from design review meetings, the virtual environments' potential in training and marketing applications was discussed.

Activity modelling	Activity and work task modelling was seen to be important for efficient and effective use of virtual environments
Knowledge sharing	The maintenance work tasks are mainly familiar to the maintenance workers even in a new construction. Therefore, the VE does not add so much value compared to a totally new setting. On the other hand, the familiarity enables reliable maintainability of the new structure [project manager]
Engineering design	VP and VE could be very useful in the product layout/architecture design phase, where module interfaces and assembly fitting could be studied without physical structures. Fitting the parts and assemblies together already in the design and engineering phase would be useful. Nevertheless, physics simulation (collisions, inertia, etc.) should be included at some level. [design engineer]
Productisation	The biggest advantages of a virtual prototype would be in the design phase where no physical prototype exists yet. [development engineer]
Development targets and new ideas	
Physics simulation	In many maintenance work tasks, physics (dynamics) simulations would be important. For instance, lifting large and heavy parts is not realistic without the dynamic phenomenon of a burden. Recognizing and solving potential problem in a virtual environment: e.g. jammed parts in a disassembling task.
Ergonomics and safety	Human reachability, visibility, ergonomics analyses in new product internal productisation. The reachability and visibility could be assessed by the user in VE.
New work tasks	Analysis of difficult and/or dangerous maintenance work tasks Verification of totally new maintenance tasks of a new design construction
Training	Training infrequent maintenance work tasks

Conclusions on feedback

In can be concluded that, from a technological viewpoint, virtual environments add value by an improved sense of depth and perspective and interaction with the virtual product model. From a process and methodology viewpoint, virtual environments add value by enabling better human participation to design reviews and the possibility to model and simulate operations and actions within the product model, which also enables better ergonomics and safety expert analyses. Virtual prototyping was estimated to enable earlier design verification and feedback from the product lifecycle, and the possibility to evaluate product properties already at the product concept phase. It was also envisaged that virtual prototypes would be useful in product marketing and the training of product-related work tasks.

The inadequacy of VE-based virtual prototyping was mainly related to a lack of physics simulation and realistic force feedback for users. It was estimated that they would add a great deal of value compared to common CAD. However, it would require heavy real-time physics simulation and haptics devices that were not available in the research. It was also reasoned that some ergonomics and safety analyses can be carried out by an expert, but many analyses or evaluations, like visibility, reachability, and postural load would require a digital human

model with appropriate analytical tools. Efficient utilization of virtual prototyping within product design and development would require improved data pipeline between CAD and VE, and a product structure that supports virtual prototyping in order to avoid time-consuming and costly manual conversions. On the other hand, this was the situation during VIRVO project, and today (2015) for instance visualization quality is much better thanks to common software and hardware development on the market.

Conclusions of the Virvo project

In the VIRVO project, Metso MAC wanted to ascertain the level of virtual prototyping and virtual environments technology and methodology, and the suitability for specific applications in rock crushing product design and development. The VIRVO project was part of a reliability technology development programme at Metso MAC. The company was seeking a suitable combination of reliability design methods (FMEA, FTA, RCM), 3D-models and techniques, "virtual engineering" technology, product knowledge management, and product lifecycle management. Virtual environments were also considered as a means for sales and marketing functions.

Firstly (2006–2007), in the VIRVO project functionality of virtual prototyping and virtual environments technology was investigated: Data and information transfer between 3D systems and tools, models conversions and simplifications, simulations performance. Possible applications in product design and development were thought through as well. In 2008, the actual case/pilot study connected with the company's new product development project was started. The pilot object was a new generation cone crusher, and the main goal was to develop a methodology that combines virtual prototyping based design reviews, maintainability analyses, reliability analyses (FMEA, FMECA, FTA). Additional sub-goals were contributing to spare part structure design and drawings, producing instructions and manuals, and use in sales and marketing.

According to the case company the main conclusion of the pilot study was that (Heikkilä, 2009):

- With the existing and developed tools and methods, an adequate level virtual prototype of a new generation product (or module) could be modelled from a concept ideal to virtual prototype in approximately one calendar week. Compared to preparing manufacturing documents and manufacturing and assembling the physical prototype, this is much faster.
- In the conceptual design phase, a virtual prototype in virtual environment is comparable with design sketches, but it is much more demonstrative.
- The efficiency of production of virtual prototype models and virtual environment simulations is an essential factor. A remarkable thing is that models produced by industrial designers should be easily portable to virtual environments. This could be managed in few hours in the pilot study.
- In the pilot study, an agile enough process for exploiting virtual environments was created. Thus, it was considered that virtual prototyping and virtual environments could be used effectively in a new product design and

development project. Nevertheless, it was understood that, in large scale usage, the product data management and integration to design processes and projects should first be developed.

- The positive result of pilot studies and VIRVO project led to follow-up studies in a EU-project called ManuVAR.

In this project, Metso MAC's case study was focused on certain critical maintenance tasks of a new crusher model. However, because of the novelty of VR technologies, it was not possible to derive clear benefit from using the new tools, as the product development project had to keep to the schedule. For Metso MAC, the most important outcome of the VIRVO project was the understanding of how VR can support different product development-related reviews, and how 3D-model information can be used in various systems efficiently. (Heikkilä et al., 2011)

New generation engine module productisation

Goal of the ManuVAR project at Metso MAC. Due to heavy competition within crushing equipment industry, the manufacturing strategy was getting extremely important for the companies. As the real challenge was seen the combination: how to design products so that they can be manufactured in multiple factories, that they are suitable for mass-customization and are easy to assemble and maintain manually, because design for assembly and design for maintenance requirements easily conflict. The ergonomics of manual manufacture and maintenance should be optimized as well, because ergonomic and safe work is normally also more productive. Product lifecycle management (PLM), and virtual reality were seen as potential solutions for combining conflicting requirements and optimizing the wholeness. The overall target of Metso MAC in the ManuVAR project was to improve time to market and reduce the number of engineering changes. This target was approached by the following factors (Leino et al., 2010):

- Improved collaboration between product development and manufacturing
- Improved HF/E requirement management and design for manual assembly and maintenance
- Improved product features for manual assembly and maintenance tasks
- Cost-efficient design verification and documentation
- Effective use of virtual techniques in new product development

In the ManuVAR project, seven general categories of gaps were recognized between the present state and desired future state concerning manual work support during a product life based on the literature review and participating company interviews. Table 7 lists how the seven gaps were manifested at Metso MAC (Leino et al., 2010).

Table 7. ManuVAR Gaps in Metso

ManuVAR Gaps	Gaps at Metso MAC
1. Problems with communication throughout lifecycle	• Lack of feedback from production and maintenance to product design and development • No systematic approach for requirements management, especially related to human factors
2. Poor user interfaces	• Work instructions in production and maintenance are not up to date, no connection to PDM • Poor presentation of product data for different stakeholders of a product life
3. Lack of technology acceptance	• Instructions are in English • VR is considered as high tech, slow and expensive
4. Inefficient knowledge management	• Feedback from product life stages is not gathered and managed systematically • Data management IT-systems do not communicate
5. Physical and cognitive stresses	• Postural loads, poor visibility, safety risks, and heaviness of manual assembly and maintenance work • Workers have to design their work equipment and tools • Mental workload due to complexity of work tasks
6. Inflexible design process	• Engineering design changes are difficult because a lot of people are involved in the product development process • Design errors are not identified in the design phase, but they cause difficulties at the production and product life stages
7. Low productivity	• Mechanical engineering is mostly in 3D-CAD, but the 3D data is not used efficiently enough • Lot of unproductive work, for instance walking around the factory searching for assembly components

From the gaps in Table 7 it can be concluded that research and development should be focused on providing user-friendly and effective tools and methods for improved communication between stakeholders of the product lifecycle, management of product related data, information and knowledge in order to improve human factors and productivity of product processes of the case company.

Pre-study in the ManuVAR project

In the pre-study of the ManuVAR project, the focus was on testing the present technical maturity and functionality of virtual environment applications, introducing them to the new participants of the project, and acquiring feedback about usability and benefits in order to plan and focus research and development on virtual prototyping in the project. The implementation and development of virtual prototyping in the ManuVAR project was connected with a new product development project and production ramp-up at Metso MAC. The pre-study was carried out at a product design review meeting which was aimed at verifying a new generation engine module for serial production and new production line. (Leino et al., 2010)

The first engine module design review meeting. The design review was the first organized meeting for the internal introduction of the new engine module concerning its manufacturability and maintainability. The purpose of the review

meeting was to demonstrate a new product module for different stakeholders (assembly workers, design engineers, product development engineers, maintenance workers and engineers, production planners, and product management) before building a physical prototype. This ensured comprehensive feedback from all the stakeholders involved in the new engine module development project. Additionally, one goal was to analyse ergonomics and safety from assembly and maintenance workers' point of view. The meeting was arranged at the VTT's Virtual Reality laboratory premises in Tampere. The goal was to introduce virtual environments and augmented reality technologies to people from Metso MAC and to use virtual environments technologies in order to review earlier mentioned product aspects.
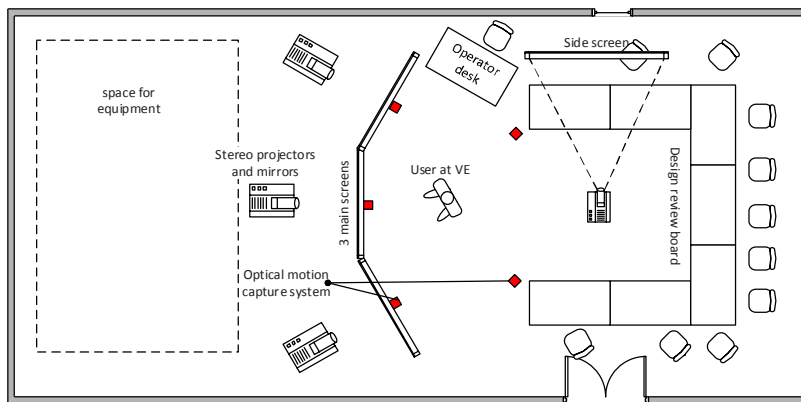
Figure 33. A Schematic laboratory setup at VTT. The user is performing for instance an assembly or maintenance work task in the centre of the room. The design review board is observing the task and discussing about the design on the right side of the room. Typically they can see the VE scene on the three main screens, and simultaneously the possible view of the user's head mounted display on the side screen.
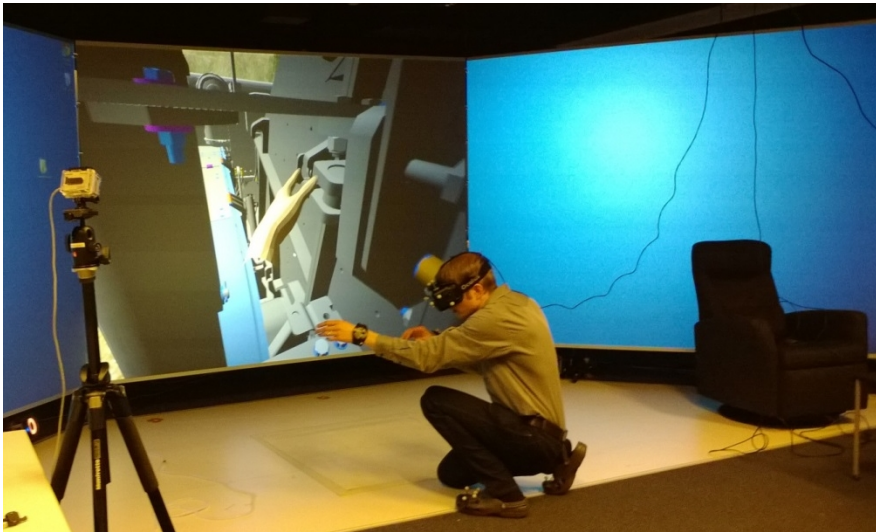
Figure 34. An example of analysing manual work task in an immersive virtual environment at VTT laboratory.

Virtual environments configurations used. The aim of the technical virtual reality system configuration was to provide a setting for virtual environments-based design review meeting (Figure 33) a schematic illustration of the virtual product design review. Basically, the review was carried out by showing a 3D-model of the engine module to the review board on a big screen and rotating it around while people identified and discussed possible problems. One actor (mainly an assembly or maintenance worker) was being tracked by a motion tracking system (Figure 34). The motion tracking system was sending the coordinates of the actor to the virtual environments simulation software (Virtools), so that the actor was able to see the product model from different angles by walking around it and tilting their head. The virtual environment was reflected to the worker through the head-mounted display (HMD). The HMD was utilized for the worker to perceive the product model on a real world scale, where the worker can interact and perceive the design as he would with the physical prototype. All participants in the review meeting were provided with an overview introduction to the system on the power-wall screen so as to understand the specific context in which the worker is communicating. The review board was able to see the assembly from a fixed position but also from the worker's point of view. Thus, the worker's point of view from the HMD was projected on one of the side screens so that all participants could see the specific part that the worker was looking at or manipulating in the given task or operation of the workflow currently investigated. To make things more realistic, it was also possible to import other virtual objects (for example, tools and flashlights, see Figure 35, to the system. The virtual reality system that

was used in review meetings consisted of several subsystems (source: ManuVAR project Deliverable9 Demonstration Report, 2012):

- Main visualization system with active stereographic rendering in three screens powerwall setup, and a side screen for HMD and other relevant data projection;
- Secondary visualization system with HMD;
- Marker-based optical motion capture system in order to capture worker's point of view for HMD visualization;
- User interface (UI) system that is a combination of the gesture control, gaming controllers and basic keyboard/mouse interaction depending on the person interacting, and the haptic device.
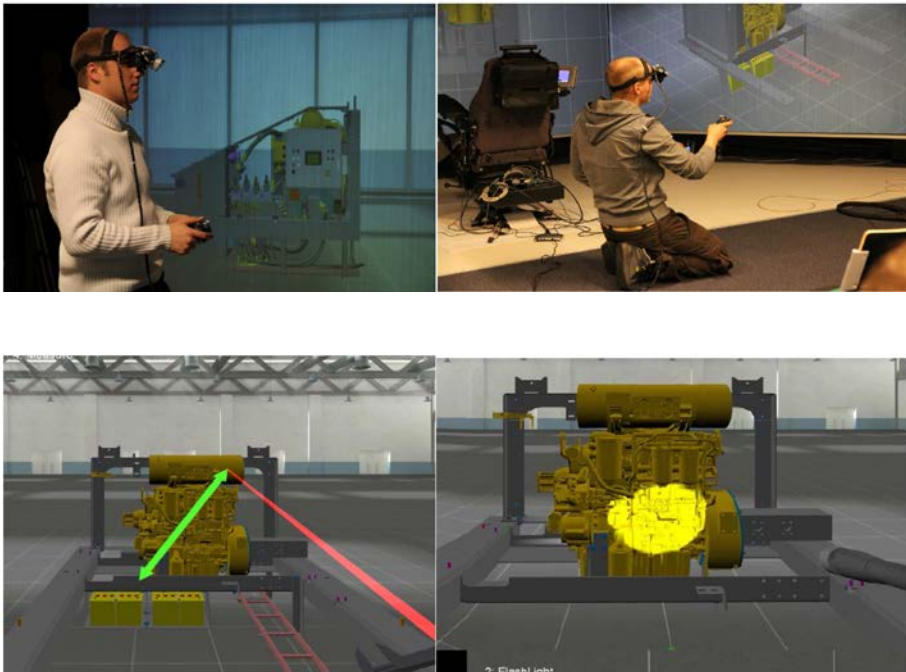
Figure 35. Features of virtual environments that add value compared to conventional 3D.

Interview and questionnaire, published in Leino et al. (2010). Over the following days, all the participants were individually interviewed based on the questionnaire. The questionnaire included questions about their experiences concerning the virtual review and their thoughts of when, where and how this kind of review event should be organized. To be more specific, the participants were asked about the state of the immersion experienced, interaction opportunities and handling of the

virtual prototype model. In addition, they were asked to say at what time of the product lifecycle they would see fit to arrange virtual reviews, who should participate in these events, and which matters should be reviewed. Finally, participants were also asked to define the prerequisites that need to be met before reviews of this nature can be permanently implemented into processes at Metso MAC.

Conclusion from the prestudy of the ManuVAR project

Most of the feedback gathered from the interviews concerning the pre-study design review was rather positive. Many of the participants saw the potential of the virtual environments technologies and generated their own visions of exploiting the technology in future. The following things (Table 8) were said to be particularly beneficial when using virtual environments in product design review and product development (Leino et al., 2010):

Table 8. Benefits of virtual environments (VE) in product design reviews and product development.

Statement	Reasoning
Increased interaction with the 3D product model	The basic properties (presence, interaction, autonomy) of VE contribute to increased immersion and interaction with the 3D model.
	Immersion, correct perspective and stereo visualization, haptics and audio improve the feeling of presence and perceiving the 3D model in a correct way.
	Ability to move parts and travel around the virtual prototype improve the interaction with the 3D model.
	Autonomy refers to VE capability of react to events at the session.
Improved collaboration between company departments and stakeholders of the product lifecycle	VE-based product design reviews gathered people together from different departments to assess the product design and discuss possible problems and development ideas. This was not a common course of action with physical prototypes.
	It is easier to arrange such sessions at a laboratory around virtual prototypes than on the factory floor.
Improved ability to asses ergonomics and safety of manual work tasks	VE provides for possibility to simulate manual work tasks and functionalities of the virtual prototype.
	For ergonomics and safety experts, it is easier to perceive and understand how work tasks are performed and what the risks are.
Utilizing the collected data in the generation of engineering change requests and work instruction	The design review sessions can be recorded as pictures, videos and notifications to 3D-models, which can be used as references in engineering change requests or in the generation of assembly or maintenance work task instructions and manuals.

Increased productivity in terms of reducing the number of design failures and assembly time	VE-based virtual prototyping enables catching many of the design flaws before manufacturing specifications are generated, physical parts are ordered and manufactured and physical prototype assembly started.
	Needless re-design and re-manufacture and assembly can be avoided, and more optimal manual assembly and maintenance work tasks can be achieved earlier.

From the benefits of virtual environments in Table 8, to the advantages of VR technology can be classified that can be linked to benefits for communication and collaboration, improved human factors, knowledge management and productivity of product development. These aspects will be discussed more with respect to scientific theories later in section 7. Almost all the people interviewed assessed the increased interaction with the product model as highly appreciated. It would enable, for instance, worker to test the actual assembly work procedure and find possible problems at an early stage of product development. Normally, this type of task can only be done with a physical prototype, which would then be re-designed and manufactured. With virtual prototyping, this re-manufacture step could easily be removed, or at least be made less iterative, which in addition leads to improved flexibility in the design and development process. From the engineering design viewpoint, designers would easily see what needs to be improved. By achieving this, the rate of feedback from production to design would most likely increase, leading to improved quality. The process would be streamlined even more if the product model could be modified immediately in the virtual environment. However, this was not possible with the VR-technology that was used in the case studies.

Based on the pre-study, it was safe to say that virtual prototyping was welcomed at Metso MAC, but it needed to become a little more mature. In order to become adopted at full-scale, the technology should be reasonably priced, located on Metso MAC's premises, and most of all be easy to operate and maintain.

Design review meetings in the new product development project

Design review meetings are important milestones within a product development process. They ensure that the design is evaluated against various sets of criteria, e.g. requirements, consistency and usability, during several stages of the design process. Therefore, review meetings are efficient tools for sharing information about the product and for managing knowledge exchange (Huet et al., 2007).

In the larger sub-case study of the ManuVAR project, design review meetings were organized in order to evaluate a product design and to gather experience and feedback about the benefits and/or drawbacks of using virtual environments in the review meetings. The feedback was collected by observing, interviewing the participants and sending them questionnaires. The questions were related to the review meetings as a user experience, how the new virtual environments-based review process felt compared to old practices, whether it affected information

transfer and whether the maturity level of VEs and VR technology used was enough for efficient observing and perception of the critical and important events that happened during task execution. Also, technical features of VE were evaluated based on their functionality and importance. There were also differently structured questionnaires with the same content used. The results from these questionnaires were analysed and compiled. (Aromaa et al., 2012)

The second engine module design review meeting, published in Aromaa et al. (2012). The purpose of the second major review meeting was to show a new revision of the forthcoming engine module to the productisation and production experts. The purpose was to evaluate the assembly, maintenance, safety and structural problems of the product, and also to discuss possible solutions. The review board consisted of an assembly worker, design engineers (mechanical, hydraulics, and electrics), a manufacturing manager, assembly foremen and product development engineers – all from Metso MAC. Also present were a virtual reality system expert and human factors experts from VTT, and the review meeting chairman. The assembly worker was using a head-mounted display to observe the step-by-step assembly procedure, while the review board was discussing, Figure 36, possible issues and putting forward various arguments concerning possible alternative solutions to the problems just identified and evaluated. (Aromaa et al., 2012)

Figure 36. A design review meeting at virtual reality laboratory.

Changes to the engine module structure and assembly task and sequence were made after these meetings. The module structure was modified due to a safety-related issue. A faulty 3D model was also repaired based of the feedback of the review board. The changes were implemented to the product structure and assembly sequence of the next product prototype. In Figure 37 is an example of a manual assembly work task at Metso MAC factory.

Figure 37. Engine assembly work task at Metso MAC (Source: Metso MAC).

Results of the interviews

Feedback collected from the interviews about the virtual design review meetings was generally positive (Aromaa et al., 2012). Results (Table 9) show that the participants felt the review meetings were interesting and a useful experience. The comments were related to the quality of the virtual reality system, communication between people, and the product model itself. The results of the interview were categorized summarized by technology level and usability, virtual prototyping methodology and utilization, and recognized design and business benefits.

Table 9. Assesment of benefits and development targets of virtual prototyping

Technology maturity level and usability		
	Benefits	Development targets
Visualisation	Visualisation is illustrative compared to common CAD Level of detail is sufficient for design review It is easier to understand product dimensions	Quality of visualisation, e.g. stability of HMD should be better, Zooming feature was requested, Possibility of hide/unhiding parts was requested, Simulation of the surrounding environment could improve the immersion, Possibility to see the person's own body was demanded
Interaction with VE	User interface (controls) was sufficient Implementation of VE was good	Possibility to modify product models (e.g. structure) was requested, Haptics (gravity, feel of touch and

	enough for design review It is easier to understand product functionality	grasp) was demanded,
Methodology and utilisation of VP		
Communication	Enables better communication and discussions on a specific product detail, Information and knowledge share between stakeholders, e.g. design engineers and production	Possibility to record design review meetings was demanded
Collaboration	Increased collaboration between product stakeholders	
Product development and business perspective		
Design review		The virtual review meeting process should be more systematic Good preparation in advance would make the review meeting more efficient
Engineering changes	Possible to test and modify the design before prototype manufacturing, Alternative assembly orders can be defined, Fewer corrections needed during the product life-cycle because errors could be removed at the beginning of the process	
Time and cost	Reduces the need for expensive prototypes, Possibility to create documentation early, More efficient assembly and maintenance process, Possibility to remove bottlenecks from standard production, Improved management of supply chain	
Quality	Better customer acceptance based on participatory approach	

Haptics and the digital human model were demanded in order to enable a more realistic performance in the virtual environment and more reliable ergonomics analyses. However, this technology was not available in the design review meetings. From the virtual prototyping methodology viewpoint, it was seen that one major benefit that comes from the use of the review meeting is gathering together people with different knowledge and getting them to communicate their knowledge in a way that all of them can understand. Therefore, the information and knowledge-sharing is a key benefit. The use of VEs enables knowledge-sharing because it establishes an environment, where everyone has the same visual understanding of the current situation. Information was shared between the design engineers and the production engineers, which was positive because the discus-

sions between the departments are usually too challenging due to time limitations. The increased assembly worker-engineer communication was also valued in the results, as many of the improvement remarks for the product were made by the worker. It was reasoned by an expert from Metso MAC product development that business benefits will come in the form of significant savings (cost – need to order fewer parts unnecessarily, and time – less time used for building physical prototypes). The benefits will also arise from savings in time and money achieved later on in the lifecycle. These findings will be further discussed and reflected with scientific theories later in this thesis. Quotes from the interviews:

"VR-goggle view was good because it got people more involved than a "normal" computer screen"

"The ability to see things through someone else's eyes was a good thing"

"The same understanding that comes from the 3D environment cannot be achieved from the 2D pictures on a projector: because only in the VEs is it possible to walk around the real-size 3D model"

"Visualisation was good and everyone in the group was able to see what was happening (especially what the assembly worker saw)"

"With these tools, it is easier to find assembly problems and decide the assembly order in an early phase"

"The use of these tools makes review meetings, task planning and ergonomic analysis more systematic"

"The design review process and concept worked well"

"Has potential but not quite there yet"

Conclusion on the engine module productisation

The virtual environments based virtual prototyping was considered very useful in the case company, but the right application areas must be recognized and processes developed (Vehviläinen, 2014). Virtual reality technology provides for improved involvement or immersion with the virtual environment and the product model. On the other hand, the technology maturity was not yet as good as it should be. However it was conceded as having advantages compared to normal 3D tools. It is also a matter of how much resource can be invested in building the virtual environment.

From the methodology perspective, the improved communication between people, and collaboration between organisational roles, functions and departments were assessed as being very beneficial. The production and maintenance workers involved appreciated the opportunity to influence their own work tasks as well as the safety and comfort of their work. Design engineers and managers appreciated their opportunity to better experience how the manual work on the factory floor is really carried out. The opportunity to get early feedback and identification of possible problems and bottlenecks from production and maintenance was seen as particularly beneficial. From a business viewpoint, it was estimated that virtual

prototyping could contribute to efficiency and effectivity in the form of cost and time savings.

Productisation in the ProMagNet project

The ProMagNet project as part of the Fimecc Manu programme started in 2013, and it will continue until year 2017. The business goals of Metso MAC in the Pro-MagNet project were set as:

- Shorter time-to-market and time-to-profit in new product development projects
- Better internal and external quality of products and processes
- Reduced cost and re-work in NPD projects
- Improved decision support of NPD projects
- Improved product life-cycle knowledge management and utilisation in product development
- Better change management including all processes and actors within the product life-cycle

The ProMagNet project was focused on new product development projects. However, the approach is different from the Virvo and ManuVAR projects. Those two earlier projects were more focused on introduction of VP for the case company, and assessment of the utility in product design and development. The approach of the ProMagNet project is more based on the real demands of improving product development and production, and the overall productivity of manufacturing by the means of digitalisation. Virtual prototyping is seen as one means for increasing the productivity. Based on the experience from the previous projects VP is considered as a potential methodology, but it requires development of processes and infrastructure first. However, one objective is to produce evidence of possible benefits of VP in this context.

The main research methods in the ProMagNet project have been workshop sessions and discussions on the NPD processes, benefits and demands of VP, and potential affects to cost and time-to-profit. There have been over twenty workshop sessions by the end of year 2014 with the representatives of the case company. The demands of VP mean for instance required changes to the design and engineering change processes, and required structures of product models, i.e. virtual prototypes. There was also one VP based design review meeting of a new engine module productization, see Figure 38.

Figure 38. Design review meeting of a engine module in a new product development project.

There were participants from product design, productisation and production departments. All participants from assembly workers to engineering designers assessed that virtual environments are significantly more demonstrative than CAD, because the perspective and dimensions can be better understood. However, it was stated that approximately one hour time is maximum in the immersive mode. After that people became unwell. Generally speaking, even though VP was assessed useful in design review, better usability of the system was desired. For instance, better interaction devices and controls were demanded. Other development targets included better product data management. It would be necessary to present some metadata, like correct item codes, in the product model. The possibility to put feedback notifications and change requests directly through the virtual prototype to the EDM/PLM system is another required function. Generally speaking, the most significant potential of using VP effectively in product design and development was related to improved possibility to involve more product life-cycle stakeholders and to enable better discussions between them. It was reasoned, that besides engineering design, productization and production departments, it would be important to also involve for instance product managers, service, procurement departments into virtual design reviews. They can discuss the design from many perspectives and therefore a partial optimisation can be avoided.

It has been reasoned that VP enables introduction of new products or modules to standard production with better design maturity level which decreases the need of engineering changes of the physical products. For instance the assembly structure and work sequence can be verified with the virtual prototype. VP enables generation of engineering change request earlier without the need of manufacture of physical parts. Generally speaking, VP provides for involvement of product life-cycle stakeholders to the design process in the early phase when no physical prototypes are available. The major preconditions for effective use of VP require changes to the way of how design and product model maturity evolves, and how the product models are managed as part of EDM/PLM. It has been reasoned that

besides these more technical aspects, also changes to the organisation and culture are required. These findings will be discussed more in the section number 7.

5.5   Concept design

A product concept is a concise description of how the product will satisfy customer needs, including an approximate description of the technology, working principles, and form of the product (Ulrich & Eppinger, 2004). The product concepts in the case study were related to product upgrade modules that were targeted to satisfy customer needs related to safety and environmental issues.

Mobile rock crusher noise reduction module

In early 2011, Metso MAC started a new product development project which aimed to find improved solutions for reducing noise and dust-related problems that are typical for crushing and screening processes (published in Heikkilä et al., 2011). Apart from a health and safety issue, noise and dust is a serious economic issue for Metso MAC's customers because noise and dust problems could hamper getting permissions from the authorities for crushing operations. Typically, this mean reduced working times and other limitations. The concept development project was looking for solutions to this demand that are accepted by the customers. The main challenge for this customer validation was to make sure that the customer is able to understand the concept correctly and easily give feedback about the details needed. (Heikkilä et al., 2011)

Figure 39. Virtual prototyping was utilized in a rock crusher noise reduction concept development. On the left is a digital model of the concept, and on the right side is the physical prototype in the field test. The assembly and functionality of the noise reduction module was assessed with virtual prototyping. (Source: Metso MAC.)

Figure 39 shows the first physical prototype of the noise reduction concept and a 3D model made by an industrial designer. Apart from the effective noise- or dust-reduction function, the major customer requirements were related to easiness and

safety in the installation and dismantling of the module, as well as maintenance work tasks (Heikkilä et al., 2011). The assembly and maintenance properties of the noise reduction concept were studied earlier with virtual prototypes.

In addition, Metso MAC needed, for instance, to define how to create modular product upgrade solutions so that the same parts can be reused with as many product models as possible. The purpose of verification and validation tasks was to make sure that both the technical requirements of the solution and the customer expectations were met. In the conceptual design phase, the customer validation was used for selecting the best solution alternatives for further development. The feedback from customers was very useful for this development, and could even result in totally new solution alternatives. Virtual reality technology enabled improved visual experience for the reviewers (customers) which supported communication between R&D and customers. VR models should support the validation of the most critical customer requirements, mainly assembly and disassembly tasks, routine maintenance tasks (accessibility) and the clearing of process problems. (Heikkilä et al., 2011)

A virtual concept review meeting was arranged for potential customers in order to get feedback and ideas about the concept. The purpose of the review meeting was to present a new upgrade concept which was an additional module to the existing crusher product. Specific topics were the assembly, dismantling and maintenance properties of the module concept. There had been product design review meetings beforehand to iteratively improve the concept before this particular meeting, which was organised for the customers. The review group consisted of one Metso MAC representative (design engineer), three human factors and virtual reality experts form VTT, and customer representatives from six different companies. One VR expert or customer was performing in a virtual environment in order to assemble the new module and to present the idea of the concept to the customers. The customers were able to make comments and suggest improvements.

Questionnaires were sent afterwards to the Metso MAC's customers in order to get their opinions and feedback about the possible utility and benefits of virtual prototyping. The results of this study were published in (Aromaa et al., 2012). In general, the virtual concept review was assessed as an interesting experience. It was said that the virtual environment experience was much more realistic and demonstrative than normal computer screens or 2D pictures. The following statements were collected from the questionnaire:

Benefits:
"Demonstrative, easier to understand dimensions and functionality (especially if you are not familiar with such machines) compared to drawings or CAD models"
"Opportunity to test and modify design before manufacture"
"Reduces the need for expensive physical prototypes"
"Significantly increases collaboration between customers and manufacturing company (and other stakeholders)"

"Enables better communication and discussions on a specific detail with colleagues and designers"

"Enables involvement of workers in the design process"

"Social dimension, meeting colleagues"

"User interface (controls) was sufficient. Needs learning first"

Drawbacks or development targets:

"Level of graphics/visualization and audio"

"3D model level of details (Lokotrack model was simplified purposely, level of details of the noise cover was good)"

"Capturing feedback within and through the VR-model was required"

"Opportunity to modify VR model on-line"

From the results of the questionnaire it can be concluded that virtual environments enable communicating and presenting new product concepts to customers and stakeholders who are not very familiar with engineering design, drawings and 3D models. This capability contributes to increased communication and collaboration between designers, customers and other relevant product stakeholders. Furthermore, it enables product operators and production and maintenance workers to participate in the product design and development process. It was also remarkable that the participants in the product concept review considered the social dimension beneficial. On the negative side of the comments, the level of visualisation and opportunity to modify the product model on-line were mentioned again.

Mobile rock crusher maintenance concept

The second minor concept design sub-case was related to developing safety equipment for a crusher maintenance work task. The maintenance task is frequently occurring wear part change, where the maintenance worker needs to go inside the rock crusher, Figure 40. The new concept would significantly increase both safety/comfort and performance of the work task.
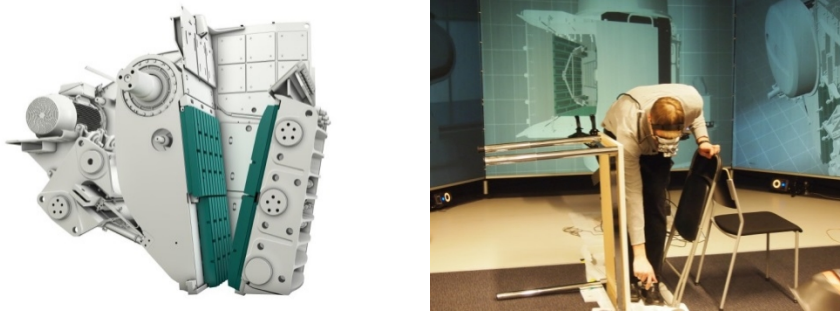
Figure 40. Testing a jaw crusher maintenance concept with a virtual prototype. On the left is the jaw crusher, and on the right side a maintenance task is analysed in virtual environment. The virtual environment is supplemented with physical boundaries in order to get more realistic understanding about the space limitation related to the maintenance task.

In this concept design phase, the main focus was on evaluation of human performance and safety with the new concept. This phase was done internally with Metso MAC's service personnel and engineering designers. The purpose was to validate the concept from a human work task viewpoint before beginning the embodiment design phase.

As a result of this minor case, it was reasoned that the virtual environment provides for better perception and understanding of the product concept and the opportunity to study restrictions and boundaries for the work task. It was also realized that this kind of work task analysis also requires physical items that provide realistic boundaries for the person in the virtual environment, Figure 40.

6. CONSTRUCTION OF THE EXTENDED VALUE FRAMEWORK

This section describes first how the empirical case study findings were analysed, categorised and reflected with the Phenomena model that was introduced in the section number 4. The analysis will show that besides advantages directly connected to technology features, virtual environments as a means of virtual prototyping seem to have benefits that have to be modelled in the context of design and even more widely in the context of organisation and other processes. This section clarifies how the value of virtual prototyping is derived beyond technological advantages of virtual environments, such as immersion, presence, interface, and features of virtual models. As a conclusion, the four dimensions of value of virtual prototyping will be established in the end of this section. Furthermore, the main theories in those four dimensions, as well as links between key concepts of the theories are introduced.

Figure 41 is a view of an assembly worker in a virtual environment where he/she is conducting a manual assembly task. The assembly worker is able to see a realistic dimension and perspective of the product assembly. He/she sees the ring spanner tool as well, but in this case the worker's own body is not visualized in the virtual environment.
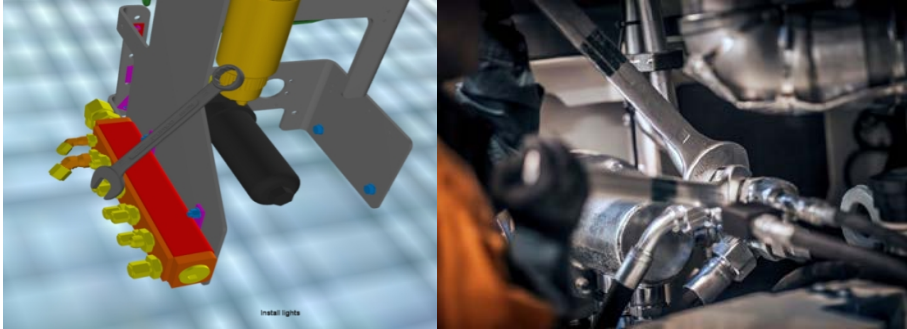
Figure 41. How an assembly worker sees the working scene in virtual environment (left side picture from a design review meeting). The right hand picture is from the assembly line of Metso MAC.

In the literature and theory section, the major advantage of virtual environments were argued to provide the most natural means of communicating with a computer that utilizes humans' 3D spatial processing capability. It was also stated that this claim is hard to prove because of a lack of objective measure (Kalawsky, 1993), (Gruchalla, 2004), (Söderman, 2005), (Bowman et al., 2007). In the empirical case studies of this research virtual prototyping and virtual environments were tested and developed. The benefits of virtual prototyping and the virtual environment were studied using interviews, questionnaires and observations. The benefits were assessed compared to conventional 2D-drawings and 3D CAD tools as well as to physical prototyping. In this section, these results will be categorized (Table 10) and reflected using the hypothetical "Phenomena Model", see Figure 24.

Table 10. Advantages of virtual environments capabilities in case study results categorized based three main components of VE

Capability of Virtual Environments	Advantages of technology	Benefits beyond
Sensory modalities	User experience, perception, immersion	
• Stereo-graphics	• More realistic and illustrative • 1:1 scale and dimensions (size) of geometry, sense of depth, perspective, and illumination • Augmentation of cues of reality phenomena; e.g. temperature • Augmentation of invisible	• Shared model • VE provides a more natural and realistic experience of a 3D model • Better understanding of system properties

	phenomena of reality e.g. visualization of fluid flows inside pipes	
Means of modifying states of models	**User interfaces, interactivity**	
• Motion capture • Data gloves • Control devices, e.g. zooming	• Ability for user to control models by him/herself; e.g. grasping parts and free movements • Ability to walk around an product model • Natural point-of-view	• Improves collaboration • Knowledge sharing between participants • Ensure that knowledge is really communicated and understood • Interactive product design review • Improves participative approach • Enables equal status (e.g. workers and engineers), for instance in product model manipulation • Talk-listen approach is avoided (typical in PowerPoint presentations) • Easier user interface of the product model
Features of objects, models, and processes (autonomy)	**Presentation of product characteristics and properties within the product life**	
• Position and orientation • Visual characteristics • Physics-based realistic behaviour, e.g. motion, kinematics, forces	• Part geometry, product structure • Realistic function of the model • Tolerances	• Combined product model, activity, context and environment • Modification of product structures within design review meetings • Ergonomics analyses, e.g. reachability, visibility, posture • Workers can do their job naturally • Designers can do the assembly work and better understand the challenges

In Table 10, the results of case studies are categorized based on the three main components of virtual environments (Kalawsky, 1993): 1) Sensory modalities, 2) Means for modifying states of models, 3) Features of objects/models or processes. Features of objects, models and processes provide for advantages of sensory modalities and means of modifying the states of models. In other words, features that can be perceived and modified with sensory modalities and the means for modifying models are programmed into the virtual models. Nevertheless, the features are not obvious to users of virtual environments, because users perceive virtuality through user interfaces and sensory modalities possibly on a different abstraction level. However, from product design and the development point of view, features of objects, models and processes are essential, because they enable simulation and investigation of the behaviour and properties of technical systems and product lifecycle aspects. This distinction between features of objects/models or processes and ways of observing them can be explained with the categorization of design properties, internal properties, and external properties (Hubka & Eder, 1988) and characteristics versus properties (Weber et al., 2003). Also, the behaviour of a product can be a purposeful function or an unintended behaviour that may even cause harm (Hubka & Eder, 1988).
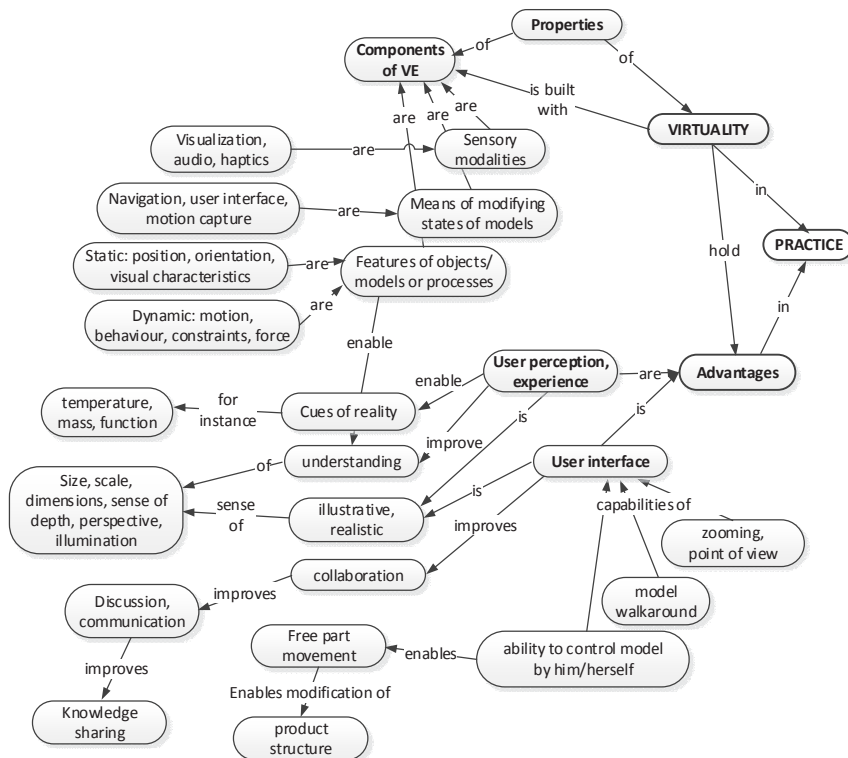
Figure 42. Concept map of observed advantages of virtual environments in practice within case studies. This model expands the hypothetical "Phenomena model" by recognizing links between theory, and empirical results that can be derived directly from virtual reality technology, and properties of the components of virtual environments.

The concept map in Figure 42 illustrates some of the observed advantages of virtual environments in results of the case studies. The upper part of the concept map is split from the Phenomena model (Figure 24), and it remains the main theoretical component (Kalawsky, 1993) of virtual environments. This map builds links from theory concepts to the results of the case study. It can be seen that the components of virtuality (sensory modalities, means of modifying states of models, features of objects/models or processes) have some 'direct advantages' that are directly connected to the technical capabilities of virtual reality and properties of the components of virtual environments compared to conventional CAD tools. The figure should be read so that, for instance, starting from "user perception, experience" there are advantages of virtuality in practice, because they improve understanding of size, scale, dimensions, sense of depth, perspective, and illumination of a virtual model. The direct advantages include:

- Better user perception and experience in the form of improved realism and illustration, which benefits from the sensory modalities of VE (visualization, audio, haptics). The experience is manifested by improved the understanding of dimensions, size and scale of objects, sense of depth and perspective, illumination, etc.
- Better user interface (UI) to model the socio-technical system, which benefits from a means of modifying states of models in VE (navigation, user interface, motion capture). The better UI include features such as zooming, point of view, model walk around, and ability for the user to control the model by him/herself
- The features of objects/models or processes can be better understood by enhanced user perception and experience as well the advantages of better user interface. This category of advantages is directly connected to understanding the properties of a technical system model, and therefore it also benefits design and virtual prototyping.

Naturally, the level of received direct advantages of virtual environments components depends on the background and experience of the users. For instance, a very experienced senior design engineer may benefit less from improved visual presentation of product model perspective compared to a junior engineer or an ergonomics expert who is not familiar with the observed products or CAD tools. Nevertheless, the designers have said, for instance, that it is often a surprise how big a machine is in reality after modelling and studying it on a 2D computer screen.

However, there seem also to be benefits that are beyond the direct advantages of virtual environments, but which can be derived from those direct features. These benefits are rooted in the methodological, and organisational processes, see Figure 43. For instance, an enhanced user perception and user interface also improve collaboration, which leads to increased discussion and communication. On the other hand, apart from the perception of actual properties of the socio-technical system model, virtual environments also enable so called augmented features. The augmented features are 'cues of reality' which are not totally realistic, but which help users to perceive and understand certain phenomena of the system. These cues may for instance include colour codes representing heat or weight of parts of the VE. This capability is important, because the level of available technology does not allow us to simulate and present all the real physics-based phenomena in the virtual environment.
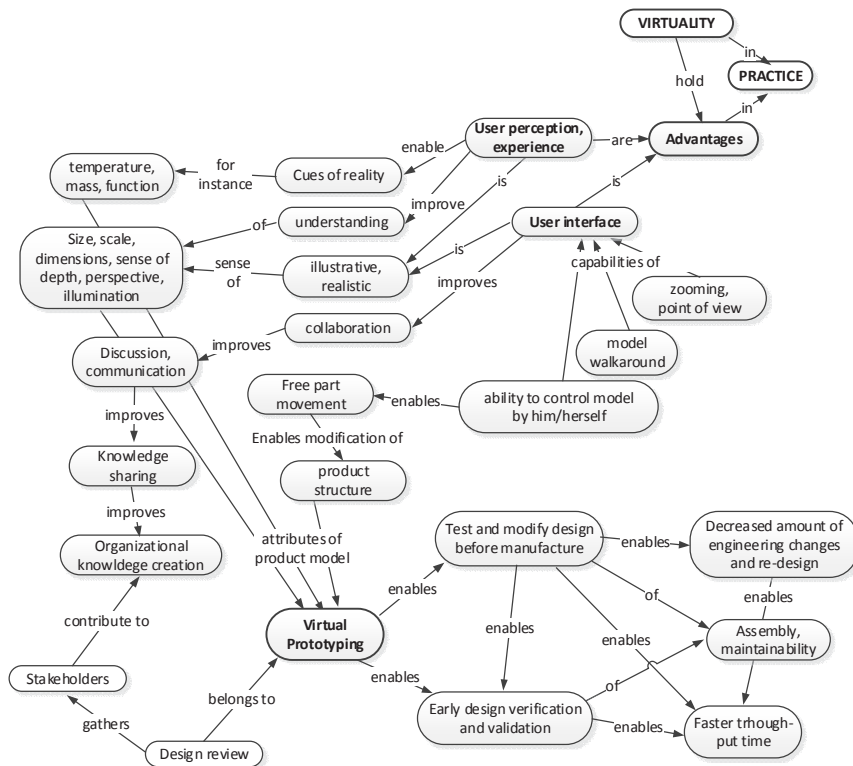
Figure 43. Concept maps of benefits beyond the direct advantages of properties of virtual environment technology components. These benefits are manifested through organisational structures and processes.

The hypothetical 'phenomena model' explained theoretically how the components of a virtual environment bring advantages in the form of the improved interaction and perception of a virtual model. The advantages may lead to better illustration and realism, understanding and collaboration in a shared environment as has been described based on the case study results. Additionally, these advantages also refer to the model of a socio-technical system in the design and virtual prototyping context. The empirical data of case studies also revealed that these advantages may lead to improved processes and organizational structures.

Virtual prototyping as a methodology and process brings together people and stakeholders from different organizational functions and lifecycle stages. This is easier at a design review meeting at the VR laboratory around a virtual prototype, instead of going onto the factory floor. The design can be evaluated and discussed from several lifecycle stages viewpoints by many stakeholders at the same time. VP enables testing and modification of a design before manufacturing the first physical prototypes, and therefore earlier design verification of product design

solutions and validation of the socio-system from the user, customer and other product lifecycle stakeholder viewpoint. Consequently, a reduced number of engineering changes and re-design is needed, which lead to faster through-put time and decreased cost.

The features and advantages of virtual environments technology compared to physical prototypes or CAD enable an improved understanding which helps and even catalyses discussion around possible product- related issues. This may lead to improved information and knowledge sharing. Additionally, workers and designers learn from each other by sharing the same experience. From a design methodology viewpoint, virtual prototyping and virtual environments enable a better use of participatory design approach.

6.1   Categorizing the recognized value elements of VP

During the ManuVAR project, two design review meetings related to the case study were analysed by (Aromaa et al., 2012). The emphasis of the analysis was on the benefits of virtual environments in product design reviews. The analysis of interviews and questionnaires of the design review participants revealed that the benefits of virtual environments in design reviews are related to virtual environments technology (compared to normal CAD), design process, and business aspects (cost savings, time-to-market, decision making). Additionally (Aromaa et al., 2012) attempted to describe the dependencies between benefits and features of virtual environments. Certain features such as immersion, interaction and improved visualization enable achieving benefits in the form of a more natural medium for communication and collaboration. This was recognized as an essential advantage in facilitating the Human Centred Design (HCD) approach in design for a manual work context. This type of classification and categorisation of the benefits from the use of virtual prototyping and virtual environments in design reviews are important for industry especially in the human-machine interaction context (e.g. operations, assembly and maintenance). The categorization aimed to make the benefits more tangible in the theoretical and industrial context. (Aromaa et al., 2012) identified three categories of benefits of virtual environments in design review meetings: 1) VP technology; 2) designing and development, and 3) business benefits. This so-called feature-benefit (F-B Pyramid) was proposed as a preliminary model that aimed to explain empirical data as a logical chain from technological features of virtual environments to design and business benefits. (Aromaa et al., 2012) suggested that the preliminary conceptual model should be developed in order to describe the benefits to the industry in a more tangible way. This research elaborates the F-B Pyramid model by studying the concepts more deeply and concretely, and by expanding the model towards value of VP.
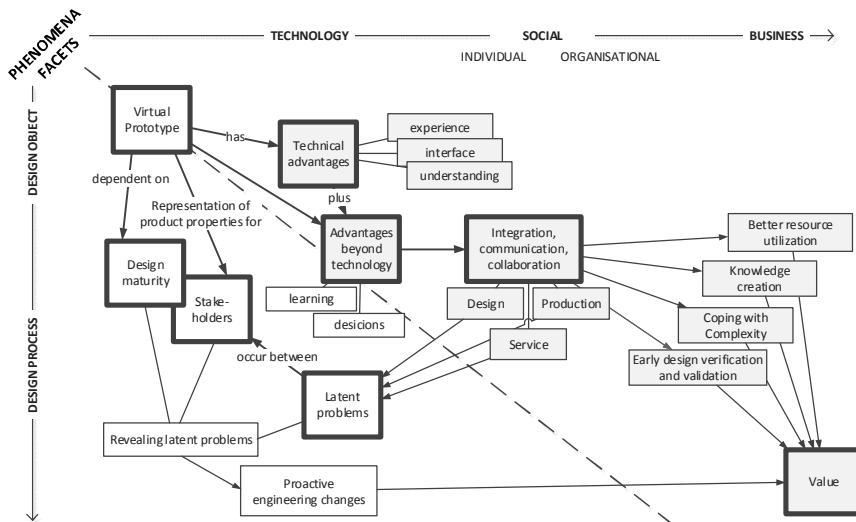
Figure 44. The phenomena facets of virtual prototyping can be divided into two main areas that are 1) dealing with designing and the design object, and 2) technological and organizational entities. The relationships between the entities and their contribution to business value are presented as well.

Figure 44 aims in the form of a matrix to collectively propose the dimensions of reality phenomena and categories of benefits and value propositions of VP, as well as their relationships. The analysis of advantages of VP firstly revealed two main areas that share the concept of a virtual prototype which can be justified by its nature as a model of the socio-technical system, and on the other hand as an object which is studied through the interface of virtual environments. So, the first area is the viewpoint of design which considers the virtual prototype as means for evaluation of behaviour and properties of a technical system, and the object of the design process. Thus, the virtual prototype becomes more mature as the design progresses. Additionally, the properties and behaviour of the design object may be assessed within different design domains (Andreasen, 1980), i.e. on different design maturity levels and by different stakeholders. An integrated method of communication and collaboration between stakeholders from many product life cycle stages, and organisational functions contributes to revealing latent problems, i.e. dispositions (Olesen, 1992). Secondly, from the product lifecycle and organization viewpoint, the virtual prototype is rather a sophisticated means for communication and collaboration that is aided by the natural user interface of virtual environments. In this social dimension, communication and collaboration will be investigated at the level of individuals and organisations. The virtual environments have certain advantages gained by the technological features, such as improved experience and interactivity with the model. Furthermore, the methodological view of VP brings advantages that are beyond this technology, but which also benefit from

139

the technology features (for instance by improved understanding, and therefore improved learning and decision making). VP facilitates integration of organizational functions and stakeholders (such as designers, production, maintenance), and enables improved collaboration and communication around the model (content) through the medium of virtual environments. This need for a communication line besides the communication content was demanded by Nonaka (1994). These advantages can be seen as a means of 'technological integration' of organizations and processes. At the business level, this technological integration may lead to 'managerial integration', i.e. better resource utilization (Wernerfelt, 1984), knowledge creation and capture (Nonaka, 1994), coping with complexity (Edwards & Jensen, 2014), and early product verification and validation. Ultimately these mechanisms also produce monetary value for business by improved cost-efficiency and better profit. Nevertheless, it is difficult to distinguish the value of designing from business and organizational value because they are so very much interpenetrating. Anyhow, reflecting with design theories and value theories reveals these aspects naturally.

Figure 45 illustrates how the F-B Pyramid model of Aromaa et al. (2012) was elaborated. Two major elements were added in order to categorize aspects of model continuum (between data, phenomena models, and reality as a target), business layers (between virtual prototyping technology, business processes (like product design and development), and people from business organisations and other stakeholders), and value formation (features of VP technology, advantages of the technology, and added value to business). Thus, this elaborated model recognizes the important distinction and cohesion between business reality and virtuality where digital product data is woven together with the processes of reality. The reality is complex and models of reality must always be simplifications of reality created for some specific purpose, for instance in design work. On the other hand, models can be the means for coping with complexity, especially when supported by an advanced user interface to content and a decent communication line organized by reasonable processes, methodology and organizational structures.
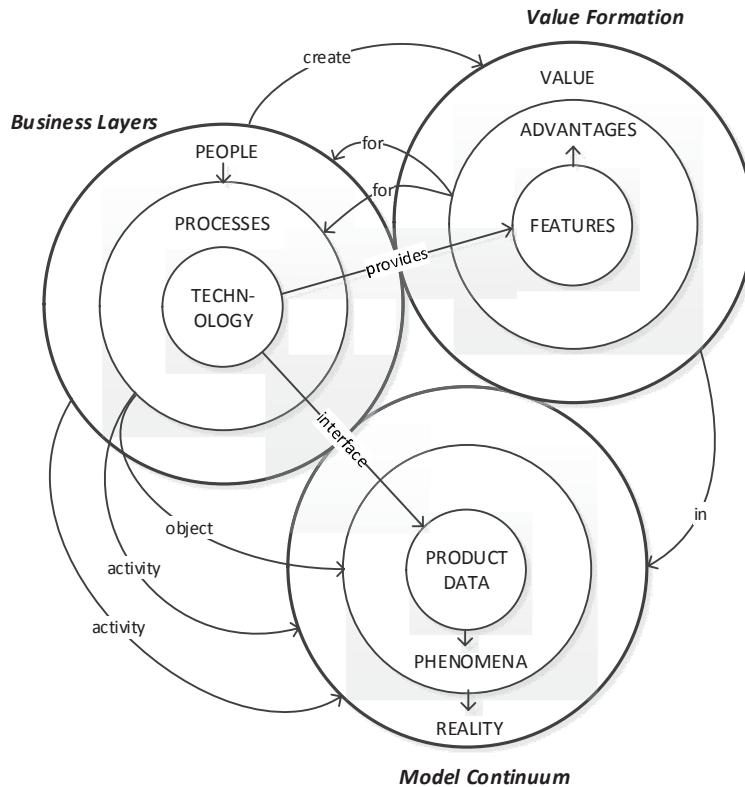
Figure 45. Elaboration of the F-B Pyramid model of Aromaa et al. (2012) by addition of three-level categories of model continuum, business layers, and value formation. This model describes how the low -level technology and product data contribute to value creation through modelling real world processes and activity and utilizing it in processes carried out by people.

Conclusion of analysis and categorization of case study results

In order to theoretically investigate and clarify the value of VP in manufacturing industry, firstly a hypothetical "Phenomena model" (Figure 24) was constructed. Secondly, empirical data from the case study was reflected with the theoretical model. The recognized advantages were categorized and the relations between virtual environments technology and phenomena of reality were established. In general, the advantages of virtual environments are that users can visualise, feel involvement and interact with virtual prototypes in real time (Cobb et al., 1995). The case data shows how these benefits actually create specific value in this type of industry, in the context of design and product development. It was also recognized that the advantages of virtual prototyping, and especially the use of virtual

environments, can be justified by better user interfaces, perception and understanding of product model properties.

Virtual assembly is a key component of virtual manufacturing (Mujber et al., 2004), and simultaneous assembly simulations are difficult because they involve a great deal of human interaction and real-time simulation (Gomes de Sá & Zachmann, 1999). Nevertheless, Toma et al. (2012) found that VR technologies represent very useful tools to visualize and interact with 3D models in the modelling and assembly process. Virtual reality-aided virtual prototyping does have the potential to reduce the number of physical prototypes and improve overall product quality, especially in those business processes where humans play an important role (Gomes de Sá & Zachmann, 1999). Furthermore, it is remarkable that there are two levels of user interfaces, namely the user interface of virtual prototype (virtual environment experience), and the user interface of virtual environment (VR technology) which refers to devices and software.

According to Cobb et al. (1995), both the quality of the virtual experience and its saliency (i.e. meaning and value) are important. The value propositions are justified by the capability of virtual prototyping of supporting design and business processes. The capabilities of VP refer to experience, user interface and content of virtual environments that support phenomena and properties of design object (e.g. product structure, dimensions), design process (understanding, learning), and product life (stakeholder needs, requirements management). Nevertheless, the participants experience both of the product itself and of the virtual prototyping method may have a great effect on the experience of the product model (Söderman, 2005). It was reasoned that, beside advantages that are directly connected with virtual environments, there seem to be benefits that have to be modelled in a wider context of organisation and management theory. Sometimes, the basic purpose of the investigation is challenged, as in a situation in which the original objective may have been to investigate a technological phenomenon, such as the use of personal computers, but in which the case study really turns out to be about an organizational phenomenon (Yin, 2009).

According to Mujber et al. (2004), VR offers the engineers new ways not only to visualize their problems but also to interact with the environment so as to resolve the problems effectively and efficiently. In practice, virtual environments allow a better analysis of the problems and modifications, for instance to product a structure and assembly sequence, or a simple creation of new geometry. These changes can be discussed and analysed in a real-time virtual environment However, with today's technology many changes to a product model need to be made in the original CAD/CAE tool based on the changes in the virtual environment. In any event, these extended presentations interactions, combined with interaction can improve the decision-making capabilities of engineers, thereby improving quality and reducing the development time for new products (Mujber et al., 2004). The virtual environment is also a new medium for information and knowledge acquisition (Mujber et al., 2004). The feedback from the case study indicates that the biggest challenges in adopting virtual prototyping and virtual environments are

not purely technical, but related to enterprise change management in the dimensions of management, processes, social aspects and infrastructure.

Four main dimensions and four sub-categories were recognized by analysing the case data (Figure 46): 1) Virtual reality technology, 2) Engineering design (object and process), 3) People (individual and organisation), 4) Business and management. Thus, as a conclusion of this section, the study of VP value will be expanded towards theories of those dimensions.
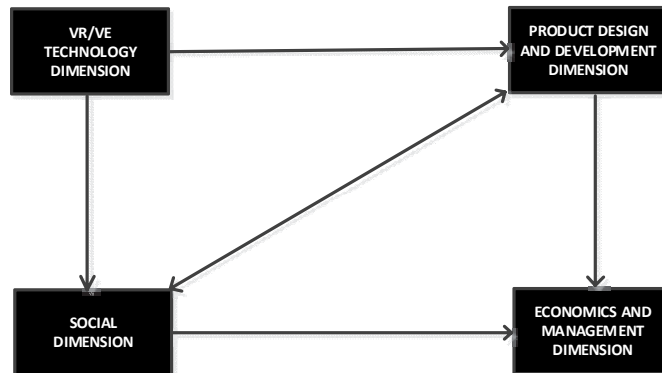
Figure 46. As a result of categorization, the case study results in four main dimensions of VP value framework were recognized. The VR/VE technology benefits people and organisation on the social dimension as well as the product design and development process dimension. These dimensions together create value for the business dimension.

6.2   Extension of the theory frame

The aim of the research was to increase knowledge about the benefits and bottlenecks of VP as well as to construct a theoretical foundation for modelling VP business value. The analysis of the case study data was firstly based on the Phenomena model, which is a synthesis of Theory of Technical Systems (Hubka & Eder, 1988), and the Theory of Virtual Environments and Virtual Reality (Kalawsky, 1993). The analysis of the data revealed that these theories are not sufficient to explain all aspects of VP. Therefore, additional theories and models were sought from literature. In order to proceed from identified VP features and benefits towards value modelling of VP, the concept of value should first be defined. Therefore, relevant value theories and models, as well as value modelling methods and approaches were studied as a starting point for expanding the theory framework. Additionally, examples of value modelling of specific domains are also topics of

interest. In the previous chapter, it was concluded that there are four main dimensions and four sub-categories in the value of VP:

1. Virtual reality technology
2. Product design and development (object and process)
3. Social (individual and organisation)
4. Economics and management.

Thus elements that somehow contribute to constructing the value model must be identified. The following concept map in Figure 47 illustrates how the dimensions virtual prototyping and its different enabling elements can be linked to business value, and how value theories and models help structuring the knowledge.

Especially in the case of collaborative human-machine design and human factors engineering, VP benefits from the better involvement of people who have valuable knowledge about many aspects during a product lifecycle. VP holds features (such as immersive and natural user interface) that become benefits (like improved communication) when combined with a good design methodology. These benefits enable value creation via better utilization of organizational resources which in the end can be captured, for instance, with better quality products and increased profit. On the other side are the elements that are prerequisites for the beneficial use of VP, namely skilled and motivated people, well-defined and tailored processes and methods, applicable tools, as well as data, information and knowledge management systems.

Now when the elements and principal concepts of value model have been recognized, the literature can be analysed in order to find and select appropriate theories and models that can explain the value of VP. In order to construct a coherent value model, links between theories and concepts will be identified and established too. The concept map of Figure 47 below illustrates which theories were selected and the relationships between them. In other words, the concept map explains methodologically how the research proceeded toward the theory framework. The selected theories and links between them, as well as relations to case study data will be discussed in the next section.
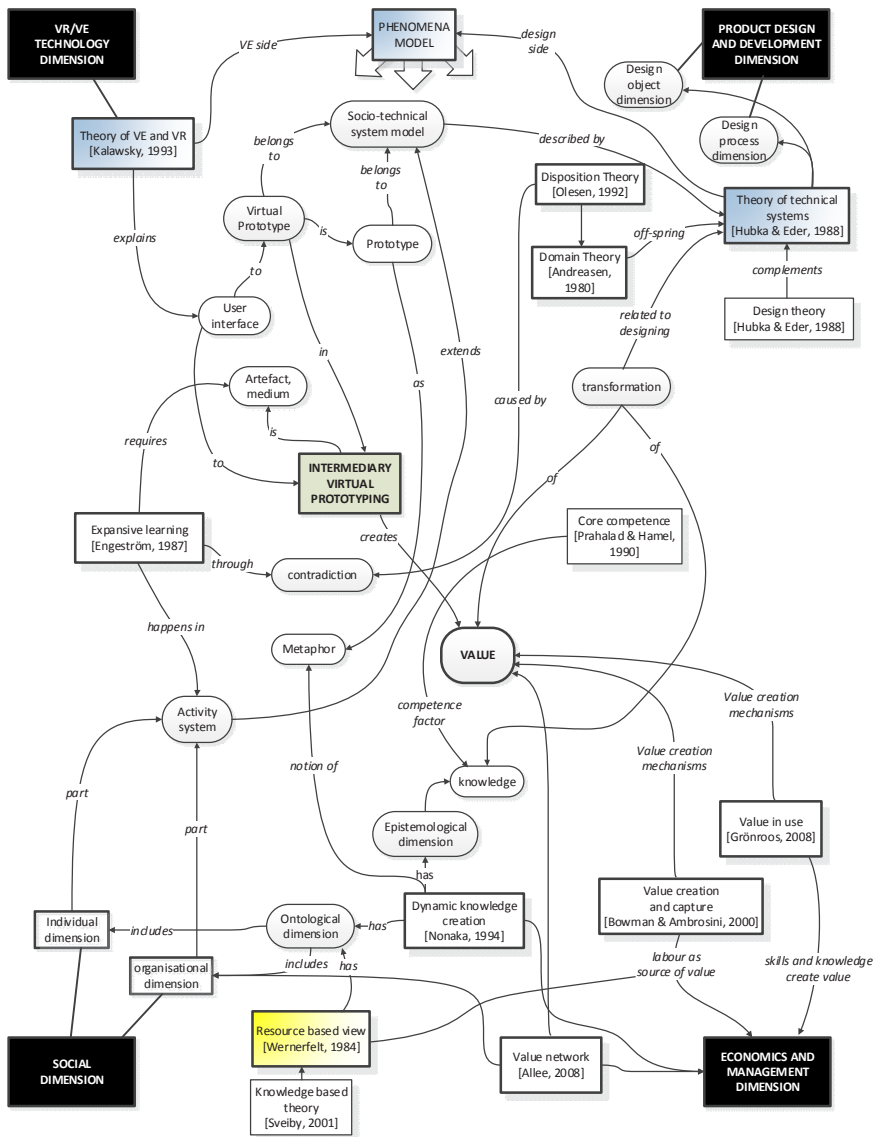
Figure 47. Concept map of the key theories that enable an explanation of the empirical findings with scientific concepts within the four recognized value dimensions of VP. The map illustrates links between the key concepts and theories of literature. The black squares are the four main dimensions. The blue squares indicate the hypothetical "Phenomena model" as a preliminary theory frame, and the yellow square is the starting point for the theory frame extension. The green square is the resulting concept of the research.

Literature about VP value is scarce. However, instead of modelling the value of VP directly, several interesting papers about modelling general information technology (IT) business value were found. Approaches and models introduced in those papers seem to offer opportunity to use analogy between general IT and specific VP. In this way the theory of "Resource-Based View to Firm" was recognized as a starting point from the literature review for value modelling. The theory of the Resource-Based View (RBV) of the Firm (Wernerfelt, 1984), (Penrose, 1959) provides a theory of effective management of the firm's resources, productive opportunities, and diversification strategy (Kor & Mahoney, 2004). In the RBV theory, a firm's resource can be defined as tangible and intangible assets (such as brand names, knowledge of technology, skilled personnel, machinery, efficient procedures, etc.), and they mean anything which could be thought of as a strength or weakness of a given firm. The RBV theory looks at firms in terms of their portfolio of resources rather than in terms of their portfolio of products, and gives a different perspective on strategic options.

The resource-based view is interesting for this research because it explains how companies' resources, such as VP, contribute both to internal business value and external customer value. Furthermore, Bowman and Ambrosini (2000) introduced an integrative model of value creation and value capture which combines several theories. They explain finely how resource investments create new use value when using labour wisely, and how this value can be captured as exchange value from the customers. In the case of VP, it is a resource investment which can create use value for a firm in form of better utilization of the firm's resources, like employees' knowledge and labour. Simultaneously VP can create surplus in the form of improved product quality for a customer and add exchange value (higher purchase price) of a product or increase profit with lower price thanks to decreased product development and production cost. However, once the purchased resource enters into the production process, it is impossible to apportion elements of its purchase price to various products (Bowman & Ambrosini, 2000). VP can be seen as this kind of resource that has great use value, but whose price cannot be apportioned to products. The innovation value chain model of Roper et al. (2008) describes interestingly how companies source knowledge through recursive processes and transform this knowledge into new products and processes.

The RBV emphasizes heterogeneous firm resource as the basis for competitive advantage. When the valuable resource is rare, it confers a temporary competitive advantage (Melville et al., 2004). For instance, VP as a rare resource which not all firms can utilize could be a competitive advantage. Companies who understand how VP must be configured for their business have a rare resource which helps to beat competitors in the market place. Gregor et al. (2006) learned that organizational transformation is seen as a component of the business value resulting from IT and also a driver of changes. Transformation includes aspects such as new business processes, new skills and new organizational structures. One asset of VP is facilitating more streamlined business processes and better collaboration within modified organizational structures. Melville et al. (2004) learned that IT is generally valuable because it offers a set of potential benefits from flexibility and

quality improvement to cost reduction and productivity enhancement. However, in order to gain those potential benefits, the great complexity of synergetic combinations of IT and other organizational resources must be understood. VP is also a resource that has a complex synergy with other resources, both technical (data, models, tools) and organizational (skills, structures, processes, management). In their model, Thatcher and Pingry (2007) explained IT investment factors that directionally impact on business value. The model assumes that IT is a commodity available to all firms, which is not necessarily the case with VP. Therefore, it may increase competitiveness as a rare resource as well.

Labour can be even unproductive and value diminishing. This means waste in Lean thinking (see Womack and Jones, 2003) terminology. The waste can manifest itself, for instance, as producing scrap, unnecessary rework or repair work. From the viewpoint of this research, an interesting question is how generic and unproductive labour might be transformed into more differential labour, and how VP could serve as a means for that transformation. This would be an essential factor of VP value. Bowman and Ambrosini (2000) defined that inside differential labour category there exist an entrepreneurial role whose task is directing labour with use value inputs so as to create new use values. Salvatierra-Garrido and Pasquire (2011) studied the perspective of value for Lean construction business, emphasizing the global perspective and beyond waste reduction understanding better what really contributes to customer value. In that way, VP can serve as a holistic means for simultaneously reducing waste and increasing quality, i.e. meeting customer needs (both internal and external customers). On the other hand, the concept of value management, see Neap and Celik (1999), should be fit for modelling VP value, because firstly it does not aim just to cut costs, but also the better utilization of resources. Secondly, it aims to tackle value systems that are not hard systems but soft and complex, in the same way as business organisations and value networks.

The theory of the Resource-Based View of the Firm was taken as a foundation for further elaboration and construction of VP value framework. This means that VP is studied as a resource that combines the technology and social aspects within a business organisation and value network. These aspects will be elaborated in the four main dimensions of technology, product design and development, and social value, as well as business and management value. The main theories and models that are discussed in these dimensions were introduced in the literature and theory sections of this thesis.

7. DISCUSSION OF THE CONSTRUCTED VALUE MODEL DIMENSIONS

This section discusses the value of virtual prototyping in the dimensions of product design and development, social aspects, and economics and business management. In the discussion, the case study findings are reflected with those theories that were selected as appropriate to explain certain phenomena by scientific notions. Thus, theories are used as lenses through which the findings are looked at from different perspectives. However, there can be seen evidently bridges between the concepts of the value dimensions.

Value is a concept that is difficult to define and to measure (Grönroos, 2008), and the definitions of the 'value' concept are strongly context- and phenomena-dependent. Generally speaking, value theories aim to understand how, why and to what degree people value things. In other words, the value of a thing is a measure of how much it is worth. In the introductory section, the concept of value was linked to technical systems' ability to satisfy someone's need in the context of design research. Therefore, the total value of a socio-technical system is the vector resultant of all the values (technical, economic, ergonomic, aesthetic, esteem, usage value), or of the measures of all the classes of properties for a given product (Hubka & Eder, 1988). Product development is the wider process that transforms market opportunities, i.e. customer needs, into a product available for sale, while product design refers to the specification of design parameters (Krishnan & Ulrich, 2001). Thus, design is a task inside the iterative product development that is managed as sequence of milestones and decisions, typically as a project (Krishnan & Ulrich, 2001). The basic value realization factors include the abilities of the design team, design time, and the number of improvements. Related to design, so called 'Universal Virtues' (Olesen, 1992); costs, through-put-time, quality, efficiency, flexibility, risk, and environmental effects are general measurable quantities for assessing a company's value creation and realization for all functional areas. In this research project, special interest is focused on the enterprises' prowess in creating value efficiently. Therefore, theories that explain value creation, transformation and capture were consulted as well (see the Theory section).

In the previous section 6, the resource-based view was taken as a foundation for further elaboration and construction of VP value model. The VP value model will be elaborated in the four main dimensions of technology, product design and development, social value as well as business and management value. The main theories and models that are discussed in these dimensions were introduced in the literature and theory sections of this thesis. In this chapter, the findings of the case studies are discussed and compared with existing theories and models of literature in order to conceptualize them scientifically.

Ultimately, companies must add more subjective value to customers than their rivals do. Therefore, they need some kind of competitive edge and core competence in value delivery. The value theory section revealed that people and their knowledge is the essential core competence of companies. On the other hand, value conversion is one of the most challenging questions for those trying to understand how to create value from intangibles (Allee, 2008). The theories and models introduced are basically of great worth in explaining value configurations, conversions and sources, but without grounding in a specific industrial context they might remain too theoretical. Similarly, the reputed common benefits of VP are actually dependent on characteristics like the business model, product characteristics, and the production mode of companies (Leino et al., 2013). For instance, in serial production mode, reduction of physical prototypes is an essential advantage, whereas VP can support building one-off products correctly the first time. This research intends to build a more practical framework of VP business value modelling on top of those theories and models.

In the analysis of case study data and during the construction of VP value model, three dimensions of benefits and value of VP were recognized besides the technological features: Product design and development (object and process), people (individual and organisation) and business value. In the chapters that follow the dimension are discussed and reflected on with the existing literature.

7.1   Value in product design and development

This chapter discusses the value dimension of product design and development. Furthermore, this dimension is discussed from the perspectives of design process, and design object. This means that value of virtual prototyping can be justified for instance by reduced through put time of new product development projects and decreased amount of engineering changes with a physical prototype. On the other hand, virtual prototyping enables observing the product description from different perspectives, and the relations between the perspectives.

The Theory of Technical Systems (TTS) of (Hubka & Eder, 1988) defines the concepts of product 'property', product 'behaviour' and product 'structure'. The behaviour of any technical system is closely related to its structure (Hubka & Eder, 1988). However, the product structure is not only important for the function (mode of action) of the technical system, but also for the principle of managing the pro-

cess of building and manufacturing the system (mode of construction). But the term 'property' may cause some difficulty for an engineer, because it also includes operational properties such as manufacturability, transportability, maintainability, operability, lifecycle costs and many others (Hubka & Eder, 1988). Nevertheless, design engineers should evaluate the design in respect of all of these properties during the system life. However, the suitability of the system is also a subjective property which depends on the viewpoint of the assessing person. This is one point where VP benefits and adds value to design, because it allows subjective evaluation and creative contribution from the stakeholders of the product life. Based on the case study results VP actually benefits designing and the whole product process on many levels that will be discussed and reflected with theory in details in the forthcoming chapters of this section. Apart from the fact that the synthesis and evaluation of product properties and behaviour is not a simple task, the design process itself is complex (Edwards & Jensen, 2014) because not all parts of a system are specified and constructed at the same time within an organisational, geographical and cultural setting, and authority distributed among the organisations. In other words, it is not fair to discuss only 'a designer' doing design, as it is often narrated in the literature. In the real world, design is a collaborative task conducted in a context where very many people are involved. However, from a cognitive viewpoint (Simon, 1995) the design process is shaped by the bounded rationality of the human mind and a very narrow focus of human attention. Thus, one single designer cannot be capable of imagining or evaluating all product properties. This is not an accusation, but a psychological fact that should be taken into account in the design and management of product development projects/processes. Additionally, the necessary knowledge and viewpoints of stakeholders of the system life is generally widely distributed throughout organisations which need to be learned during the design process (Simon, 1991). This is another level of VP benefits, and value was also prominent in the case study. VP is a means and paradigm for improved collection of this distributed knowledge and these viewpoints, and enables organisational learning compared to a conventional process where normal CAD and physical prototypes are utilized. The mechanisms and reasoning of this phenomenon is discussed with notions of social, psychology, and management theory later in this section as well. Virtual prototyping and virtual environments can be seen as a means of examining the suitability of a designed system in a very early phase of product process also involving the real end users and customers, before physical products are built. This VP-based transfer process should be seen as a means of closing the knowledge loop (Ameri & Dutta, 2005) of the product lifecycle already in the virtual design phase of the product process (Leino & Pulkkinen, 2012).

Design process dimension

Design Theory (e.g. Hubka & Eder, 1988) regards engineering design from the perspectives of the design process, and the perspective of design object. Based on the case study findings, and by reflecting design theory, the

design process dimension discusses how the virtual environments based virtual prototyping benefits the products design and development process-es. On the basis of the case results, virtual environments as a means of virtual prototyping hold properties that benefit product design and development process-es as described in previous sections. The key properties of VE are autonomy, presence and ability to modify the states of the virtual models. These properties have direct benefits which can be further turned to advantage that create value in dimensions of design, social aspects, and management. The chapters following first reflect the case results with design theory in order to conceptualize and further explain how VP creates value for product design and development.
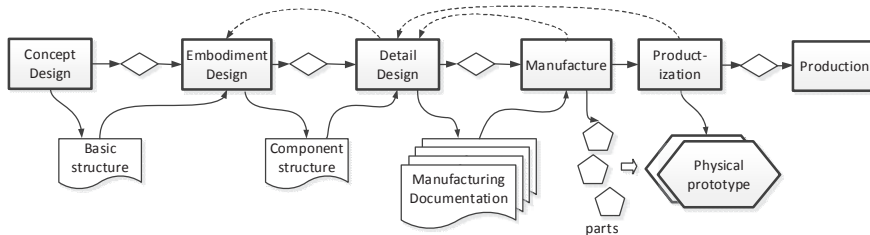
Figure 48. An example of a conventional productization process within an NPD project at the case company. The design process must be progressed to delivery of manufacturing documentation, and parts must be manufactured before a physical prototype can be built in order to assess suitability for assembly and mainte-nance of the product.

Figure 48 illustrates an example of a 'conventional' productization process within a new product development project in the case company, where mainly physical prototypes are utilized for assembly and maintenance structure and task evalua-tion. In this mode, designers have to detail all drawings and other documentation that is needed in order to manufacture the parts and sub-assemblies of the physi-cal prototype. The parts of the prototype must be manufactured before manual assembly may begin in the productization. The manufacture is outsourced and only assembly of prototypes is carried out in the case company. The main problem of this mode can be illustrated with the following principled Figure 49 (original version published in Aromaa et al. (2012). In the conventional productization first design progresses from concept to detail design through embodiment design where the product architecture, i.e. principles and basic structures, are deter-mined. When the design is already largely detailed, traditional design reviews are carried out with normal CAD from the productization and lifecycle perspectives. So, productization and other stakeholders are involved quite late, and the user interface (CAD) to product model is not optimal. The design review is related to the gate where a decision is made to start purchasing parts from suppliers for the first prototype. The supply delivery time for large and complicated parts or sub-assemblies may be even a couple of months. Therefore, it is critical to order the

correct parts early enough. If the delivered parts or sub-assemblies are not correct, or the delivery timing is bad, or the planned assembly structure, i.e. the sequence and process of assembly, is wrong, it will cause confusion and downtime in productization. Recognized flaws are reported as engineering change requests (ECR) or by other channels to the design function that will re-design the parts and structures needed. After that, the parts of sub-assemblies are purchased, manufactured and delivered again before the prototype can be completed, or new version of the prototype can be built. Due to the re-manufacture and delivery of parts, this process is time- and money-consuming, and it is difficult to shorten the through-put time of NPD projects. However, time-to-market is one of the major strategic lifelines of today's manufacturing companies, as described in the Introduction section. Though, it is natural and unavoidable to have iterations in the design and development process. However, it would be much more effective to do the iterations in the virtual product phase before beginning the physical manufacture of prototypes. The pressure of introducing new products to market may lead to a situation where immature products are launched to standard production. According to the results of the case study, this risk can be significantly reduced by virtual prototyping.
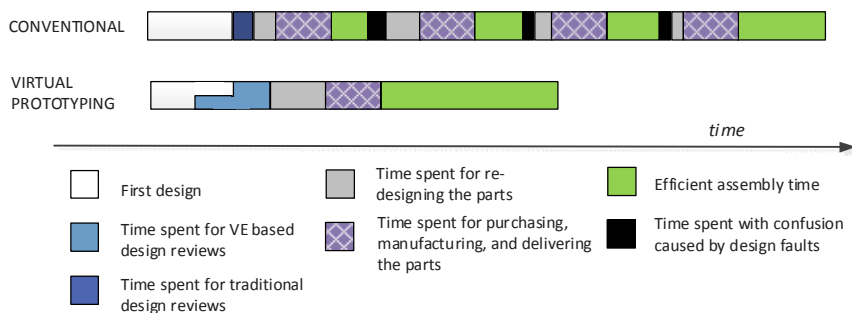
Figure 49. A principle difference between the conventional productization based on physical prototypes, and productization based on virtual prototyping on a timeline. The scale of the timeline is approximately a couple of months.

VP provides for the concurrent engineering (CE) paradigm. During an NPD project, there is a necessity to perform tests, such as assembly and maintenance properties with the product (Zorriassatine et al., 2003). This can be done using a) physical prototypes and real humans, b) virtual prototypes and digital humans, or c) virtual prototypes and real humans aided by virtual reality (Ferrise et al., 2013). However, physical prototyping does not enable CE in an optimized manner, because stakeholders cannot simultaneously share their knowledge (Zorriassatine et al., 2003). Furthermore, verification of complex manual tasks may need the building of several physical prototypes which increases product development cycle

times and cost (Chryssolouris et al., 2000), with poor process flexibility (Ferrise et al., 2013).

Figure 50 illustrates how VP changes the process of new product development according to the results of the case study. In this mode, the internal productization with respect to product assembly and maintenance can be done earlier, or at least in parallel with detailed design, because (all) components do not need to be fully detailed for manufacturing documentation. Thus, internal productisation can be shifted towards embodiment design, which means an allocation of functions and logical structure (organ domain) of product concept to basic structure (Tjalve, 1979) and form of parts. Furthermore, the virtual prototype does not need a complete model of the system, but only the phenomena and properties that are investigated. For instance, assembly properties together with maintainability properties can be assessed with the basic product structure and part dimensions. Thus, this approach requires that a virtual prototype supports this view of product structure. The detailed design and preparation of manufacturing documentation needs to begin later, when the corrections to assembly structure and parts geometry have been made (Figure 49). Consequently, not so many physical prototypes are needed for the productization purpose. This saves money, human resources and calendar time. Time saving is justified because manufacture is time-consuming and often out-sourced including logistics as well. On the other hand, preparation of virtual prototypes also requires effort. Naturally, the cost of this effort in terms of money and calendar time should be less than with physical prototypes in the aggregate. Therefore, virtual prototyping should be an optimized process supported with product data management systems. This dimension is discussed more in the chapter 7.4.

However, because human rationality is bounded and thinking works with incomplete models of design problems (Simon, 1995), commitments during the design process must be tentative and enough flexibility is needed. Simon means cognitive "mental" models of design, but also models of product requirements and specifications are incomplete. Their maturity increases during the design process, but the process has to be frontloaded and flexible in order to allow the examination of many viewpoints on the system. The Figure 50 shows how virtual prototyping and first design can be made partly parallel, allowing flexibility to be maintained for longer in the product process. Furthermore, it improves coping with bounded rationality and mental models, because more stakeholders can be involved in the early phases of the design process.
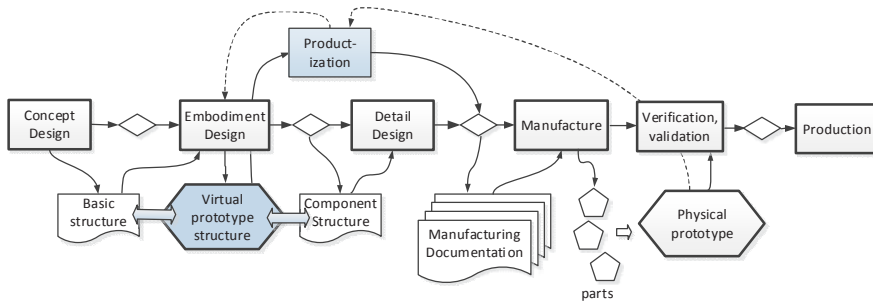
Figure 50. Illustration of how virtual prototyping changes the productization process within a NPD project. It also brings a new product structure apart from the product design structure (functional) and assembly structure, because the virtual prototype must be configured and simplified from the complete product model.

The following statements about benefits of virtual prototyping were given by the case company representatives (Roundtable discussion on the thesis research, 2013):

"VP reduces the number of engineering changes in detailed design" [engineering manager].

During the research project, it was estimated that "VP aided concurrent design and productization could save from three to six months calendar time" [productization engineer]

On the other hand "catching serious design flaws in the internal productization phase is very important. Those flaws may cause the suspension of standard serial production which is very costly incident" [productization engineer]

"In the conventional way of organizing internal productization, designers begin to get feedback from assembly personnel when a physical prototype is being assembled, sometimes only from the standard production line. This is unduly late. VP enables getting feedback earlier in the digital product specification phase." [engineering manager]

"Additionally, a virtual prototype enables testing and investigating several product configurations and variants compared to one physical prototype. This is an important matter, since theoretically even thousands of different configurations may exist." [engineering manager]

"Furthermore, a virtual prototype allows investigating properties and phenomena, which is not possible with a physical prototype. One can, for instance, go inside the machine or conduct test scenarios which would be too dangerous in a real environment." [engineering manager]

Generally speaking, it was concluded that VP adds value to human factors (safety, ergonomics) design due to an improved understanding of work activity and environment. [engineering manager]

Engineering change management proved to be one of the most significant product design and development process in with relation to productivity and time-to-market. This chapter discusses how VP provides for management of change in proactive engineering design. Designers must be modest about their ability to anticipate the future – and even less their ability to control it (Simon, 1995). This idea makes product design and development challenging and complex. However, it is very apparent in real world business that not everything can be perfectly planned and designed correctly the first time. A product development project, especially new product development, faces several risks coming from technical, market, budget and schedule dimensions (Keizer & Halman, 2009). These risks are normally managed through iterations, i.e. feedback based redesign. Actually, design is always tentative, at every point of time subject to revision (Simon, 1995). At least in the case study context where products are variants, it can be questioned whether the design of a product is ever complete? Iteration may be (Unger & Eppinger, 2011) small including minor changes to components of a product, or large including for instance market feedback that changes the whole design. The large changes include more uncertainty in the early concept phase. The more early uncertainty, the more engineering changes will probably occur and the more difficult it is to implement the changes during the product development (Ovtcharova, 2010). Most requests for changes arise because stakeholders' knowledge has not been integrated into the design process (Fleche et al., 2014). Fleche et al. argue that the use of collaborative tools such as VR can reduce the emergent changes in the later NPD phases when it is used early enough. This was a very clear finding already from the first sub-case studies, but it was also understood that managing the design and development so that virtual prototyping is utilized effectively is not a trivial task. This will be discussed in the chapter 7.4.

The new product development projects described in the case study section can be seen as large iterations, but inside these iterations minor changes are conducted in productization, but also in the standard production phase. For instance, the engine module and rock crusher projects are major iterations to old products. Within the iterations, engineering changes have various causes, for instance identified design errors within productization, production or use of the product. Engineering change management (ECM) normally refers to a formal process when product manufacture specifications have been released and need to be modified, and it is usually understood as part of standard production of released products. However, engineering changes occur of course also in NPD projects, and these changes are attempted to be managed nowadays with a more formal ECM process. However, there are remarkable differences (Pulkkinen, 2007) between the management of engineering changes in engineering design projects and configure-to-order mode, which can be considered as standard production in this research context. Engineering design processes are iterative, and propagation of changes cannot be anticipated, because the standard product structure is missing. Thus, product design has dispositional (Olesen, 1992) relations with other tasks of the project (Pulkkinen, 2007). Therefore, ECM in new product development pro-

jects is a particular process which can be improved and streamlined by VP (Leino & Pulkkinen, 2012). Also for instance, Aurich and Rößing (2007) have described how virtual reality can be utilized in analysing engineering changes and evaluating the impact of the change on the elements of the production system. In ECM, VP has certain advantages compared to conventional new product ramp-up in production. Firstly, change requests can be initiated before physical manufacture and confusion on the production line. Another advantage is gained by the communication and collaboration aspect of VP. For instance, assembly workers can assess a design change by walking around a virtual product, or designers can assemble products in a similar way to the real product. In this way, the engineering change propagation can be assessed from production and other lifecycle stages viewpoints. Nonaka and von Krogh (2009) saw re-designing in NPD of car manufacturing as an example of organizational knowledge creation. This phenomenon can be boosted by VP, because it enables a more collaborative way of designing. VP provides for Leino and Pulkkinen (2012) a proactive population, communication, evaluation of change propagation and validation of engineering change requests, because the context-dependent product requirements and specifications can be better understood in the context where the human-machine system operates. During the case study at Metso MAC Vehviläinen (2014) estimated that the virtual prototyping can remove a large part of major design flaws before manufacture of the first physical prototype. Concerning the long manufacture/assembly period of weeks or even months taking into account also the supply chain, the time saving is also substantial.

Examples of identified engineering change requests in a new product development project are introduced in this chapter. During a two-hour product design review meeting at the virtual environment laboratory, the following types of notifications or engineering change requests were identified (Table 11). Approximately 40 notifications or change requests were reported. It was anticipated by the case company that many of these issues would not have been recognized with a traditional 3D CAD setting, which means that most probably they would have caused ECRs, re-design, and re-manufacture in the physical prototype phase, or in the worst case in standard production.

Table 11. Examples of identified ECRs and notifications in a VE based product review.

Topic	Issue
3D model	• Three errors in the geometry of the 3D model reviewed were found
Product structure	• Change request related to component layout • Some discussions about the build-up-level and module variations • Assembly structure and sequence
Part dimensions and form	• Change request related to the dimensions of two supporting structures to give more space for assembly

	• Change request related to the form of one supporting structure to enable the attachment of a component
Assembly procedures	• Four different change request related to needs in assembly order and/or methods • Some feedback was collected about assembly tools and methods • Changes to part mounting • Updates to assembly instructions
Safety and human factors	• Change request related to one safety-related issue; lifting a heavy part • Holistic production, maintainability, and operation aspects • New maintenance hatches and fastenings • Parts/components were relocated for the sake of safety, e.g. oil leakage • Improved ergonomics and well-being

Design object dimension

The design object branch of engineering design theory studies how the technical products should be laid out and detailed in order to fulfil their requirements. Drawing from Domain Theory and Disposition Theory, this chapter discusses how virtual prototype structures benefit the design object dimension with relation to the holistic product development activity. The Theory of Domains (Andreasen, 1980) is important for this research because it emphasizes the characteristics of a product, its process domain and the division of activities between a technical system and operator (Olesen, 1992). A virtual prototype and its structures should support these domains as the design becomes more mature. Each domain in the Theory of Domains describes a particular degree of abstraction and detail in the creation of a product, and is represented by a series of structural systems which together describe the product completely[11] : the process system (i.e. the processes which transform energy, materials and information), the function system (i.e. the functions which are necessary for us to be able to realise the processes), the organ system (i.e. the general solutions and the collection of solutions which realise the functions by exploiting physical effects), and the structural system (i.e. the components or machine elements which make up the machine), (Olesen, 1992). Another similar type of formal representation of a design process and designed artefact on a different level of specificity and abstraction is Gero's (1990) function-behaviour-structure (FBS) framework. In this framework, a design prototype may firstly contain function and behaviour with little information on structure, but later it increases in the details of the product struc-

---

[11] As explained and reasoned in the Theory section of this thesis, the "function domain" was later abandoned, but in this thesis the original Domain theory with four domains is used in order to avoid a mismatch and confusion in respect of the Disposition theory.

ture. However, these theories are focused on the product, but not so much on the production and other product lifecycle stages.

Olesen saw the life phases of the product system which can be considered as transformation systems with certain characteristics as well. Thus, for instance an assembly line in production, or product service systems are such transformation systems in which the product elements are the operands of the transformation. Both the characteristics of the product and the assembly or maintenance systems are affecting the holistic productivity. VP creates value for the process of concurrent engineering of both these dimensions. Hubka and Eder (1988) pointed out that designers are responsible for the product's fitness for life, but Olesen (1992) dug deeper, seeking the relations and mechanisms in the product life's influences on the product and vice versa (Andreasen & McAloone, 2008). The transformation systems (Hubka & Eder, 1988) of product life phases with certain characteristics are influencing and influenced by the product. Furthermore, decisions on the product may be taken independently of decisions regarding organisation and management of the product life process due to the complexity of the design process (Edwards & Jensen, 2014), and only partial views of complex matters and a fraction of the knowledge needed are available at different stages of the design process (Simon, 1995). Olesen called these relations between engineering design and other product life stakeholders, dispositions which are seen from the viewpoint of the stakeholders of certain lifecycle phases.

The disposition means that part of a decision made in one activity which affects the type, content, efficiency, and progress of activities within other functional areas (Andreasen & McAloone, 2008). Therefore, how one set of decisions influences and delimits other decisions (Edwards & Jensen, 2014) should be studied, involving HF/E in designing all stages of system life (Dul et al., 2012), (Hollnagel, 2014). As described in the case study results, this human factor and ergonomics dimension in engineering design and revealing unwanted dispositions between design and people in other lifecycle stages is one of the most remarkable benefits of VP.

An example of an unwanted disposition found in design reviews of the case study is how the assembly task of a large and heavy part causes serious safety risk and problematic working postures for the assembly workers. Touching the dispositions, system life and temporal dimension of production systems, there is also a difference between dynamics (Hollnagel, 2014) of performance (e.g. quality, efficiency, safety) and well-being, including stress, satisfaction, illness, pleasure, personal development. In this respect, VP can create value by involving people whose safety and wellbeing is on stake. One focus area of this research was design for human factors of manual work in industry, especially manual assembly and maintenance tasks. Therefore, accounting for those issues in design is essential. Hence understanding the needs of humans in production and stakeholders of a product lifecycle is very important, but the needs of humans are often in the form of tacit knowledge (Nonaka, 1994).

The case study results indicate that VP contributes to communicating tacit knowledge for designers and other stakeholders. In general, models may be used in the analysis of work and to describe the context and constraints in which the

work takes place (Norros, 2013). Additionally, according to Norros (2013) the context and constraint models could be generalized as features that could be used in design work and technology. This approach to knowledge transformation and sharing will be further discussed in the chapter 7.2 on the social value of VP.

If we now consider the relationship between Domain Theory, Theory of Dispositions, and utilization of VP, it can be argued that, by the utilization of virtual prototyping, the design can be elaborated and determined further in the organ domain, because the success in the part domain can be evaluated based on characteristics of assembly function and manual assembly stakeholders. In other words, the dispositions influencing the assembly function (process domain) of the product can be recognized already in organ domain instead of the part domain (at least some of them) based on the basic product structure (Tjalve, 1979) and part form and dimensions. Consequently, this must have an impact on how the structures of virtual prototype models should be managed. The virtual prototype should be manifested in an earlier domain than the detailed part structure of the product, and it should be connected with the process domain of assembly and production functions. Weber et al. (2003) discussed the possibility of establishing links between product characteristics (synthesis) and properties (analysis) in a PDM/PLM system, and managing them through workflows. In that article, they did not address specifically virtual prototyping, but it would be an interesting approach for improved utilization of VP within the dispositional thinking.

Figure 51 (adapted from Olesen, 1992) shows that design progresses through the iterative process due to the fact that the success of a solution on a particular level cannot be evaluated without having determined the details at lower levels. In practice, this means that, for instance, the design of new functionality of a rock crusher cannot be verified before building a physical prototype and testing it from all aspects including strength. However, the ability to manufacture the crusher is a fundamental property also in competitive business. Furthermore, design decisions are typically spread over time (Edwards & Jensen, 2014) in a continuous process because all parts of a system are not specified and constructed at the same time within common organisational, geographical and cultural settings. Product design and production are typical examples of functions where decisions are spread over time, and they can be located globally even in separate continents. The figure aims to show what kind of decisions are made and how design maturity progresses from the product perspective (engineering design) and from a production perspective, and how these decisions are interrelated. This approach also reveals the mechanisms for how the unwanted dispositions are born between engineering design and production, and similarly for instance between engineering design and product service. For instance, decision of principles of product structure affects how production operations, like product assembly can be carried out, e.g. can it be automated or are manual work tasks needed. This selection may be obvious, but the dispositions are hidden in lower level details of the assembly tasks and equipment. The devil is in the details, and these details can be better investigated by utilization of VP.

On the other hand, the product view is often focused on product functions at the sacrifice of production and other product lifecycle aspects. Anyhow, as Gomes de Sa and Zachmann (1998) have proposed, virtual environments-based virtual prototyping enables frontloading the process by design evaluation already in the concept phase.
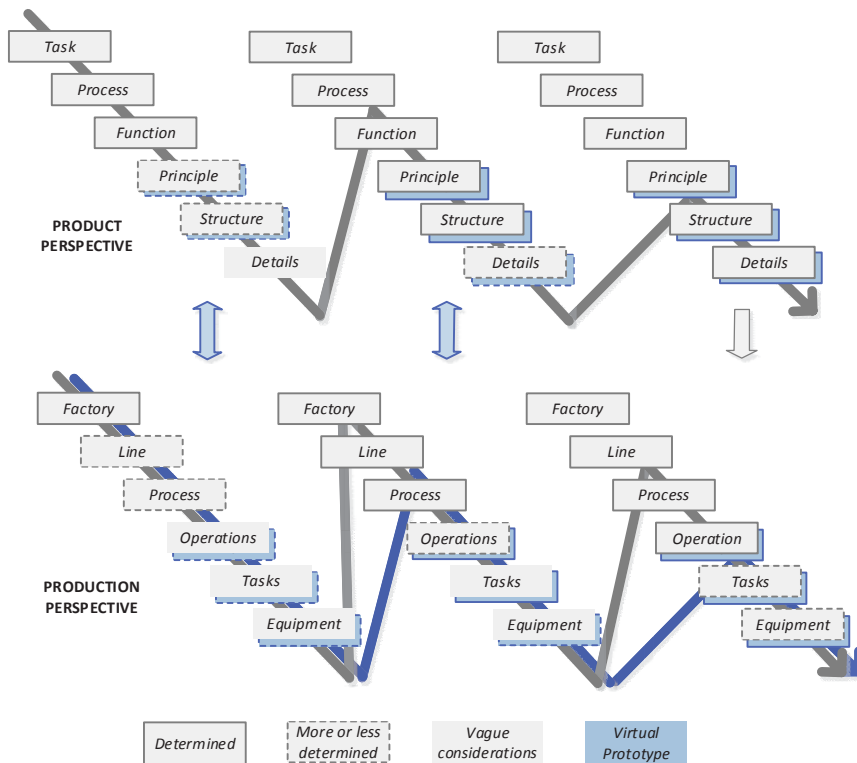
Figure 51. Theoretically, product design progresses from requirement definition, to principles of functions, structure and detailed parts definitions. However, in practice iterations must be done, for instance, to test the functions of a product concept or possibility to build it on an assembly line. Conventionally, these tests are made with physical prototypes, but virtual prototypes are proposed to enable these tests earlier. It is not possible to know everything about a solution on a particular level before determining details at a lower level. The figure is adapted from the original diagram by (Olesen, 1992).

The figure aims also to illustrate the difference between the virtual prototyping-based concurrent design process of product and production (blue arrow), and the conventional process (grey arrow) where product design must progress further to details and to physical parts before suitability for production, and the unwanted disposition can be revealed. The grey squares show the progress of product ab-

straction from the descriptions of requirements, i.e. the task and transformation process that the product is intended to fulfil, to detailed parts and product structure from the product perspective. At the beginning of a NPD project, there are only vague considerations of the product on every domain and abstraction level. According to Domain Theory (Andreasen, 1980), design progresses on every domain from simple to total, and from abstract to concrete. However, it is not possible to know everything in a particular domain before determining details at a lower level (Olesen, 1992). Similarly, the grey boxes from the production perspective show how the decisions and descriptions of production activity progress from the selection of a suitable factory, production line, process principles, operations, work tasks and equipment. In the case company, the productization department aims to contribute to production and product life perspective. At the beginning of an NPD project they aim to consider how a new product fits into production along with the old product. In the development phase, the objective of productization is to consider the suitable product structure for the production principle, what tools and equipment are needed, and what are the main processes and work procedures (Leikko, 2012). Frequent design reviews are crucial for recognizing major problems with manufacturability, assembly and lifecycle issues as well as for evaluating the safety of manual work before building the first prototype. In design verification, the goal is to make all development suggestions, engineering change requests and re-designs before launching the product in standard production.

Unfortunately, with the conventional approach the production operations, work tasks and equipment can be fully determined and decided only when the product is fully detailed and the physical prototype is built. The blue squares show how it is possible to start building a virtual prototype for the assembly and maintenance evaluation purpose already when the principle (basic structure, Tjalve, 1979) and main dimensions of a product are determined. This approach enables starting to ascertain how the production operations can be carried out by investigating the virtual prototype from the production perspective. Thus, it is possible to give feedback and reveal the unwanted dispositions earlier, and design iterations can be done before detailed design. The blue arrow indicates how the design maturity of the production system evolves faster compared to conventional productisation, and the product is more ready for assembly when the first prototype is built. This is essential for faster time-to-market and cost-cutting, but it is also essential for the HF/E approach because stakeholders can influence both the design of product and production when it is still possible. However, this description of how virtual prototypes can be utilized in internal productisation also affects the way the virtual prototypes should be built. Therefore, it should be supported both from the design process and product model data managements, i.e. how the design project and the progress of design maturity is managed, and how product data is managed in IT-systems like EDM/PLM. This will be discussed further in the chapter 7.4.
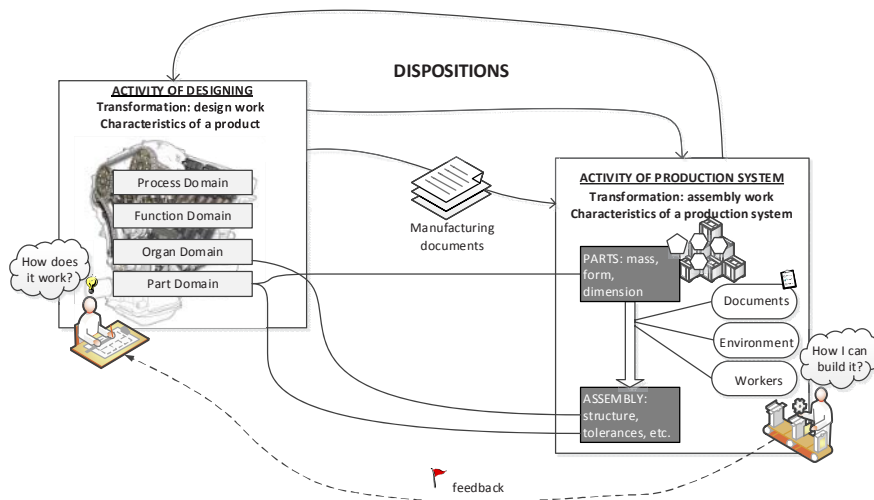
Figure 52. Dispositions may occur in conventional product process between engineering design and production. The product description is focused on the product functionality, and the manufacturing documentation on the part structure. However, the actual activity of production is affected by the product part structure, but the affects may been invisible for the engineering designers.

Design activity can be characterized (Gero, 1990) as "*a goal-oriented, constrained, decision-making, exploration, and learning activity that operates within a context that depends on the designer's perception of the context*", and "*design activity occurs within two contexts: the context within which the designer operates and the context produced by the developing design itself*" (Gero, 1990). These statements may sound self-evident, but in practice the design object (product) context broadly speaking and perception of the target context are not trivial. Furthermore, as Gero states, designers also change the context by designing. This can be also explained with the Theory of Dispositions of Olesen (1992). Therefore, the product and its context and related activities should be designed as a holistic system.

Figure 52 above illustrates how context perception and dispositions may occur in productisation between product design and lifecycle at the case company. En-

gineering design is transforming the knowledge of needs of the product process domain, i.e. operation (rock crushing) into a complete product description. The product descriptions of part domain are transferred to production in the form of drawing and instructions. In the production function at the case company, supplied parts and components are transformed i.e. assembled to sub-assemblies and finally to the complete product. However, the product descriptions are lacking information concerning the complete process of product assembly and material flow. Therefore, the system model is very product function-centric without sufficient descriptions of the production context, activity and human role. As Olesen (1992) proposed, the production system could be modelled using the Domain Theory (Andreasen, 1980) as well. Thus, designing the whole system should see assembly as transformation from the process and context domain to the completed individual product. In other words, process domain refers to the higher demand of turning the bill of material into the final product or sub-assembly, while function domain concerns how the assembly process is broken down into tasks, and organ domain is the manifestation principle for conducting the activity with the physical parts and equipment.
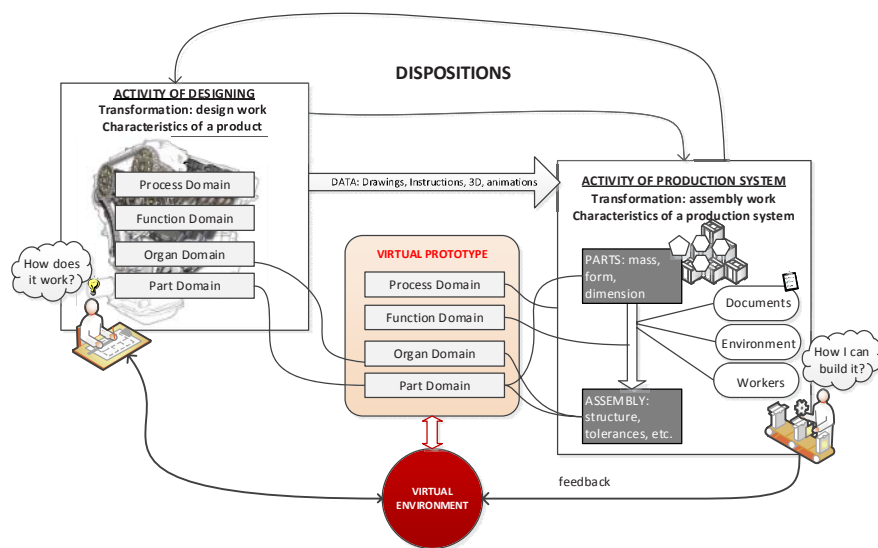
Figure 53. Catching the dispositions through virtual prototyping. VP represents the design object, but it enables also assessment of product properties from the production activity perspective enabled by the capabilities of virtual environments.

By virtual prototyping and the use of virtual environments, the process domain of production can be designed and evaluated early besides the part and organ domain of a new product. The virtual prototype, i.e. the virtual model of the product, enables the investigation of product properties that are interesting from the prod-

uct lifecycle viewpoint already in the design phase when not all details have been decided, and physical parts have not been manufactured, as described before.

The virtual environments allow a better interface and interaction with the product model, as described in the section where case results were analysed. One example of this comes from the VIRVO project where maintainability of a new generation rock crusher was analysed. The maintenance task included adjusting a bearing through a manhole, but in the design review in the virtual environment it was noticed that the maintenance persons would not be able to adopt the correct work posture through the hole. This was done in the embodiment design phase, where the basic structure and dimensions were designed but final decisions were not made so far. This design flaw would have been recognized only with a physical prototype, because it was not possible to see it with normal CAD. Thus, VE enables simulation of the product-related processes and procedures in a realistic context with the actual stakeholders. Hence, the hidden problems and unwanted disposition can be revealed before realising the product and production systems, as well as other lifecycle systems. Hence, VP is a wider concept than a model of the product, but it actually extends the product model, and the whole concept of a product system in the virtual world. Figure 53 illustrates how VP could support discovering the unwanted dispositions between engineering design function and production related to product assembly before the manufacture of physical prototypes. As Norros (2013) states, production is also an activity of which the outcome has two intertwined aspects, namely the materialised product and potential for development of the product. With VP, the development can be done before materialising the product. Furthermore, discovering the dispositions can be seen more than the improvement of the product through re-design and re-manufacture, but also a possibility of learning about the activities around the product.

Conventionally, data from the organisational design function has been transformed to productization in the form of a bill of materials (BOM), assembly drawings and instructions. Nevertheless, this data has been lacking aspects of assembly processes and methods, work tasks and environments, and other such contextual and situational matters. In other words, the process domain from the assembly viewpoint has not been described well enough in design. Due to this flaw, bad dispositions may occur for instance in the form of bad ergonomics for the assembly workers. Thereby, the transformation of assembly process should be understood by the designers including all the elements (human systems, technical system, information system, management system, and active environment) of the transformation model (Hubka & Eder, 1988). On the other hand, the virtual prototype should include all the domain elements that determine the necessary characteristics and properties of the designed production system depending on the focus of the analysis. From the product part and organ domains, the virtual prototype must include design properties such as part form, dimension and material definition, product structure and tolerances. Required level of totality and concreteness of the design at a certain domain depends again on the focus, as described in Figure 51. For instance, for analysis of the properties of higher level assembly or maintenance operations, basic structure characteristics of the product in the organ

domain are sufficient, while detailed work task analysis also requires more detailed models in the part domain. From an assembly viewpoint, process domain (activity) should include the assembly context, environment, people and instructions and the fundamental principles of assembly work. In the organ domain (action), the actual assembly sequences, where product parts are connected to each other, should be modelled. In this way, the external properties of products can be evaluated with a virtual prototype in a virtual environment based on design properties (product characteristics). This approach contributes to learning, because a designer constructs connections between different aspects and characteristics of the design object through experience (Gero & Kannengiesser, 2004). Similarly, designers should build their knowledge by constructing connections between product structure and assembly through experience and interactions with the production environment. This principle is connected with the notion of situatedness (Gero & Kannengiesser, 2004) drawing from ideas from cognitive science. Situatedness emphasizes how the actor's view of the world changes depending on what he/she does.

Product assembly studies and review were recognized as one of the most profitable areas of virtual prototyping. This chapter discusses how virtual environments benefit product assembly reviews compared to the conventional methods. Evaluation and verification of product structure and assembly work reflect the success of a NPD project (Leikko, 2012). On the other hand, productisation should be involved already in early project phases where the main principles for production and lifecycle operations are determined as was explained in the Figure 51. Nevertheless, there are practical work tasks that should be evaluated with an experienced worker. It was reasoned by members of the case company that many problems related to production could be recognized already in design reviews before manufacture and assembly of physical prototypes (Leikko, 2012).

The Value of VP can be justified partly by the fact that the majority of total product lifecycle costs are determined by decisions in the early design, and product assembly is one of the most cost intensive stages (Gomes de Sá & Zachmann, 1999). There are methods such as Design for Assembly (DFA) (Boothroyd, 1987) aimed for optimising the product structure and form for assembly tasks. However, they are claimed (Liu et al., 2006) to be hard to use and non-intuitive. Liu et al, (2006) proposed using virtual reality-based analysis for improving the accuracy of assembly analysis. VP contributes to the decreasing cost of assembly by reducing the working hours needed. Assembly tasks can be divided (Zimmermann, 2008) into manufacturing assembly and maintenance, which also includes disassembling as an important factor. These sectors should also be designed and reviewed together in order to find a holistic optimum and avoid partial optimization following the product lifecycle management principles. It is not a trivial task, because in factory assembly there are more possibilities to implement good sequences (Zimmermann, 2008), while in maintenance assembly it is more complicated, because of the many limitations in field conditions. VP enables designing and evaluating

product assembly properties holistically from both production and maintenance viewpoints.

Nowadays, many computer-aided engineering (CAE) tools have algorithms that enable automatic part path finding. According to Seth et al. (2011), expert assembly planners today typically use traditional approaches in which the three-dimensional (3D) CAD models of the parts to be assembled are examined on two-dimensional (2D) computer screens in order to assess part geometry and determine assembly sequences. Nevertheless, they do not often include (Zimmermann, 2008) the human action and ergonomic assessments such as reachability or postures of the assembly or maintenance person. To some extent, ergonomic aspects of assembly work can be studied by integrating a digital human model (mannequin) into the assembly task within a CAE tool. However, our previous research indicates that human-machine simulations without a true human action in the virtual environment do not produce reliable results. This finding was also supported by Chryssolouris et al. (2000) and Ferrise et al. (2013). Assembly work in virtual environments is very challenging because it is not just visualization but a highly interactive task (Zimmermann, 2008). However, the improved perception and interaction with the product model enables better ergonomics analyses because real humans are involved.

In studies of automotive industry, Zimmermann (2008) compared conventional physical assembly tasks with assembling in virtual environments (Table 12). It can be concluded that, even if virtual environments lose in respect to realism, they have many essential advantages compared to physical prototypes. When valuing virtual prototyping in this context, the focus should not be on a single product review meeting or such action, but on a wider scope. Hence, for instance, the ability to review product variants and observe the product (human-machine system) from various viewpoints with relatively low cost contributes to the holistic value of VP. However, for the final verification, physical prototypes are assembled by workers who identify issues with either the assembly process or the product design (Seth et al., 2011).

Table 12. Comparison of assembly try-out (Zimmermann, 2008).

ITEM	VIRTUAL REALITY	CONVENTIONAL (PHYSICAL)
Realism	Average	Excellent
Availability of data[12]	Excellent	Poor
Number of assembly checks	Many	Little
Check of variants	Yes	Hardly
Disassemble parts of better viewing	Yes	Hardly
Zooming	Yes	No

[12] The equal status of parts in the conventional assembly is normally not guaranteed because design is in progress during hardware manufacturing

Front loading effect	Excellent	Average
Costs	Low	High

Conclusion on value for product design and development

Design process dimension. The value of VP for product design and development was studied in the dimensions of design object and design process. In the design process dimension, VP enables shifting from part domain and physical prototypes to product organ domain, where the characteristics of basic product structure, part form and dimensions are determined. Thus, a virtual prototype enables feedback from production, productization and later product life phases to be gathered before making the detailed manufacturing documents and drawings. For instance, assembly and maintainability studies can be made already when the basic product structure and dimensions are designed in concept design or the embodiment design phase. Therefore, manufacturing documents can be made after the major engineering changes, and fewer engineering changes have to be done in prototype manufacturing and the standard production phase. Consequently, a lower number of physical prototypes and engineering changes results in savings in cost, calendar time and human resources, taking into account also outsourced manufacturing and logistics. From a business viewpoint, it was estimated that VP contributes to efficiency and effectivity in forms of cost and time savings. These quantitative results could not been measured within this research, but it is a topic for further research. The possibility to acquire early feedback and identification of possible problems and bottlenecks from production and maintenance was seen as particularly beneficial. Configurable products and the variant production mode requires flexibility, which leads to manual work- intensive assembly tasks and production style. VP enables testing and investigating several product configurations and variants compared to just one physical prototype.

Product design reviews are one of the areas where VP contributes a great deal in value creation. From the methodology perspective, the improved communication between people, and collaboration between organisational roles, functions and departments as well as between product lifecycle stakeholders were assessed as very beneficial. From the technological viewpoint, virtual reality technology provides for improved interaction and perception with the virtual environment and the product model compared to a conventional CAD and computer interface. Understanding of design increased mutually. For instance, assembly workers better perceived the new product structure, while designers appreciated their opportunity to experience how the manual work on the factory floor is really carried out. Furthermore, human factors issues such as safety and comfort can be assessed earlier and more easily in virtual design review meetings.

VP is a means for examining the suitability of a designed product in an early phase of the product process involving the real end users, customers, stakeholders before physical prototypes are built. Thus, it improves understanding of tacit

human factors and expands the design object from a product-centric model to include actions and activity of the total work system. Therefore, the technical product and work system can be designed as a holistic system and in parallel. The production and maintenance workers involved appreciated the opportunity to influence their own work tasks as well as the safety and comfort of their work. VP enables an investigation of properties and phenomena that is not possible with a physical prototype, e.g. safety-related issues.

In the design object dimension, VP can be seen as a means for investigation and revealing unwanted dispositions between different product lifecycle stages, for instance between engineering design and production. Dispositions mean that part of a decision made in one activity affects other functional areas. Models of the product as a set of attributes tend to ignore the constraints of the underlying product and productions technologies (Krishnan & Ulrich, 2001) causing unwanted dispositions. VP enables linking the organ domain and part domain of the product perspective with the process domain of the production perspective. Thus, process domain i.e. production activity can be designed earlier in parallel with the product, i.e. the technical system. Therefore, VP contributes to the optimization of the integrated product development and total activity system. The disposition thinking together with VP contributes to the paradigm of closing the knowledge loop of the product lifecycle. This approach may also lead to paradigm of proactive engineering change management where feedback through VP can be used in communicating, assessing or validation of proposed engineering design changes. On the other hand, engineering changes can be initiated by VP.

The most remarkable areas of contribution to value in product design and development dimension:

- VP enables *shifting from part domain towards organ domain*, and linking organ domain and part domain of the product perspective with the process domain of the production perspective
- VP is a means for *investigation and revealing unwanted dispositions*
- VP is particularly beneficial in *manual work-intensive variant production*
- Improves *communication* between people, and *collaboration* within organisations, thus providing earlier feedback from downstream lifecycle
- *Saves time and resources* by a decreased number of physical prototypes and engineering changes

This section concluded that a remarkable share of VP value is related to social perspectives, such as communication and collaboration within organisations. This social dimension needs to further elaborated in the next section.

7.2   Value for people

This chapter discusses the value of virtual prototyping in the dimension of individual people and organisation. It is discussed, based on the scientific knowledge on

human behaviour, how the findings of the case studies can be explained. In relation to individual people, these theories draw from psychology and cognition science. The collective organisational aspects are discussed with social and management theory.

The analysis of material in previous sections revealed that there are benefits and advantages of VP that are beyond the technological features of virtual reality, but which can be derived from those advantages. Part of these advantages and value beyond technology were explained with the engineering design theories, whereas some advantages and values turned out to be related to higher level social (individual and organizational) and business process factors. This chapter deals with those elements and mechanisms, categorizes them and reflects them with existing theories. The previous chapters dealt with engineering design and product development processes. Therefore, the starting point here is a description of a product.

It was previously (section 4) discussed that virtual prototypes are models of a product, and virtual environments can be considered as interfaces to those models. Additionally, it has been discussed that the design process is a transformation process from abstract mental models and demands to concrete and more detailed product descriptions (Figure 54). Figure 54 also adds the second dimension between demands and complete product descriptions, namely the transformation between tacit and explicit knowledge. The human (e.g. customer and product user) demands are typically in tacit knowledge mode, reflecting the person's mental model within the product process domain. When the design progresses and the synthesis become more mature in all domains through several viewpoints, the knowledge also shifts between tacit and explicit modes. On the other hand, evaluation of the product model and feedback to design is required as early as possible, but the feedback is often based on tacit knowledge and mental models as well. In the chapters that follow, how VP contributes to the product design and development process within these human perspectives will be discussed. Thus, designing is a purposeful and goal-oriented activity with a meta-goal of transforming system requirements into design descriptions (Gero, 1990). However, a common observation of design is that different designers interpret the same requirements differently (for instance, the expected re-negotiability of certain requirements) depending on their individual experience and interpretation of particular circumstances (Gero & Kannengiesser, 2004).

Obviously, based on the author's experience, demands and requirements related to human factors are typically understood differently, and they may be treated as "soft" requirements that do not need to be taken so seriously. On the other hand, those human factors requirements are often difficult to transform into formal and explicit requirement specifications. But that does not make them less important than "hard" technical requirements. However, expert designers respond intuitively, based on the recognized situation and their personal knowledge (Simon, 1991). Moreover, an individual designer does not necessarily know how a product is really assembled (Leikko, 2012). On the other hand, externally specified requirements are never complete, but design processes produce implicit require-

ments that are part of 'common knowledge' or result of the expertise of the individual designer (Gero & Kannengiesser, 2004). Thus, design is a process of continuously forming, finding, and solving problems (Simon, 1995). VP can be seen as a means for communicating and discussing these human factors related demands and requirements for designers and for transforming them into formal requirement specifications. VP is also a means for making implicit requirements, and knowledge in general explicit because it enables presenting circumstances that are often missing from a product description.

Now this approach will be discussed in detail from the viewpoint of human factors and socio-technical system. The transformation from mental models to concrete product descriptions require organisational knowledge creation (Nonaka, 1994) and transformation between tacit and explicit knowledge as well. The knowledge creation will be discussed in individual and organisational dimensions highlighting the significance of communication medium. It will also be reasoned that the concept of activity system explains the purpose of medium in a social context including individual and organisational aspects. The concept of medium will be discussed in more detail and the concept of intermediary object will be adopted in order to clarify the relations between virtual environments and activity systems. Finally, the mechanism of organisational learning and knowledge creation will be further clarified.

Constructional Domain

Organ Domain

Functions

Process Domain

Demand

Abstraction level of a product specification

feedback

Instructions

Drawings

8,00

Components

Parts

Sketch of structure

PRODUCT MODEL

Design specification

Product concept

Requirements specification

Human requirement

Knowhow

Mental model

Working skills

Product functions

Knowledge Mode

tacit

explicit

Figure 54. Design is a transformation process from ill-defined demands to precisely defined product specifications, and transformations between tacit and explicit knowledge increasing the design maturity iteratively. The product model is proposed to improve these transformations, and earlier feedback from the product stakeholders with the advantages of virtual environments. The figure is adapted from the figure originally published in Leino and Pulkkinen (2012).

Models and specifications are essential means for transferring information within product design and development. This chapter discusses the meaning of models and specifications from the communication perspective. In the context of system ergonomics, a model can be defined (Sheridan, 2014) as a representation of the structure or function of selected aspects, for instance for the purposes of communication or specifying a design of a thing or set of events. A specification or design description is generally represented graphically, numerically or textually with the purpose of transferring sufficient information about the designed artefact to stakeholders, like manufacture (Gero, 1990). Therefore, specification can be used as a synonym for the model having overlaps with terms such as abstraction, construction, explanation, portrayal, depiction, story, theory, idea, concept, paradigm and pattern (Sheridan, 2014). This definition is in line with the Theory of Technical Systems of Hubka and Eder (1988) who defined the notion of model in the context of engineering design as a representation of the real technical system, the process, or the idea by suitable means, and for a certain purpose, for instance for verification, communication or instruction within a product process. Additionally, a product model can be seen as a generic model representing all types of artefacts related to product design and manufacturing (Tseng et al., 1998).

Hubka and Eder (1988) made a conceptual clarification defining that a prototype typically enables determining most of the final product properties, whereas a model only permits determining some of the system properties. This clarification can be agreed especially in the terminology of product design and development. However, a prototype is still a model because it is "an approximation of the product along one or more dimensions of interest" (Ulrich & Eppinger, 2004). This clarification makes prototypes a specific class of models. Prototypes may be virtual or physical. In this context, the word "virtual" does not necessarily refer to computer models, but for instance a drawing or other artefact can be considered virtual in this sense as opposed to the physical "machine". Some industries, such as the construction industry, cannot typically build physical prototypes at all. However, literature defines "virtual prototypes" mostly as computer-aided models, and that notion was not common before computers. In the context of the case study, a prototype may be very close to a final commercial product. Actually, a physical prototype can, for instance, be leased to a key customer in order to test largely product properties and acquire feedback from the field. On the other hand, a prototype may be restricted to specific company-internal investigations of a limited set of properties. The virtual prototypes are typically restricted and optimized for investigating a limited set of properties, for instance assembly or maintainability properties. The way of using prototypes influences the product design and development process, and the success of the product and process with respect to time and cost (Zorriassatine et al., 2003). Furthermore, the utility of prototypes and other models depends on the mental models of individual people.
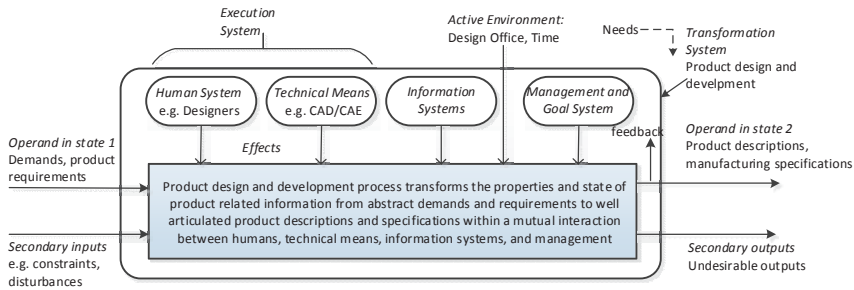
Figure 55. Transformation model of the design process. Demands and product requirements (Operand in state 1, i.e. initial information) refer to Figure 56 below. The virtual prototyping can be structured with this transformation model (original picture by Hubka and Eder (1996) in order to see the human system elements, technical means, information systems, and management system.

Mental models and knowledge are discussed here, because people see the world in different ways, depending their background and experience. Therefore people may also understand product related information differently. This chapter discusses how VP can contribute to solving the problem of different mental models. The exemplary (Figure 54) aims to explain how diverse types of product-related descriptions may be transformed (Figure 55) between different abstraction (Hubka & Eder, 1988) levels (from customer or user needs to detailed product part and structure specifications, and transformation (Nonaka, 1994) between tacit and explicit knowledge. It is remarkable that product descriptions include tacit and abstract mental model forms as well. The concept of mental model means that human beings hold their own dynamic viewpoint on the world based on their own constraints, objectives, experiences and knowledge (Mahdjoub et al., 2013). Thus, truth of knowledge is dependent on the individual's mental model and memory at a certain moment (Nonaka, 1994). Furthermore, the notion of constructive memory based on the cognitive concept of situatedness proposes that memory is not fixed at the time of the original experience, but must be constructed again every time when needed (Gero & Kannengiesser, 2004). Therefore, in human activity it is important what people know here and now, not what they know in principle (Simon, 1995). Simon linked this difference with the notion of bounded rationality, meaning that people know more than they might be able to utilize at a certain moment. VP can stimulate the construction of memory and knowledge by providing a context where the original experience can presented. On the other hand, taking the notion of "context" seriously means the complexity of particular situations, at particular times and for particular individuals, because the context is both internal with specific objects and goals, and simultaneously external involving artefacts, other people, and specific settings (Nardi, 1996). The concept of constructive memory also includes the idea of accumulation of memory and change of mental model through experiences after the original situation. Thus, memory must be seen as a process rather than a fixed state (Gero & Kannengies-

ser, 2004), and therefore also the mental model is a process. Because knowledge is dependent on the mental model at certain time, knowledge is a process as well. VP is proposed to add value to this process by providing for the improved possibility of expressing the viewpoints of different stakeholders and persons.

Human memory works so that people store some parts of what they know in long-term memory, while some parts of knowledge are stored in external encyclopaedias such as drawings and computer memory, keeping only the index of knowledge in human memory (Simon, 1995). These external memories accumulate information that must be evoked by some kind of stimulus. The virtual prototypes can be seen from two viewpoints in this paradigm. They store and accumulate knowledge of both the product and production process, and they may be an environment that provides cues for stimulating human memory to remember something that might remain hidden otherwise. This approach is similar to the Theory of Dynamic Knowledge Creation (Nonaka, 1994) and conversion between tacit and explicit knowledge. Introduction of modern CAD has contributed to the design process by providing the third dimensionality that helps interpretation compared to 2D drawings (Simon, 1995). Additionally, virtual prototyping contributes to 3D CAD by providing action and context to static 3D models.

Mental models are naturally evolving models which people formulate through interaction with a target system (Engeström, 1987). By aid of mental models, people construct their internal working models of the world, and structure their knowledge (Badke-Schaub et al., 2007). People can cope with new situations because they can understand them through their mental models and previous experience (Engeström, 1987). These explanations are important for describing the value of VP. People can supplement perception of a virtual prototype with their mental model that they have formulated through interaction with a physical target system in previous experiences. This is valid, for instance, with factory or maintenance workers who have a lot of practical experience of manual work with physical machines. But also the other way round, people who do not have much experience of physical target systems, can construct and structure their mental models through interaction with the virtual target system.

The higher level demanded properties of a socio- technical system must be transformed (Hubka & Eder, 1988) from mental models into more concrete and detailed requirement specifications and design specifications including human factors. This transformation from human demands to requirements specifications is critical, but often very difficult because of their nature as abstract and tacit knowledge. Additionally, there are two knowledge dimensions (Nonaka, 1994): the epistemological knowledge dimension that varies between tacit and explicit (codified) knowledge, and the ontological dimension including social interaction between individuals, departments, and organisational boundaries. Furthermore, tacit knowledge can be divided (Nonaka, 1994) into cognitive (mental models, beliefs, perspectives) and technical (know-how and context specific skills). Therefore social value of VP must be studied on individual people level and organisational level.

Activity system is a framework for discussing the systemic social dimension, including the relationships between individual people, the organisation network and boundaries, peoples' motives and goals, and means for achieving the goals. This chapter introduces the framework where the findings of value of VP are discussed. Activity has been a key concept in social science and practical philosophy since the days of antiquity. The Theory of Expansive Learning (Engeström, 1987) founded on the Cultural Historical Activity Theory (Vygotsky, 1978) helps explain the perspectives of an individual person or group, and the community where he/she or they are performing. In these theories, activity is the key concept. Vygotsky's idea of mediation is commonly illustrated as the triad (see an example in Figure 58) of subject, object of activity, and mediating artefact (Engeström, 2001). The mediating artefact may be (Allen et al., 2011) physical (e.g. tools), or abstract (e.g. skills, experience, competence). Engeström (1987) expanded the first generation activity system of Vygotsky to include elements of community, division of labour, and rules or norms (Allen et al., 2011).

Five central principles of the Theory of Expansive Learning are a) activity system as unit of analysis, b) multi-voicedness of activity, c) historicity of activity, d) contradictions as driving force of change in activity, and e) expansive cycles through zone of proximal development as a possible form of transformation in activity. The Activity Theory may be useful as a clarifying descriptive tool (Nardi, 1996), a heuristic guidance for empirical research and a theoretical lens in analysing and explaining empirical research results (Allen et al., 2011). Thus, the activity system is taken as a unit of analysis selecting members of the local activity through whose eyes and interpretations the activity is constructed (Allen et al., 2011). This refers to the first central principle of the collective, artefact-mediated, object-oriented activity system as unit of analysis. Activity Theory has been applied e.g. for describing the structure, development, and context of computer-supported activities (Kaptelinin & Nardi, 1997).
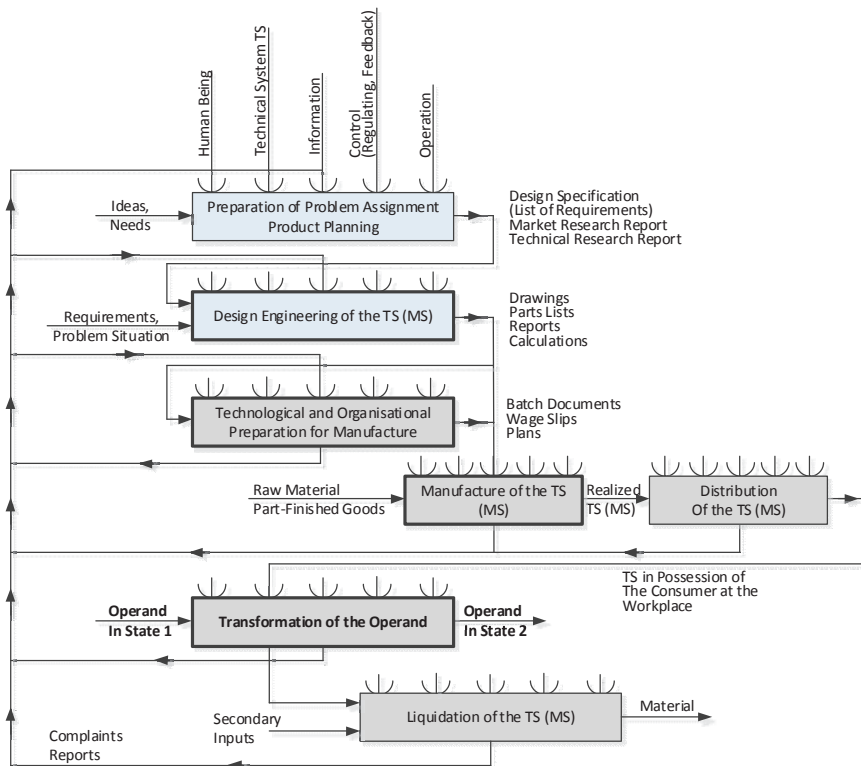
Figure 56. Different types of transformation systems during a product life. This research is mainly focused on the boxes with bolded lines. The blue boxes indicate the virtual product phases in the original picture in Hubka and Eder (1988), while in the phases of the grey boxes the product becomes materialized physically. This research studies how bolded grey boxes can be taken into account in the virtual product phase.

This chapter discusses how different mental models and motivations manifest within the product development activity system, what kind of challenges it may cause, and how VP can help. An activity is committed by a subject (an individual or group) with an underlying motivation to act on an object (person, collective, a thing) in order to achieve an outcome (Allen et al., 2013). However, subjects have their own often different mental models, and perhaps also different motivations. The different mental models and motivations are related to the various transformations that may occur during a product life (Figure 56). Nevertheless, the idea of multiple motives seems to conflict with the actual concept of an activity system which is defined in terms its motive (Allen et al., 2013). However, Allen et al. argued that recognition of multiple motives rather reflects the complexity of reality.
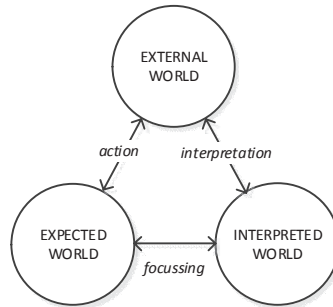
Figure 57. An individual designer interacts between three different kind of environments (Gero & Kannengiesser, 2004): A) external world (representations outside the designer), B) interpreted world (built up inside the designer in terms of sensory experiences, perceptions and concepts), and C) expected world that the actions of the designer will produce. Virtual prototyping is proposed to improve the interpretation process by providing the means for representing the external world.

By representing design in an open and dynamic context and drawing from cognitive science, the concept of situatedness, Gero and Kannengiesser (2004) introduced how an individual designer interacts between three different kind of environments (Figure 57): A) external world (representations outside the designer), B) interpreted world (built up inside the designer in terms of sensory experiences, perceptions and concepts), and C) expected world that the actions of the designer will produce. In the expected world, the effects of actions are predicted according to current goals and interpretations of the current state of the world. A designer works in a recursive interrelationship between these three worlds, trying to interpret the external world and making an expected world better. Virtual prototyping is proposed to improve the interpretation process by providing the means for representing the external world. Furthermore, if we consider other stakeholders, such as assembly workers, as co-designers of the product and production they also benefit from the improved interpretation. In this way, VP can contribute to the paradigms of concurrent engineering and value co-creation. However, this approach requires a wider theory frame including perspective of many interacting people.

Based on Vygotsky's work, Leont'ev (1978) developed a basic three level hierarchical structure of human activity: Activity – motive, actions – goals, operations – conditions (Allen et al., 2011). The actions are carried out with certain operations i.e. methods in certain conditions crystallized with the necessary tools (Engeström, 1987). Thus, activities satisfy a higher level collective motivation, while goal-

oriented actions and lower level operations of individuals contribute to the activities. Simon (1964) distinguished goals and motives so that goals mean value premises as an input to decisions, while motives are the causes for individuals to select some goals for their decisions. Therefore, activity systems should be investigated in many dimensions. Additionally, the object of activity is a moving target which cannot be reduced to short-term goals (Engeström, 2001). This also refers to the principle of historicity of activity systems, which will be explained later.

Leont'ev used a beater participating in a "primeval collective hunt" as an example for describing the difference between action and activity. The beater is stimulated by a need for food or need for clothing, but his action is limited to frightening a herd of animals towards other hunters who complete the hunt asynchronously. The action of the beater does not satisfy his need, but this is satisfied by the joint labour activity because he gets his share of the prey. The processes, the object and motive which do not coincide with one another are called actions (Leont'ev, 1981). Similarly, product design and development can be seen as a sequence of individual asynchronous actions performed by dozens of people from several organizational functions with their own goals, while the whole process activity share a common motive, i.e. launching a good quality product to market at a good price. After all, success of the product affects the economic situation of the company, and in the end also the situation of an individual person at the company. Thus, the successful search for a new product for market satisfies also the need for food for the person. Actions may be individual, but activity is always co-operative. The activities are realized by goal-directed actions. However, individuals are not necessarily conscious of the objects and motives of the whole activity, which is a system of systems. Additionally, the total activity controls the individual instead of the individual controlling the activity. (Engeström, 1987.)
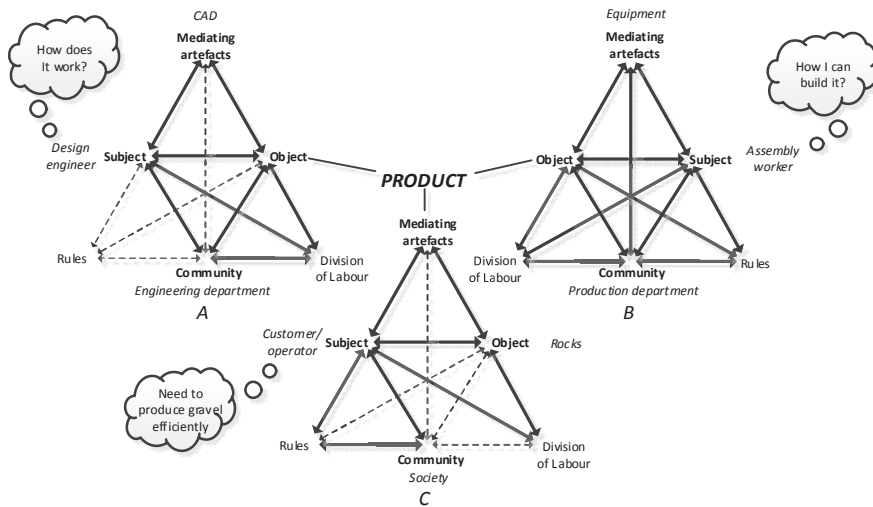
Figure 58. Different mental models of activities. A – product functions (design engineer at engineering department), B – product assembly work (assembly worker at production department), C – Rock crushing operation (customer/operator in mining and construction business).

Based on the activity system model, exemplary Figure 58 above aims to illustrate how, for instance, a mental model of a design engineer within the activity system of an engineering department may be different from the mental model of an assembly worker within production activity. A customer who purchases the product or an operator who is using the product has concerns about productivity and the sustainable development of his/her business. Nevertheless, all these actors share the same product in their activity but from different perspective. However, the engineering designer may emphasize the functionality and quality of the product from the customer perspective, while the assembly worker sees the product as bill of materials that must be compiled as a complete machine as described in Figure 52 with the Theory of Dispositions. These multiple viewpoints, traditions and interests refer to the second principle (Engeström, 2001) of multi-voicedness of activity systems. The object of an activity is its true motive, distinguishing it from other activities (Engeström, 1987). Thus, a shared object with different motives leads to different kind of sub-activity systems.

Focusing to the common object (i.e. product) of activity systems is the necessary glue that keeps the nowadays distributed work together beyond the short living goal-oriented actions (Engeström, 2004). However, the common object should also be the glue between different activity systems, e.g. product design, development and production as well as more widely between all organisational functions and stages of the product life following the principles of PLM (product lifecycle management). Thus, the glue must be manifested by common processes, information management, and organisations. The productization function at the

case company can be seen as such glue that adds value to the product development process. According to the case study results, VP contributes to this process as described previously, but the information management and organisational management should be better organized. This will be discussed further in the chapter 7.4.

The object of the activity system integrates the other elements of the activity system, and shapes the characteristics of the other relationships, since it motivates acting but also loads the system with particular constraints (Norros, 2013). Therefore, the integration must be studied and developed between the activity systems as well in order to maximize the total productivity. It will be discussed in the paragraphs following how the different mental models may cause contradictions, and what kind of consequences may follow from them. Contradictions are sources of trouble, but also sources of innovation (Engeström, 2001). The characteristics of innovative product development have three dimensions (Alves et al., 2007): diversity (of actors and competencies), coherence (respecting the integration of complementary activities) and interactivity (strong cooperation relationships) which should be stimulated by a collaborative environment. Besides these three structural dimensions of organisations, innovative product development also requires a practical "learning by doing" approach.

On-spot-ism is a concept of management theory that high-lights the importance of learning by doing in organisational knowledge creation. This chapter discusses how virtual prototyping can contribute to this approach. It is important to bear in mind that well-articulated product description for a design engineer (e.g. a new product concept) might be very abstract for a factory worker. And vice versa, those workers have experience-based tacit knowledge about their manual work tasks which an individual design engineer does not necessarily know or understand profoundly (Leikko, 2012), but which they could capture and learn through experiencing the work tasks and context in a virtual environment (Leino & Pulkkinen, 2012). However, designing involves learning through changing and exploration of emerging features of the system as the design proceeds (Gero, 1990). This approach refers to the notion of 'on-spot-isms' (Nonaka, 1994) which emphasizes the importance of hands-on experience in companies. However, for instance novice engineering designers today have typically less hands-on experience of the factory floor or other practical work because of more theoretical education and lack of internships.

Simon (1995) saw that there are two sources of new knowledge in the design process: memory that is evoked during the process – and learning new thing through experience that may change one's preferences. Furthermore, according to Nonaka (1994), natural thinking and ways of dealing with prototypes maximize the level of information with a minimum of energy, compared to formal attributes of concepts. Boujut and Laureillard (2002) claimed that the materiality of a product, through its various representations (prototypes, mock-ups, plans, CAD models, etc.) is fundamental as a means for co-ordinating activities applied in co-operative processes. Collaborative virtual prototyping adds value to this process by also providing the actions-activity context besides the mere product model as was

discussed with the Theory of Dispositions in Figure 53. In other words, collaborative virtual prototyping enables a genuine human-machine and socio-technical system view. Gero (1990) saw traditional CAD systems that produce 'static' design descriptions and graphic representations as the 'syntax of a design' and required translation to the semantics of the design. Gero was demanding better utilization of the CAD data in the design process. He was thinking about automating design processes through so-called design prototypes and knowledge schemas, but VP can be seen as another approach for better utilization of 3D CAD data in a design process based on human interaction. However, it should be automated to some extent too, as will be discussed in the chapter number 7.4.

Social dimension – organisation

This chapter introduces how the different mental models and motivations may lead to organisational contradictions within and between departments, and how the contradictions may lead to organisational learning and development. Nonaka (1994) pointed out that a prototype is a model that acts as a metaphor for transforming tacit knowledge into explicit knowledge by recognizing product-related contradictions. Contradiction is also a key concept, and the fourth principle in the Theory of Expansive Learning (Engeström, 2001), meaning that contradictions have a central role as a source of change and development within activity systems, i.e. organisations. The concept of contradiction refers to anything that opposes the overall motive of the activity system (Allen et al., 2013). However, they are not the same as problems or conflicts (Engeström, 2001), but rather historically accumulating structural tensions within and between activity systems. Possible tensions between the engineering and manufacturing departments of companies may be seen as instances of such historical contradictions. In a multi-person situation, such as in product development, one stakeholder's goal may be another's constraint (Simon, 1964). The contradictions are often related to product properties, e.g. assemblability and maintainability, but they should be studied through the activity of people. The concept of contradictions can be seen as a link to the Theory of Dispositions (Olesen, 1992), since the thrust of activity system is to locate opposite propositions, i.e. contradictions (Allen et al., 2013).

The clash between individual actions and the total activity system is the basic internal contradiction of human activity caused by the division of labour (Engeström, 1987), and the directions within an activity system, and between two activity systems, are essential for the concept of expansion (Engeström, 1987). In the third generation of Activity Theory, the basic model is expanded to include minimally two interacting activity systems (see Figure 59) aiming to understand dialogue, multiple perspectives, and the networks of interacting activity systems (Engeström, 2001). The multiple perspectives between the engineering design department and production is a classic example of contradictions. In real life situations, there is little communality of goals among the several parts of a large organisations, therefore goal conflicts are unavoidable (Simon, 1964). So, this is a great

challenge for business management in practice. The concept of expansion will be explained in greater detail in later chapters.
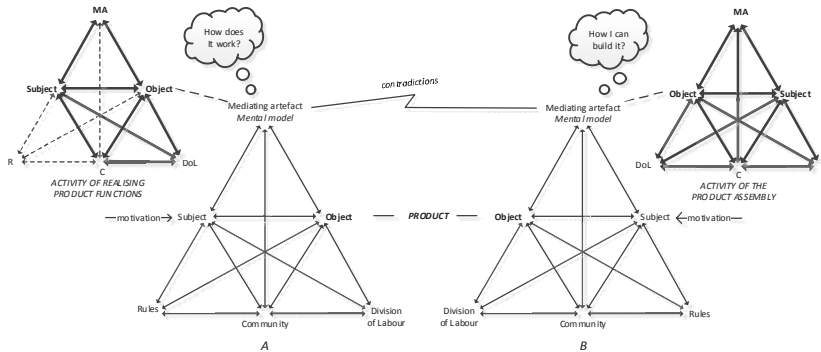
Figure 59. Contradictions between activity systems: A – engineering design, B – production.

The importance of organization structure and culture in relation to utilisation of virtual prototyping in value creation is discussed in this chapter. How VP can support the organisational field of interaction? Engeström saw that Nonaka's model is a good attempt towards explaining organisational knowledge creation and learning, but in that model he (Engeström, 2001) saw a problem in the role of management in facilitating the process, because it cannot be decided by senior management from above what is to be learned. On the other hand, Nonaka (1994) emphasizes the need of self-organizing teams combining members from several functional departments as "fields for interaction" enabling bringing personal knowledge into a social context. However, it is a critical question how and when these self-organizing teams are managed in practice in a complex manufacturing company. Nonaka (1994) called this dimension "management rhythm" and every organisation have their natural frequency for that. This rhythm of the organisation should be studied, and how VP impacts it when implemented effectively in the product design and development should be discussed. In the chapter 7.1, how the design process can be frontloaded was discussed, but it is not just a matter of VP technology and data management. The process does not change or continue without coordination.

In activity systems, the management of self-organizing teams refer to elements of community, rules and division of labour. However, Boujut and Laureillard (2002) argue that, for instance, the famous and still often vague link between product development and production is caused by the informal, unstructured and unpredictable exchanges are not yet supported. In the American new product design practice, manufacturing expertise has typically been consulted far too late, causing extensive redesign and time delays in time-to-market (Simon, 1991). This approach seems also to appear in Finland, see e.g. Leikko (2012). On the other

hand, there seems to be a cultural difference between western and oriental (Japanese) companies (Nonaka, 1994). Social interactions between individuals, groups and organizations are fundamental to organizational knowledge creation in Japan, while explicit and digitalized knowledge management is dominant in western business culture. This statement is also supported, for instance, by Morgan and Liker (2006) who have described the Toyota product development system. Toyota's engineering check lists or lessons-learned books serve as the knowledge repositories for different functional domains and have evolved over time (Ameri & Dutta 2005). In the Japanese culture, communication between different organisational functions is based on respect for others' expertise and its relevance to their own problems, sufficient knowledge and understanding of the other person's problems (Simon, 1991). This approach is enabled by extensive lateral transfer of people between functions and the actual experience with the activities and responsibilities of the other groups (Simon, 1991).

Nevertheless, virtual prototyping and especially virtual environments can serve as a field for interaction also providing the product model as a metaphor for knowledge transformation. It is proposed that VP improves knowledge creation and conversion because it provides a more natural media for communicating product information. This advantage is particularly important because only a share of knowledge can be managed or controlled, and therefore knowledge management should be seen rather as a process (Sveiby, 2001) than an IT technology and explicit information issue. This highlights the importance of studying VP value from the social perspective as well and the importance of considering VP as a combination of technology, information management, social structures and organisational management.

This chapter discusses virtual prototyping in relation to historicity of activity. The principle of historicity of activity (Engeström, 2001) system means that problems, but also development may be difficult to recognize, because of the temporal dimension of product design and development. Bringing together different biographies, i.e. people from different social practices, diverse organisational functions and departments enables the acquisition of fresh ideas and insights, which is a source of creativity (Alves et al., 2007), (Nonaka & von Krogh, 2009). Virtual prototyping can be a methodology that provides the flexible field of interaction as a hub, and the medium for understanding the product description content and context for people with different biographies. The context model is important because the history needs to be studied as a local history of the activity and its objects (Engeström, 2001).

Self-organizing teams with different biographies, such as product design review boards that are organized around a virtual prototype, perform the tasks of socialization and externalization (Nonaka, 1994) compared to traditional hierarchical and formal organizations that mainly carry out the task of combining of document-based information and internalization of knowledge, e.g. reading or watching documents. VP is a mediating artefact that is easy to understand and, therefore, improves the discussion between stakeholders. The socialization is very difficult without an interaction field, such as a collaborative virtual prototype (virtual envi-

ronment). According to Nonaka (1994), formulation of self-organizing multi-disciplinary and cross-functional teams, and mixing people should be supported and managed by the mid-management of companies in order to increase overlapping and redundancy of information and knowledge. This approach was also demanded by Leikko (2012), and it has been successfully tested in the case company.

The knowledge conversion may have both a knowledge and a social practice outcome (Nonaka & von Krogh, 2009). Therefore, besides possible product innovations, the ultimate outcome of organizational knowledge creation could be process innovations through historicity of activity. In other words, the value of VP should not be observed only from the product perspective, but should expand the perspective towards the competence of a company as an innovator. However, organizing such cross-functional groups increases the complexity of organisational structures and processes as well as management. Therefore, value network analysis (Allee, 2008) could assist in revealing the advantages of this kind of approach. It is remarkable that these communities reflect the way in which people actually work, as opposed to the formal job descriptions specified by the organisation attempting to solve practical problems (Nonaka, 1994). This kind of value configuration can be modelled as a value shop (Stabell & Fjeldstad, 1998) where value is created by mobilizing resources and activities in order to resolve a particular and unique problem, see Chapter 7.3. The Activity Theory can be used as a heuristic tool for modelling these social systems as well.

The knowledge and concepts created by members of a self-organizing team is crystallized (Nonaka, 1994) for instance in the process of testing the concretized product or prototype by various organizational departments. Therefore, prototyping is a critical process in organisational knowledge creation, and internal productization is a knowledge hub between organisational functions. Thus, products are the embodiments of the core competencies of the company (Prahalad & Hamel, 1990), objects of this activity system. Similarly, the virtual prototype as a model of the product can be seen as a digital and explicit embodiment of tacit knowledge and core competence.

The human subject is social in nature and shaped by culture, but the material world also consists of culturally produced artefacts created and transformed during common activity (Allen et al., 2011). The virtual prototypes can be seen as digital models of these artefacts of the material world. Previously, the cognition theory notions of situatedness and constructive memory were discussed in the context of design and interaction between the external, interpreted and expected world. Gero (1990) proposed that designers generalize and schematize their individual design experiences into design prototypes. Virtual prototyping and VE-aided product reviews can be considered as such design prototypes and crystallization processes, representing both the object model, and the interaction field in crystallization. Through experimentation, knowledge of different stakeholders is internalized by observing, socialized by discussing, and externalized by notifications to the virtual prototype and documentation of design reviews, but new knowledge creation is also triggered iteratively based on the recognized contradictions and dispositions

between the stakeholders. When the virtual prototype is understood also on the meta-level as a configuration of product data and product data structures, for instance in a PDM/PLM system, the tacit knowledge can be made explicit there.
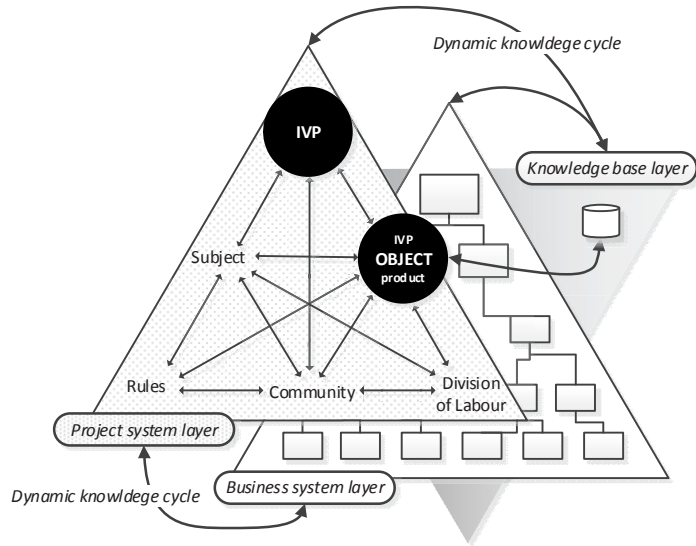
Figure 60. VP is a node in a knowledge-creating organisation combining the new product project activity system layer, business system layer and knowledge base layer in a "hypertext organisation" (adapted from Nonaka et al., 1992) (Nonaka, 1994).

This chapter discusses how and why the concept of virtual prototyping should be expanded in order to argue the value in the organisational dimension. Virtual prototyping is discussed in relation to the concept of hypertext organisation. A good company culture and shared values are the glue that holds companies together and the key to integration across the company and knowledge and resource sharing (Tushman & Reilly, 1996). Nonaka et al. (1992) introduced the concept of "hypertext organization", meaning that knowledge-creating organisations have three interacting layers: business system (formal), project team (cross-functional), and the knowledge-base which stores and shares the explicit knowledge in the form of documents, files, databases, etc. The hypertext organisation describes an approach to organisational design that provides a managerial structure for the strategic process of organisational knowledge creation (Nonaka, 1994). It is based on a dynamic cycle that links concepts and knowledge from many organisational areas, providing different views of the knowledge in different formats. Figure 60, adapted from Nonaka (1994), illustrates the idea of hypertext organisation and continuous knowledge-creating interaction between a formal business system and a project system. Manufacturing companies, such as the

case company in a partial configure-to-order mode, are often organized and opti-mized for the standard production of goods and the material flow, and making money. This mode is well described – for instance – by the value chain model of Porter (1985). However, in the new product development project, the main value chain is not material, but virtual including knowledge, information and many kinds of virtual artefacts. The physical prototype is built with material parts, but this pro-cess is very different from the standard production of launched products. So, the NPD project and prototyping (physical and virtual) are critical for time-to-market and cost, but also for knowledge creation and knowledge management.

Figure 60 is adapted by substituting the original project organisation chart with the presentation of activity system by Engeström (1987), because it is proposed that, for instance, new product development project organisations are dynamically configured around VP consisting of actors of the formal organisation. This means that, while the core business is organized, for instance, as separated departments of engineering and production in standard production mode, the new product de-velopment projects may dynamically involve people needed from those depart-ments. When we take a whole new product process as an activity system and unit of analysis, and the product as an object of activity system, we can see that the new product motivates the common activity, but the stakeholders commit their goal-directed actions partly independently causing the contradictions. Thus, such activity systems realize and reproduce themselves by generating actions and operations (Engeström, 2001). On the other hand, as Engeström (2001) proposed, it is probably more reasonable to observe these two departments as separate activity systems that share the common object, i.e. a product with different per-spectives and historicity. This approach will be elaborated in forthcoming para-graphs.

This chapter discusses how virtual prototyping is related to participatory design approaches and shared mental models. Design management philoso-phies such as Integrated Product Development (Andreasen & Hein, 1987) have succeeded in shortening lead times and reducing production cost simultaneously, increasing the need for good team communication (Badke-Schaub et al., 2007). As pointed out, for instance, by Nonaka (1994), increased cross-functional com-munication is good in principle. Communication is also an integral aspect of every activity (Engeström, 1987). However, effective communication within a cross-functional team requires (Badke-Schaub et al., 2007) a mental model that is to some extent shared between the team. Each person has his/her own dynamic viewpoint based on constraints, objectives and experience (Mahdjoub et al., 2013), and with the aid of mental models, people construct their internal working models of the world, and structure the knowledge (Badke-Schaub et al., 2007). Shared mental models are useful, for instance, when the team has to envisage future needs and use of a product. Thus, the global product behaviour perceived by the user should be seen as more important than the local problems of an indi-vidual design engineer (Ferrise et al., 2013).

Social dimension – individual people

The chapters following discuss the purpose of virtual prototyping as a communication medium from the perspectives of different roles of a product design and development activity system. Figure 61 emphasizes the proposed role and potential of VP as a node point (Leino & Pulkkinen, 2012), and virtual environment as a medium in the knowledge transformation process. In the context of HF/E and psychology, the concept of medium refers to a generic mode of influencing people and involving them into action (Norros, 2013), and it may be something more abstract than a tool. A model as a medium can be verbal, mathematical, symbolic, imagal/graphical (Hubka & Eder, 1988). The virtual environment is an effective medium, because (Norros, 2013) it can be coupled with human senses and therefore incorporated in sense making, and human eyes are well adapted to scanning visual scenes to notice a variety of cues in them (Simon, 1995). Therefore, it is also a medium for visualizing and communicating (Ma et al., 2011) abstractions and tacit knowledge.

VP based knowledge transformation mainly covers the socialization, externalization and internalization of Nonaka's (1994) paradigm, because there is typically not so much explicit to explicit combination. Nonaka did not refer to Vygotsky, but Vygotsky also emphasized the psychological process of internalization and externalization as basic processes at every level of human activity (Allen et al., 2011). The importance of the virtual environments (Ma et al., 2011) comes up specifically by enabling communication for those who are not familiar with engineering (e.g. 3D CAD) tools, e.g. for the assembly workers or customers. This was clearly visible in the case study, for instance in the sub-case where a new concept of noise cover module was introduced for customers and machine operators. Actually, the advantages of virtual environments compared to conventional methods, such as 3D CAD or 2D drawings, come from the ability to make better observations of the product model, for instance in product review meetings.

This chapter introduces the concepts and importance of artefacts and intermediary objects in an activity system. It is discussed how the features of virtual environments based virtual prototyping create value as an intermediary object, and what are the particularities of VP. Vygotsky (1978) saw that artefacts, both abstract and physical tools, are central in the activity system because they mediate and control human activities (Allen et al., 2011). The mediation can be distinguished between the primary level of mediation (tools and gestures dissociated from one another, not real psychological tools), and the secondary level of mediation by tools combined with corresponding signs or other psychological tools (Engeström, 1987). Design requires a representation framework with sufficient expressive power to capture the nature of the concepts that support the design process (Gero, 1990). Boujut and Laureillard (2002) saw the role of artefacts in supporting shared mental models among cross-functional teams. Artefacts are important intermediary objects especially in co-operative design processes (Boujut & Laureillard, 2002) with three conceptual levels: product level

(e.g. CAD model), organisational level (interface and organisational learning), and actor level (developing reflective practices). Inversely, the concept of intermediary objects, rooted in sociology, is a general category of physical (plans, mock-ups, sketches, etc.) or digital (CAD models, calculation results, etc.) artefacts produced by the participants during their work covering all kinds of externalisation (Boujut & Laureillard, 2002). Mahdjoub et al. (2013) defined intermediary objects as supports for the social interactions and communication by making the actors' cognitive implicit (tacit knowledge) frames explicit. Intermediary objects should not be seen just as the product model or the enabling technologies (Mahdjoub et al., 2013). Thus, virtual environments can be seen as intermediary objects because they are merely interfaces to product model representations, and they are not just about the technology (Kalawsky, 1993). In their case study (Mahdjoub et al., 2013), virtual environments as an intermediary object of social interactions played an extremely important role in the participatory product-use review related to automotive design.
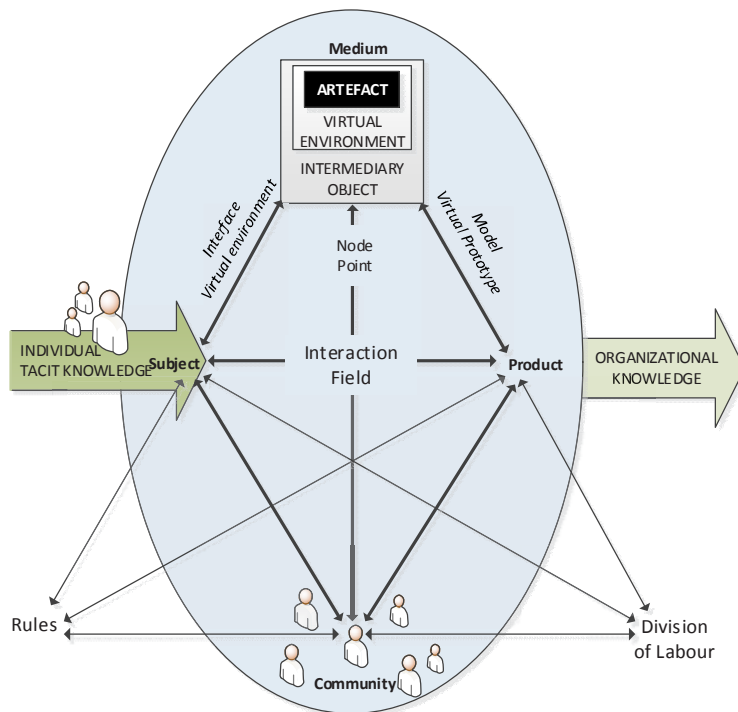
Figure 61. The role of virtual environment as an intermediary object and interface to the design artefact i.e. to the product model within an activity system where individual tacit knowledge of a person of group of persons is transformed through communication and collaboration into organisational knowledge.

The notion of mediation of Activity Theory imposes limitations within information and human-computer interaction studies, especially concerning virtual realities (Allen et al., 2011). Kaptelin (1996) has argued that in virtual realities the boundary between a tool (i.e. medium, instrument) and reality is unclear because the user is acting with the representations of objects of reality but also with a sort of reality as such. Therefore, according to Kaptelin (1996), Activity Theory should be enriched taking into account the special role of virtual realities. This is an interesting viewpoint, because the subjects of the case study were sometimes confused about whether they were discussing the object (artefact, product model) or the medium, i.e. virtual environment. In the ideal virtual reality where the user cannot distinguish virtuality from reality, it is possible to focus only on the object, but this was not possible with the present technology in the case study, nor is it possible anywhere with the technology level of today. Of course, people's consciousness can be obfuscated for instance chemically, but this is a topic of other research. However, this philosophical discussion is related to the difference between "real", "virtual", and "physical" and the different levels of interfaces as illustrated in Figure 22. It was discussed before that, in the context of design, artefacts and prototypes, the opposite of "virtual" is not "real" but "physical". However, when a person is performing in a fully immersive virtual environment, what he or she is observing is not "physical", but a virtual representation of a physical artefact, and what is seen is nonetheless "real" because it can be observed. This can be seen as a key benefit of virtual environments, namely the ability to observe virtual representations of properties of physical artefacts in a similar way to in the non-virtual world, i.e. reality.
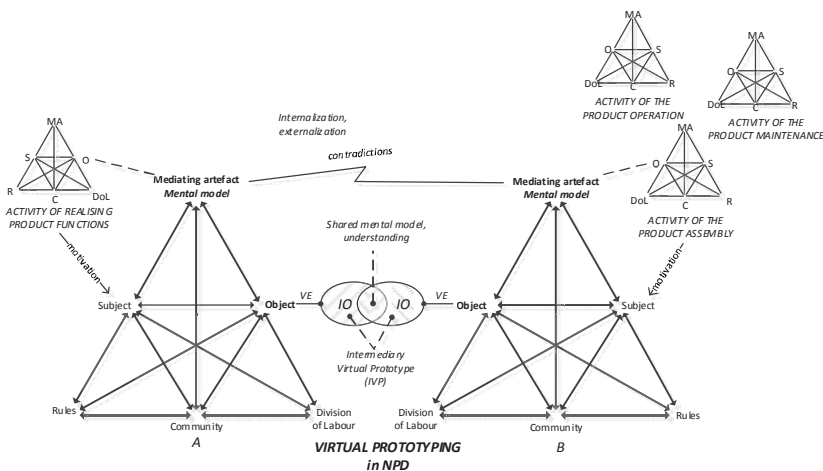
Figure 62. Exemplary activity system of Intermediary Virtual Prototyping (IVP). IVP combines the objects of two activity systems (A – engineering design, and B – product assembly) through an intermediary object that enables the shared mental model. Therefore IVP is an activity system itself. Besides the product assembly, also for instance activity systems of product operation and product maintenance can be linked through IVP.

This chapter discusses further the meaning of contradictions within a product development activity system. The new concept of "Intermediary virtual prototyping" (IVP) is introduced here. Figure 62 aims to illustrate possible contradictions between two activity systems, namely the perspectives of engineering design and product assembly. Actually, the contradictions may be caused by the different mental models (the smaller triads; activity of realising product functions, and activity of the product assembly) of designers and assembly workers. They share the same object, i.e. product, but their goals are different. They conduct actions towards reaching their goals which causes tensions inside and between the activity systems. The bigger triads (engineering designer perspective and assembly worker perspective) represent the activity systems of virtual prototyping where the shared object (product) is motivation of the activities. The intermediary virtual prototype (model of the object) enables sharing the different mental models.

The interviews of the case study revealed how subjects representing different functions and roles of the company see the object of the activity system (i.e. product) in different ways. The chief designer of a new product (e.g. the Lokotrack mobile rock crusher) perceives the whole product system, while engineering designers mainly perceive functions of their subsystem (e.g. power-train, crusher, frame, engine-module, etc.). Representatives of the production function perceive the subsystems as modules to be assembled, but suppliers might see only one component or sub-assembly without really understanding where it belongs in the whole product system and the interfaces and restrictions in production. Thus, in principle these subjects share the common motive and object (design and manufacture of a product of good quality), but their viewpoint on the product splits the higher level activity (product development) into sub-activity-systems with their slightly different motives. This split causes contradictions between the activity systems, but there are internal contradictions as well. The chief designer sees all members of the product development project as a team with a shared motive and goal, but the division of labour, i.e. the formal organisation and value network, causes contradictions between the project and functional areas of companies. On the other hand, this set-up may also be turned to strength through the "Hypertext organization" (Nonaka, 1994). The intermediary virtual prototyping supports this by providing possibilities to see the total object and motive of the activity by providing the context and actions in an early phase, which might lead to improved organisational learning. Here again is a link to the Theory of Dispositions (Olesen, 1992) and the Domain Theory (Andreasen, 1980). The former deals with the design and development process view and the latter with the maturity of object, i.e. the product description. VP helps recognizing the unwanted dispositions and contradictions earlier with different perspectives that also contribute to common learning.

This chapter discusses how the phenomenon of organisational learning and development from the perspectives of individuals and organisation activity system with the notion of "zone of proximal development". In this context, the "zone of proximal development" can be defined as "the distance between the present everyday actions of the individuals and the historically new form of the societal activity that can be collectively generated as a solution to the dou-

ble bind (i.e. social dilemma) potentially embedded in the everyday actions". This fifth principle of Activity Theory deals with the possibility of expansive transformation in activity systems. It means that, in the long run, individual participants in an activity system become provoked by the contradictions and begin to deviate from the established norms, which may escalate into deliberate collective change and development. (Engeström, 1987)

In the previous chapters it was proposed that VP could improve knowledge transfer and organisational learning. The principle of the zone of proximal development explains in greater detail the mechanism of learning and development in an activity system such as, for instance, product development organisation. Actually, learning is a necessary precondition of any development, and inversely development is a necessary ingredient of learning (Engeström, 1987). An activity is modified and enriched by a transition (learning) from internalization (individual actions and contributions) to the often delayed collective activity of externalization and objectification crystallized in a product (Engeström, 1987). In other more common words, the learning happens first in individual persons and after that it will somehow be shared within the collaborative work, for instance through intermediary virtual prototyping, and finally cumulated and made concrete in the product.

On the other hand, individual learning is a social phenomenon (Simon, 1991) including transmission of information between members and groups of the organisation. With respect to organisational learning, this transition from individual actions to common activity is essential because tacit knowledge (Nonaka, 1994) is deeply rooted in action and it is context-dependent. The development from actions to activity, i.e. the expansive generation of new activity structures, requires a mastery of double binds, i.e. social dilemmas which cannot be resolved through separate individual actions alone but only through joint co-operative actions (Engeström, 1987).

This chapter discusses further the organisational learning from the business management perspective in relation to Activity Theory. In the Dynamic Theory of Organizational Knowledge Creation, this kind of dialogue between individual and organisation (ontological dimension) and between internalization and externalization (epistemological dimension) is present as well, but (Nonaka, 1994) also talks about modes of socialization (tacit to tacit knowledge, development of ideas between individual through a common experience) and combination (explicit to explicit knowledge). Nonaka's notion of "Spiral of organizational knowledge creation" explains how the organisational knowledge creation, i.e. learning, is cumulating and amplified through the two dimensions. On the other hand, Nonaka's model stays on higher social system and practical business innovation level (although he refers, for instance, to theories of organizational culture), while Engeström delves deeper into the cognitive and psychological mechanisms (why and how) of learning in an activity system. The contradictions within and between activity systems are the reasons for change, and mitigation of the contradictions leads to expansive learning of the organisation. Nonaka formulated it less severely, and saw contradictions as opportunities for people to reconsider their thinking. He also refers to the "double-loop learning" of Argyris and Schön (1978), i.e. ques-

tioning and reconstruction of existing perspectives in organisational learning, and states that this kind of mechanism is built into the knowledge creation model. However, both Nonaka and Engeström emphasize the dynamic and collective social interaction between individuals and the organisation, as well as the common objects, models and metaphors with different experiences and viewpoints in order to recognize contradictions in learning and knowledge creation. Individuals create the knowledge (Nonaka, 1994) and are the co-producers of social development, but they are also producers of their own development (Engeström, 1987).

On the individual level the 'push-pull' process of (Gero & Kannengiesser, 2004) represents the interaction of designer (or other actors) with both its external environment (by interpretation driven by the sensed data) and its internal environment (pulled from constructive memory). This interaction also means that interpretation may be biased to match the current expectations, and that the interpretation may impact on the construction of memories. This is interesting if we reflect the push-pull process with organisational learning and the dialogue between knowledge modes of Nonaka. VP as a shared interaction field can reduce the risk of accumulation of biased interpretation to organisational learning capital. However, the organisational learning needs to be motivated and enabled by establishing the dialogue between tacit and explicit knowledge somehow, thus (Nonaka, 1994) has proposed suitable management principles like "learning by intrusion" and "redundancy of information". It means that individuals should enter each other's' areas of operations allowing people to provide new information from new and different perspectives. Based on the case results VP and virtual design review meeting creates value for this process.

Boujut and Laureillard (2002) saw the potential of an intermediary artefact-aided co-operative product – process development in organisational learning through experiencing and trial-error process on a common ground, and the created knowledge actually as an interface between the product and co-operative process. This approach is common with the Theory of Expansive Learning so that the actions (trial-error experiences/ process) are transferred to the activity system (knowledge) and crystalized in the product (object of the activity). Then VP can support organisational learning by providing a common ground for co-operative experiences. Consequently, if a virtual prototype and virtual environment is a means for co-operation, it is also a means for knowledge creation, and an interface between actors and the product model.

This chapter discusses the challenge of value co-creation, and the value of intermediary virtual prototyping (IVP) for co-creation, and design for human factors and ergonomics. Innovations could be boosted (Mahdjoub et al., 2013) by considering and designing more product use value, and also taking widely into account stakeholders such as ergonomists, sociologists, marketing. Co-creation (or co-configuration as Engeström [2004] named) offers potentially radical strategic advantages. Product use is defined throughout the design of the product requiring interaction between the user, the product and the use context, while convergence between actors and dimensions can be built through social interactions around intermediary objects concerning problem formulation, test-

ing/selecting design alternatives, and evaluation of design (Mahdjoub et al., 2013). However it is a very demanding because successful co-creation that requires dialogue and real-time feedback from the stakeholders as well as new tools, rules and infrastructures (Engeström, 2004).

Based on the case study analysis, VP can add value to co-creation by enabling the social involvement of many stakeholders and their perspectives. Additionally, virtual environments enable interaction between the user, the product and the use context, providing the intermediary object as well. VE base product reviews are fields for dialogue and real-time feedback from all stakeholders. The role of the product model is being changed from information description to medium for the communication between engineers (Horváth & Rudas, 2009). Involving stakeholders such as customers and suppliers in the design process, and sharing tacit knowledge between them through co-experience and creative dialogue is critical in creating relevant product knowledge (Nonaka, 1994). From the expansive learning perspective (Engeström, 2004), an object of co-creation should be studied from its lifecycle and social perspective involving the stakeholders in dialogues and negotiations, and organising the possibilities for stakeholders to construct new shared models, concepts and tools. In other words the co-operative activity expands the object causing the learning and knowledge creation. Therefore, the object of co-experience and dialogue is essential, not just the knowledge sharing.

Human centred design and participatory approach are design methods that can aid in revealing the dispositions described by (Olesen, 1992) in a socio-technical system, especially from human aspects. They are design approaches based on the active involvement of users (and other stakeholders) to improve the understanding of user requirements, and the iteration of design and evaluation (Mao et al., 2005), i.e. iteration of synthesis and analysis. These methods are generally recommended in HF/E discipline, yet there are unsolved methodological problems related to design thinking and the formative approach in the early design process phase (Norros, 2013). As described in the literature review, one goal of HF/E discipline is to become more design-oriented. This means involving human factors and stakeholders who represent them more into the synthesis phase instead of pure analysis. Norros (2013) saw that modelling methods, simulations or virtual techniques could be developed in order to enable experiments with the users of systems, to make implicit (tacit) knowledge explicit, and to create dialogue among disciplines and perspectives. It is natural that HF/E has been focused on analysis where the product properties are observed and evaluated. The characteristics or design properties in the synthesis phase may be too abstract for people other than designers, but as Norros proposed, virtual prototyping can be a means for improving the discussion already in an early phase.

Based on our research, the HCD method combined with appropriate virtual prototyping tools and methods enable the acquisition of feedback from several lifecycle phases already in the virtual product development phase. Virtual environments enable "on-line" knowledge transfer, but "off-line" knowledge management is also needed, enabled by PDM/PLM systems.

Conclusion on the social dimension of value

This chapter dealt with the recognized social value elements and mechanisms by categorizing them and reflecting them with existing theories in order to articulate the social value of VP with scientific concepts. The most significant areas of value contributions to people and social system are summarized here. The next chapters will explain how these areas could contribute to value in business, management, economics linked with social value and value for product design and development theories.

Engineering design is a demanding transformation process from abstract and tacit human demands to well-articulated, explicit and concrete product specifications. Models are artefacts that mediate the transformation from mental models to final product specifications. A virtual prototype is such a mediating artefact and model of the product, but a virtual environments-based virtual prototype is also an intermediary object that facilitates the interface between human senses and the model. Additionally, the transformation from mental models to concrete product specifications also requires organisational knowledge creation and transfer in an epistemological dimension (tacit–explicit) and ontological dimension (individual person – organisational groups). VP can be a metaphor and interaction field for knowledge creation and transfer. Thus, besides a description of a product, the product model is a collaboration medium as well. VP supports experience, learning by doing and on-spot-ism by also providing the product- related actions, operations and context. Therefore, VP should be seen beyond the product model as a platform for hypertext organisation which increases information redundancy in the organisation.

The Activity Theory provides for explaining the mechanisms between subjects and objects (product) in the product development and organisational context. The product is the common object of an activity system that glues the business together, and VP is an interface between mental models and the product model. However, people with different experience and biographies have different mental models and demands. This causes contradictions which are also sources of creativity, innovation and organisational learning. VP enables sharing mental models between people, and therefore expansive learning and knowledge creation by expanding the object (product) perspectives from the technical system to individual actions and even to contradictions within the total activity system and between activity systems.

VP improves value co-creation by providing improved creative dialogue among the social activity system and getting real-time feedback from the stakeholders of the whole product lifecycle. The expanded object and increased systematic dialogue enables better problem framing and therefore identification of unwanted and latent dispositions. Human/user centred design and participatory approach are iterative design methods that benefit collaborative virtual environments in particular by improved involvement of human stakeholders into the design process, and therefore an improvement in the understanding of human requirements.

The most remarkable areas of contribution to value:

- Collaborative virtual prototyping is an intermediary object that enables shared mental models, organisational learning and knowledge creation crystallized in the product and services
- VP enables expanding the object (product) of activity system (product development) improving the expansive learning and knowledge creation
- VP is also an organisational interaction field that provides for modelling the context and actions related to the product and involving widely stakeholder of the product life
- The expanded object enables revealing contradictions and latent dispositions within the product life

These conclusions are summarised as the new concept of "Intermediary virtual prototyping" (IVP). It recognises value propositions from organisational perspective. However, in order to explain VP value from the business perspective, the theoretical framework must be expanded into business management theory in the section following.

7.3 Value for business management

This chapter expands the theoretical framework into business management dimension by discussing the empirical findings and reflecting them with the models that can explain business value creation, conversion and capture in a scientific way. In this research, the business value dimension covers the resources that contribute to operative and strategic success of a company.

In the previous chapter, it was argued that designing products together with the related activity and context would provide a competitive edge, and that involvement of all stakeholders in the design process may improve this approach. It was also proposed that HF/E methods such as HCD/UCD and participative approaches make this approach more systematic. However, it was pointed out (Norros, 2013) that HF/E discipline should be piloted more towards design thinking from the current focus on understanding the nature of present systems. Furthermore, Norros (2013) anticipated that modelling methods and virtual techniques could enable this approach. In the previous chapters, the results of the case study were reflected with the theories of HF/E literature and reasoned the advantages of combination VP and participative approach on the individual and organisational dimensions. It was concluded that, from the social viewpoint, a virtual prototype is an intermediary object for sharing mental models, and IVP is a interaction field that enables expanding the design object, i.e. product scope, thus improving organisational learning and knowledge creation.

These contributions are the starting point for discussing value in the dimension of business and management. The business dimension means taking into account largely the activity that is carried out in order to provide goods or services in exchange for money. Management practice is largely dealing with decision making,

including all activity that supports decision making, e.g. communications and negotiations (Nicolai & Seidl, 2010). As reasoned in the previous chapters, virtual prototyping can be considered as an intermediary object and interaction field that supports knowledge transfer and creation. Knowledge is naturally important in the decision making situation, because it affects how the decision situation is perceived and constructed, and influences what courses of action are selected (Nicolai & Seidl, 2010). However, successful new product development is a classical organisational problem in respect to gathering necessary knowledge that originates in many parts of the organisation as well as in the market and from other stakeholders (Simon, 1991).

An analysis of virtual reality research drivers in Europe (Amditis et al., 2008) targeted opportunities for process agility by extending the virtual approach to the whole product lifecycle management, multi-domain simulations and interactive experience of users and engineers during product development. For that purpose Activity Theory recognizes activities, actions and operations as part of a wider network of activity systems, taking account of human perspectives and dynamic changes of the system (Allen et al., 2011), which guided towards modelling VP in a business context. However, the classical economic theory of the firm does not distinguish between organisational goal and individual goal, but in real life this is not the case (Simon, 1964) when we are interested in the internal structure of an organisation. The different goals are related to the values of different stakeholders. In the chapters following, the position of IVP is discussed in a business and management context from the perspectives of individuals and organisations, and the mechanism of value creation and capture are reflected with models and theories from the literature.

Modelling the value configurations

This chapter introduces value configuration models which enable position virtual prototyping in the context of business organisations and processes. Furthermore, the IVP value creation, conversion, and capture is described by use of the value configuration models. Besides the sequential value chain model (Porter, 1985), business organisations can be modelled as value shops where value is created by mobilizing resources for resolving a problem, and the value network models that create value by facilitating a network relationship using a mediating technology (Stabell & Fjeldstad, 1998). Indeed, value is not embedded in the technology or service, but value is created in using them and adding the capabilities of human resources (Grönroos, 2008).

Firstly, IVP is analysed using the value chain model of Porter, because it is a well-known framework for structuring the business and economic value creation of a manufacturing company. The original value chain model is highly focused on material flow and cost cutting within the functions and networks of a value chain. However, the later "Shared Value" model (Porter & Kramer, 2011) contrarily emphasizes the importance of social benefits and capabilities, understanding customers, creating value for all stakeholders and their non-material contributions to

value creation and improved productivity. Thus, this notion is a clear link to the social value dimension of IVP. According to Porter and Kramer (2011), few companies have gained the full productivity benefits in these areas, and few companies really understand deeply the essence of productivity, merely focusing on short-term profits and cost-cutting. In a similar way, the original Lean thinking (Womack et al., 1991) was focused on eliminating non-value adding tasks from the material flow, but later it has also been applied in non-material flows for instance in Lean product development (Haque & James-moore, 2004), (Grieves, 2005), (Hines et al., 2006), (Morgan & Liker, 2006). In the case company, the internal productization is an example of an organisational function that does not directly generate money, but which contributes to productivity by reducing time-to-market, production cost and sharing product knowledge (Leikko, 2012). This fits very well with the Lean product development principle. It was previously discussed how IVP could boost this function and therefore contribute to the increased productivity of a manufacturing company.

On the other hand, industrial companies seem often to have difficulties in understanding how virtual prototyping, and especially virtual environments and virtual reality techniques, could contribute to economic value, and where it belongs in a business context. Apparently, it is not clear (Leino et al., 2013) whether they should be considered just as another engineering tool, or what? The value chain model of Porter (1985) helps position IVP in the context of business systems (Figure 63). It does not belong to the primary material value chain, but is rather a supportive process with a different logic that combines human resources, organisational functions, technology and the infrastructure of a company or enterprise network.

On the other hand, it also has an impact on organizations, roles, technology and infrastructure. Therefore, it should be seen as a strategic asset that significantly contributes to value creation, but is simultaneously a remarkable investment when adopted in business. It is a remarkable investment also because it is fairly expensive when all the changes to business enterprise are taken into account, including organisational, processes, and information management. However, in that way IVP may become a rare asset and competitive edge for manufacturing companies. These aspects will be discussed further in the chapters following.
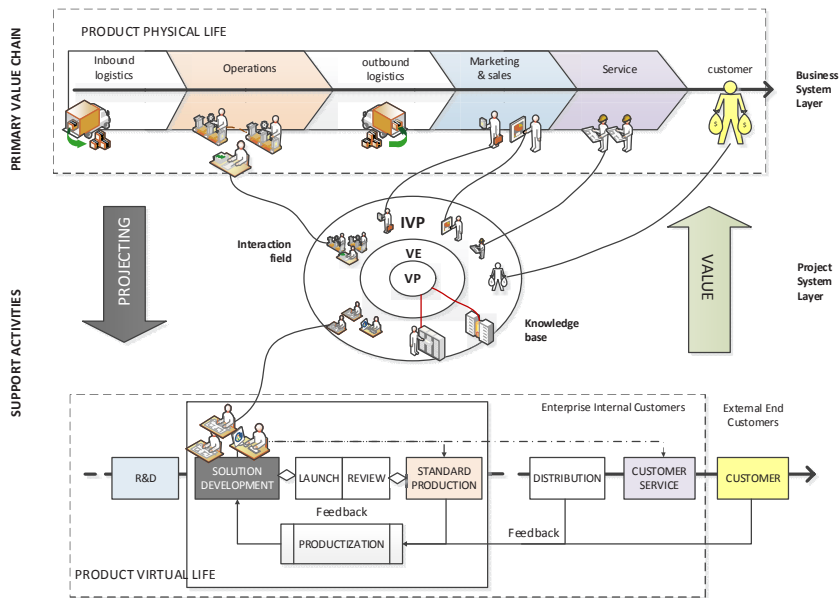
Figure 63. Intermediary virtual prototyping (IVP) is positioned in Porter's value chain model and case company's product process as a technology asset that provides the interaction field for knowledge creation.

IVP supports the primary physical value chain e.g. by better problem solving capabilities already in a product virtual life phase. The discussion between problem solving in product development project system and the formal organisation can be referred to the hypertext organisation of Nonaka (1994), while the people and infrastructure (e.g. PLM systems) constitute the knowledge base of the company as a hypertext organisation. Intermediary virtual prototyping provides the interaction field for the discussion and knowledge creation. The interaction field involves stakeholders from several organisational functions, levels and product lifecycle stages. In this context, stakeholders refer[13] to everyone interested or concerned in the product during its lifecycle.

In the case study, stakeholders included, for instance, representatives of engineering design, design management, production workers, productisation, production management, maintenance service, human factors, project management, and customers. According to the Activity Theory, these stakeholders should be considered both on an individual action level (what a single person does in a specific work task) and on an organisational activity level describing the sequence of actions that jointly lead to the final outcome also at the group level. This was discussed in the previous chapter from a social perspective. In the chapters following, value creation with IVP in the social context will be discussed further.

---

[13] "A person with an interest or concern in something, especially a business." (http://www.oxforddictionaries.com)

Value network analysis provides for a systemic value capture, conversion, and creation modeling. According to the notion of value in-in-use (Grönroos, 2008) value is not embedded in goods or services, as they are value propositions, while value is really created in users' value-generating processes when goods and services are used. The value network analysis of Allee (2008) is a framework providing a systemic and dynamic approach for modelling the more detailed mechanism of value capture (turning a value proposition into real benefits that contribute to the success of the participants and their organizations), interconvert-ability, value conversion (the act of converting or transforming between financial and non-financial value), and value creation (converting assets into negotiable value). So, actual value is not exchanged, but rather resources as a value foundation and asset aiming at facilitating use value (Grönroos, 2008), thus exchange value can be assessed only after knowing whether use value has been created. The value network analysis combines business management practices where human interactions and relationships reside in one world of models and practices and business processes and transactions reside in another (Allee, 2008). The exemplary value network map in Figure 64 includes the transactions and deliverables that were recognized as enabled or improved by intermediating virtual prototype and virtual environment.
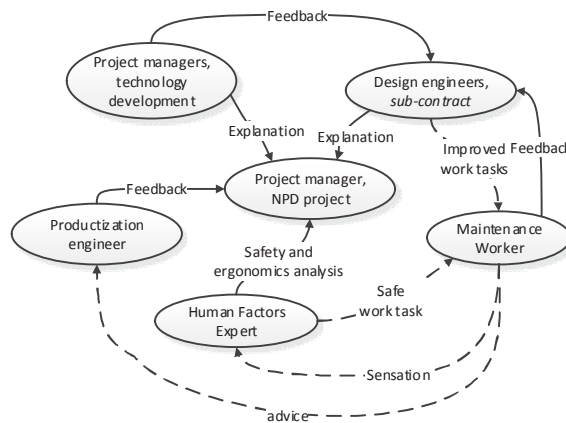
Figure 64. Value network analysis of the new generation rock crusher development and maintainability review

This chapter discusses, as an example, the value network analysis of the new generation rock crusher maintainability sub-case on an actor level. The roles of value network (Figure 64) of sub-case 2 consisted of the rock crusher new product development project manager (responsible for the NPD project budget and schedule), two technology development project managers (responsible for developing new technology concepts and solutions for new generation rock crushing equipment), design engineers (sub-contracted, detail design), productization

engineer (accounting for the internal productization including assembly and maintainability), maintenance workers (analysing and commenting feasibility of actual maintenance work tasks), and human factors expert (analysing and reporting safety and ergonomics issues).

In the Figure 64, transactions (i.e. operations or actions) are shown as solid (formal exchanges) or dotted (intangible flows of information and benefits) arrows between the roles. The arrows are labelled with deliverables, i.e. the actual things received during the transactions. The deliverables can be physical (e.g. document) or non-physical (e.g. verbal message), and tangible or intangible. A deliverable may be a piece of knowledge, expertise, advice, information, or a favour or benefit. It is helpful to explore value creation at the level of key roles (Allee, 2008) when an impact analysis shows whether a role is realizing value from the inputs it receives.

In the case study, product review project managers and design engineers gained improved understanding of realistic manual work tasks, and wider activity and context in assembly and maintenance. The knowledge of experienced maintenance workers could be communicated because the workers could utilize their experience as the interaction field provided the intermediary virtual environment, where issues could be explained easier compared to drawings or normal CAD-visualizations. Through the virtual prototype, the productization engineer received more mature design understanding which is conventionally available later in the physical prototyping phase. It is remarkable that the productisation feedback was available already in this phase of the project. Design engineers received early analysis and possibly verification of part/module interfaces and fittings without a physical prototype. This chapter discussed value on an individual actor level, but value creation and capture should be studied also on a higher enterprise level.

This chapter discusses how IVP contributes to value creation, conversion and realization on the holistic business success level. The value is discussed in the context of internal and external customers. Value creation, is the act of turning a value input proposition, either tangible of intangible, into real benefits, or assets that contribute to the success of the participants and their organization (Allee, 2008). Intangible value inputs typically include favours that keep things running smoothly. These inputs may be invisible to management, but they can also be a way to transform tacit knowledge into explicit knowledge as was described in the previous chapters. Sometimes, created value can be measured in terms of money (e.g. cost savings), but value always has an attitudinal component such as trust, affection, comfort and ease of use (Grönroos, 2008) as well. Figure 65 is an exemplary adaptation of the value creation and value capture process by (Bowman & Ambrosini, 2000). It explains the logic of IVP value creation, conversion and capture between parties of a product value chain. Finally the figure explains the position and benefits of IVP in value creation, conversion and capture by dint of a product development scenario.

The case studies were related to collaboration between product stakeholders, such as product designers, internal productization, production, maintenance organizations, and customers. Thus, the cases were dealing with internal and exter-

nal customers of the company. Product quality is justified by customer satisfaction. Therefore, both internal (q-quality) and external (Q-quality) are important (Mørup, 1993). This approach was also emphasized in the case company (Leikko, 2012), and the approach was seen as one motivation for investigating possibilities of wider utilisation of 3D data and product data in general as described in the case study section.

From the holistic business success viewpoint, it is important to see the needs of internal customers and try to ascertain how indirect cost within a NPD project can be minimized (Leikko, 2012). Therefore, in the case studies the manufacturing company (Firm B) purchased VP as a service from a service provider (VTT), see Figure 65. In this way, the value creation process can be actively supported by a service provider (Grönroos, 2008). The service provider (Firm A) provided both the technology and know-how for using VP. The service included virtual environment laboratory facilities (hardware and software), and the labour of laboratory staff. The use value of VP was captured in the form of both technological advantages and methodological facility. The use value of VP was formed by value conversions using combination of these intangible and tangible value propositions and adding the knowledge of the people of the manufacturing company. Together, they created a new value in the form of improved properties of the product as well as in the form of better resource utilization and knowledge creation as described in the previous sections. The created use value was added to a delivered product and service. Value was finally realized by a customer (Firm C) as objective value (measurable product properties and functionalities) and subjective value (improved use value), and by Firm B as increased productivity and better exchange value.

In this way, all the stakeholders benefit because designers learn about external properties required and their relations to design properties, i.e. product characteristics. Assembly or maintenance workers may influence and improve their work tasks, and contribute to HF/E design, safety and well-being. All stakeholders create value for themselves by applying their skills and knowledge when using the service provided (Grönroos, 2008).
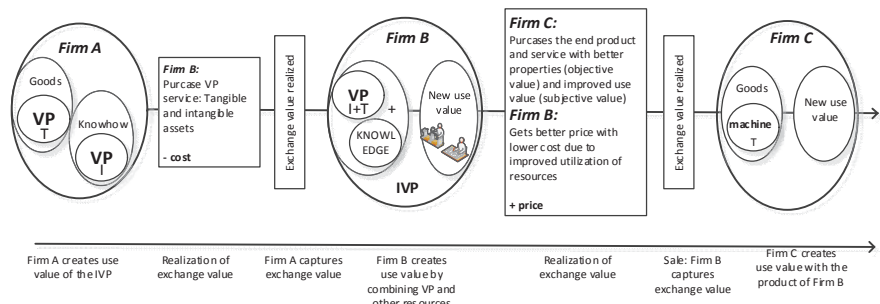
Figure 65. An exemplary schema of VP value creation and capture within a value chain (adaptation of the model of Bowman and Ambrosini, 2000). I = intangible resource, T = tangible resource, Firm A = VP service provider, Firm B = manufacturing company, Firm C = end customer of the manufacturing company.

In the value creation process, it was important to recognize both internal (functions/departments of the company) and external (end) customers. Besides the customers, who are considered to be the purchasers of products and services, it is also important to recognize the needs of end users, i.e. the operators of the product and services. Often the customer and user are different actors in business organisations. In a micro-company, the same person may own the company buy machines and operate them by himself, but in larger companies these are typically different stakeholders. Therefore, it is important to understand which product properties are valued by each stakeholder, and how they contribute to the success of the business.

Mørup (1993) discussed this distinction between end customer perceived value (Q-value), and what is perceived as necessary (q-value) efforts to establish a certain level of Q-value. Mørup's theory established a theoretical relationship between quality thinking and the Theory of Properties (Hubka & Eder, 1988), as well as a practical link between design and production in respect of quality. The Theory of Properties concerns quality as the perceived and resulting evaluation of a product's properties, when the maximal obtained quality is seen as ideal and desired value. Mørup also studied relations between quality and Domain Theory (Andreasen, 1980), i.e. system's process, function, organ, and parts characteristics. From a design methodology perspective, Mørup recommended eight elements for DFQ-efforts in a company related to strategy, organisation, methods, and quality mind-set. (Andreasen, 2011.)
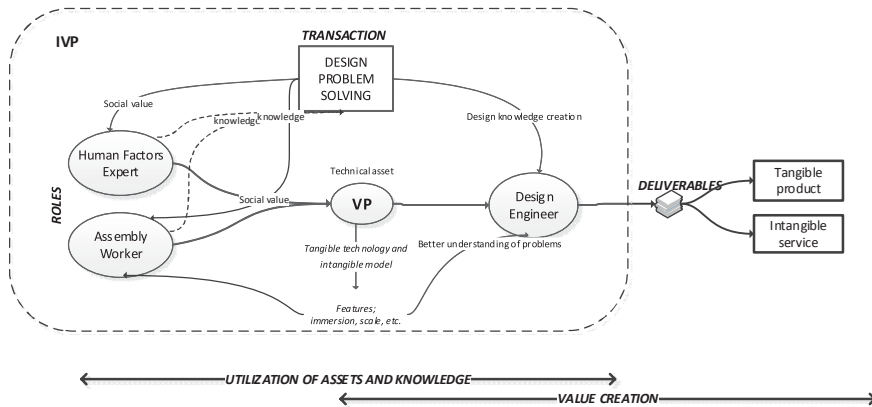
Figure 66. Simplified illustration of VP's role in value conversion transaction. VP serves as a tangible and intangible asset providing benefit as a communication medium for better understanding of design for assembly workers, and better understanding of possible problems for designers.

This chapter explains the logic of value conversion and transaction from VP as a technical asset into deliverables by an example of the new generation engine module productization sub-case. Figure 66 presents a simplified illustration of the role of intermediary virtual prototyping in value conversion and creation within product development and productisation process. It aims to illustrate the main logical chains from the technological and methodological advantages of VP to tangible deliverables. In the figure, IVP is positioned as a value proposing asset which is utilized in communication and collaboration between assembly workers, human factors experts and design engineers. For instance, assembly workers and human factors experts benefit from the technical features (perception, interaction) of IVP for instance by improved understanding of design models caused by the experience and interface of virtual environments. On the other hand, design engineers benefit from IVP because they can better understand possible problems, i.e. dispositions that exist in production. Without such communication, the medium of the virtual prototype understanding is difficult, because the representation of reality is different for designers than it is for workers due to their different mental models. So, use value is realized in the form of social value and knowledge creation, and exchange value is created in the form of improved product properties, reduced cost and increased profit. Virtual prototyping enables both an improved intermediary object, and the communication lines that were demanded by Nonaka (1994).

Business value analysis of virtual prototyping

This chapter discusses the business value of VP, based on the empirical case study findings, and the value configuration models. The findings and models are reflected with notions of business management theory, starting from resource based view to firm.

As discussed in the literature review, measuring the business value of partly intangible assets such as intermediary virtual prototyping is difficult. Any theories or models that truly enable estimation of the business value of virtual prototyping and virtual environments were not found in the literature. Instead, that analogy with models and methods for IT value estimation seemed be a helpful approach anyway. Some of those models apply a strategic resource-based view (RBV) to firms as a fundamental principle for value evaluation. This is a natural approach, because value is created when a good or service is used (Grönroos, 2008). Those models explain how resources of firms (human resources and technology) contribute to internal business value and external customer value. However, only part of the value can be quantified when the use value of an asset can only be described qualitatively. The RBV also emphasizes that when organizational resources are rare, imperfectly imitable and substitutable, they are a competitive advantage to firms.

Vehviläinen (2014) discussed the potential benefits and viability of introducing VR and AR to the case company within this research. He reasoned that those IT applications that were studied were mostly commercial (COTS) products, and, therefore, not rare or imperfectly imitable. However, if we take a broader view including also the human resources, skills and knowledge, as well as product development process innovations and product data management as the proposed notion of "Intermediary virtual prototyping", this resource can be considered rare and difficult to imitate. Moreover, Vehviläinen (2014) assumed that VR and AR technology improves profitability and decreases time-to-market creating internal value for the company, but he did not see added value for customers. This research argues, based on the wider case study that IVP has great potential also for added external customer value when the customers are involved in the product development in an early phase. Vehviläinen (2014) also concluded that adoption of such technology should be seen as a strategic decision because he envisioned the demand for further development of the utilization. In the chapters following the resource-based view to value modelling is discussed with a more practical business and management perspective.

Business management, and within that framework, product development is largely dealing with decision making with more or less high level of uncertainty. This chapter discusses how IVP contributes to management of uncertainty. According to Edwards and Jensen (2014), the literature shows that integration of HF/E gives a direct cost benefit with relatively short payback periods. However, Grote (2014) claimed that the benefit of HF/E can be really justified if it becomes part of strategic decision-making by directly contributing to the business

and competitive edge. Grote (2014) also reasoned that, on the strategic level, management of uncertainty through the HF/E approach can be such a business asset. Uncertainty means "not knowing for sure" (Grote, 2014) caused by a lack of information or ambiguity of existing information. Uncertainty is not only about finding the right information and solutions, but recognizing the significant problems. Problems do not present themselves as given but instead have to be constructed from the available knowledge at a certain point in time and context (Nonaka, 1994). Thus, management of uncertainty is connected with contradictions within and between activity systems and latent dispositions.

Design is a typical exploratory process where stakeholders learn what they can have, and what they want (Simon, 1995). This is particularly true at the "fuzzy front end" of an NPD project where the demands of stakeholders are in tacit mode and even they cannot articulate them clearly. This increases uncertainty in the process. Uncertainty impacts daily business, linking the individual well-being and organisational level performance, as well as strategic decision in companies with different degrees. For instance, daily standard production and supply management are more predictable than new product development (Grote, 2014). Intermediary virtual prototyping can enable management of uncertainty and reveal the unwanted latent dispositions by providing an interaction field for knowledge creation and recognition of problems as has been described in the previous chapters.

In the case study, it was reasoned that, for instance, a decision about a standard production ramp-up can be taken earlier, and the quality of decisions can be improved by using IVP, because feedback from production and maintenance functions can be gathered at the virtual product life stage (Figure 67). Naturally, the adoption of IVP and reduction of uncertainty cannot be achieved without cost. Therefore, the costs and benefits of reducing uncertainty should be compared to the cost and benefits of maintaining or increasing uncertainty in the organisation together with real capabilities for managing the uncertainties (Grote, 2014).
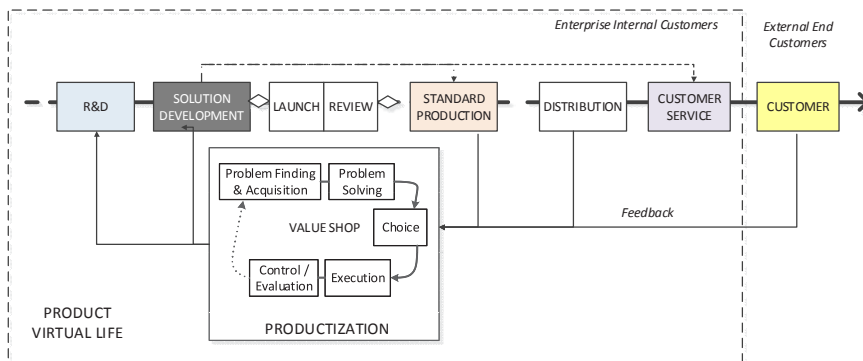
Figure 67. Value shop configuration within productization. Feedback from downstream product life can be gathered already at the virtual product life phase

Organizational knowledge creation and conversion was discussed in the previous sections from the social perspective. This chapter discusses the value, and challenge of knowledge from the business management perspective. It is also discussed how VP contributes to knowledge management.
Organisational learning is a core competence of a company (Prahalad & Hamel, 1990), and successful companies learn by using feedback from the market in order to continually improve their operations (Tushman & Reilly, 1996). Besides the market feedback, feedback from internal customers is also equally important. The learning and feedback is very much linked with knowledge management. The knowledge creation and transfer is a crucial competence for a business, because reactions to the product by internal and external customers are in a tacit form which they cannot articulate by themselves (Nonaka, 1994). It is not enough to say that an organisation "knows" something because it is very important to know where the knowledge is stored (be it in individual's head or in databases) and is it available for a specific decision point (Simon, 1991).

As discussed in the chapter 7.2, organizations need a media that enables sharing the mental models of different stakeholders (e.g. workers and designers) to communicate knowledge (Nonaka & von Krogh, 2009), and an interaction field (lines of communication) (Nonaka, 1994) which refers to methodology and processes within organizations. This is particularly important because only a share of knowledge can be managed or controlled. Actually, knowledge management should be seen rather as a process (Sveiby, 2001) than a pure IT technology and explicit information issue. In organisational memory, much of the memory is stored in human heads and a little in an explicit format in computer memories or other such media memory (Simon, 1991). For instance, the success of Japanese car manufacturers (Prahalad & Hamel, 1990) during past decades has been partly explained by oriental culture and understanding the meaning of knowledge processes in decision making and problem solving.

IVP adds value by improving organizational knowledge creation and conversion (tacit – explicit) as described in the previous chapters, because it provides both a more natural media for communicating product data content in designing enabled by the improved experience, user interface and simulation capabilities, (Leino et al., 2013), and a communication line in the form of bringing people together. The tacit knowledge is socialized when it is shared in communications, and internalized when people learn about explicit product descriptions by interacting with the product model together with other people. Furthermore, tacit knowledge can be made explicit when it is documented and stored in PDM/PLM databases. Therefore, the virtual prototype, i.e. digital model of the product system, should be linked with the information model of those IT systems. The word explicit refers to codified knowledge that can be transmitted by formal and systematic language. Tacit knowledge has a personal quality and cognitive mental model which make it difficult to formalize and communicate.

The concept of a spiral of organizational knowledge creation (Nonaka, 1994) means interactive amplification of tacit and explicit knowledge held by individuals,

organizations, and societies. The Dynamic Theory of Organizational Knowledge Creation emphasizes the joint creation of knowledge by individuals and organizations, bringing a humanistic knowledge society beyond the limitations of economic rationality. The theory also proposes a framework for organizing the management structure of companies in order to support efficient knowledge creation. This organisation management perspective is discussed below.

The challenge of coping with multi-perspective, complexity and contradictions in today's business is discussed in this chapter. IVP is proposed as a means to ease this challenge. Social systems such as business organisations are complex (Amaral & Uzzi, 2007), (Davis et al., 2014) because of many interdependent but autonomous actors i.e. human beings. In this way, also socio-technical systems, such as production systems, are complex. The activities of such social systems are becoming increasingly societal, larger, more voluminous, denser in their internal communication, causing impacts on growing numbers of people in increasingly interdependent, complex networks exceeding their formal affiliation (Engeström, 1987). Human rationality is very limited with the complexities of organizational life (Simon, 1991).

In the reality of increasing internal complexity and interconnectedness with high volumes of production, especially intensive changes or acute disturbances cause situations where no one, including managers, actually quite masters the work activity as a whole, i.e. there are grey zones where actions may have unexpected effects (Engeström, 1987). In actual organizations, the decision-making mechanism is loosely coupled and partially decentralized which makes organisational goals complex (Simon, 1964). The complex nature of such systems may result in the problems occurring being typically (Norros, 2013) many faceted and requiring a diversity of views. Thus, the literature points out that taking the stakeholders of product life with various perspectives more widely into account could radically boost both product and process innovations. However, designing such activity systems needs to address issues on many levels of complexity (Edwards & Jensen, 2014). It is also a fact that an optimum design synthesis does not exist nor criteria where needs and desires of all stakeholders are evaluated or fulfilled, but the design process is about evaluation against discrete criteria, changing the design and criteria and making trade-offs until the design is good enough (Simon, 1995).

Contradictions within these activity systems are inevitably caused by the market demands for high quality, flexibility, variability, and short time delivery products requiring complex manufacture systems which should simultaneously be very cost-efficient (Engeström, 1987). Also, information complexity is growing and virtual environments as user interfaces have been proposed as a means for coping with this challenge (Amditis et al., 2008). The technological, economic, and organizational complexity of the production process seems to be absolutely overwhelming for an individual, and therefore it is difficult to master the total work activity where he/she performs only comparatively minor subordinated actions (Engeström, 1987). However, as a system, the organization could strive to preserve rationality in the face of individual limitations (Nonaka & von Krogh, 2009).

Intermediary virtual prototyping is proposed to make possible the study of the total work activity system by providing an improved communication platform and intermediary object for interaction between the human, the product, the action and activity and the context. However, the form of organisational complexity depends on the nature of certain business. This is discussed in the chapter below.

This chapter discusses the importance of organizational learning in relation to the dominant design and production paradigms within the dynamic business environment. It is proposed that IVP contributes especially to the strategy where flexibility of product development and production is important. To gain mastery of the whole work activity requires an expansive shift from single action orientation to activity taking into account the possible contradiction within the transformation. This expansive shift requires learning activity (Engeström, 1987), which is particularly important because the ongoing industrial transformation of production paradigms from old-time handicraft to mass production, process enhancement, mass customization and present co-configuration also requires a change in the knowledge and learning types needed (Engeström, 2004) due to increasing dynamics and the changing needs of the stakeholders. The mass production and process enhancement are targeted to improving competitiveness primarily in terms of the price and performance of end products which, in turn, may cause erosion of core competencies (Prahalad & Hamel, 1990). For instance, outsourcing can provide a shortcut to a more competitive product, but it may also lead to loosing important product knowledge that cannot be rented in (Prahalad & Hamel, 1990).

From a social perspective, there are production strategies that aim to remove or at least reduce the number of humans in factories (e.g. robotization), and on the other hand strategies that are built on human skills and knowledge. The latter emphasizes the flexible response to changing market demands and requirements, innovation and learning capability, creativity and production knowledge of people (Engeström, 1987). Different competencies, strategies, structures, cultures and leadership skills are needed in different dominant design situations, e.g. when competition is based on product variation or efficiency and cost (Tushman & Reilly, 1996).

From this perspective, intermediary virtual prototyping seems be a means for improving the competitive edge in the market where product variation and flexibility is important, as in the case company and widely in Finnish manufacturing industry. However, in addition to product flexibility in the design process also allows utilization of new knowledge concerning the whole product lifecycle (Simon, 1995). Added value of IVP is derived from an opportunity to involve human stakeholders and expand the design object from a technical system and single actions (tasks) to a total activity system including the product context and lifecycle. This also means a difference between focus on the individual to collaborative and participatory design. Additionally, virtual prototyping enables making the mistakes and learning with immaterial prototypes compared to trial and errors in the conventional physical value chain. There IVP facilitates the human interventions needed for the designed product in hand. Nonaka (1994) highlighted the importance of personal

bodily experience, which he also called "on-spot-ism", compared to pure objective conceptualization and knowledge of rationality. These two distinct aspects can be also considered as different approaches to investigating the contradictions and dispositions within the activity system. For instance, the Design for X-methods, see e.g. Andreasen (2011), can be seen as objective and rational approaches whereas IVP represents the "on-spot-ims" approach. Competencies are enhanced, as they are applied and shared and inversely for instance knowledge fades if it is not used (Prahalad & Hamel, 1990). The chapter following discusses further the role of IVP in competence management.

Core competences enable differentiation of companies in the market place, and success of business in the long term. This chapter discusses how IVP enables innovations and the mobilization of core competencies. In the short run, a company's competitiveness derives from the price and performance of current products, but in the long run, competitiveness depends on an ability to build the core competences (Prahalad & Hamel, 1990) quickly at a lower cost than the competitors. For instance, the capability of creating relevant organisational knowledge is the strategic core competence of a company, which is built on communication, involvement and the deep commitment of people and functions on many levels of the organisation (Nonaka, 1994).

The key to understanding the knowledge economy lies in understanding intangibles such as knowledge as assets, and how they are set into motion in unique configurations of relationships, interactions, and resources in value conversion networks (Allee, 2008). Thus, people are precious assets of companies, and individual people should be seen as competence carriers (Prahalad & Hamel, 1990). Therefore, for instance, contradictions of product development organisation should be studied both on the levels of individual action, and total activity system.

Ability to design and package more complicated product functions implemented with mechatronics (mechanics, hydraulics, and electronics) to small spaces quickly and reliably is an example of a core competence of the case company. This competence is crucial because the mobile rock crushing units are transported on truck trailers on highways, and the main dimensions of the machine are limited. The demand for new complicated functions comes e.g. from changing engine emission legislation, and environmental trends. On the other hand, the high density of mechatronic components and devices in small spaces causes challenges for assembly and maintenance work. Thus, it is a core competence to cope effectively with these challenges. Based on the benefits of IVP that have been discussed in the previous chapters, it proposed to contribute to the mobilization of core competences by a better involvement of necessary stakeholders.

The organizational ambidexterity hypothesis of Tushman and Reilly (1996) suggests that successful organizations achieve a balance between being efficient in running today's business, while being adaptive to changes in their environment, ensuring that they also survive in the future (Nonaka & von Krogh, 2009). However, many companies have problems with their business because they view value creation narrowly, optimizing short-term financial performance and ignoring the most important customer needs and broader influences that determine their long-

term success (Porter & Kramer, 2011). Intermediary virtual prototyping could support this balancing between short-term efficiency and long-term success for instance by cutting the cost of physical prototypes and engineering changes, and simultaneously add more value capitalizing on the core competence by providing an interaction field for organisational knowledge creation.

IVP improves future innovation management and creativity, because more ideas can be tested in early NPD phase. The terms "innovation" and "creativity" are suffering from hype and inflation, because they are often used wrongly, and often as synonyms. If the definition of Alves et al. (2007) is used, the terms make sense in the context of this research. They consider creativity as idea generation while innovation means a transformation process of new ideas into new products or services. This innovation process can be divided into stages of a) fuzzy front end, b) new product development, and c) commercialization. Thus, innovations can be managed and IVP can boost this process as has been described above. On the other hand, IVP itself is a core competence, because core competence is also about the organisation of work and the delivery of value (Prahalad & Hamel, 1990).

Conclusion on value for business and management

In the chapter that discussed social value, it was concluded that a virtual prototype is an intermediary object for sharing mental models and that IVP is an interaction field that enables expanding the design object thus improving organisational learning and knowledge creation. These contributions were a starting point for discussing value in the dimension of business and management.

The literature pointed out that the value of many-faceted technology such as IT may be analysed by adopting the resource-based view of the firm. In that approach, value is created by utilization of human and technological resources, and the value has always both use value and exchange value components. The value-in-use approach proposes that value is not embedded in the intermediary virtual prototyping technology or service itself, but value is created when it is used and combined with the skills and knowledge of the users. Therefore, it is also important to understand where IVP can be used in order to create value. Part of the created value can be estimated as exchange (monetary) value in the short term, but the whole value is beyond analytical and factual measures, having multiple qualitative dimensions. Thus, IVP should be considered as a strategic investment that will produce income in the long run. The mechanisms of value creation, conversion and capture were analysed using value configuration models. They helped reflect the empirical case data and explain how, for instance, knowledge can be transferred to exchange value.

Good integration of HF/E and a participatory approach could be a strategic competitive edge for companies facilitated by IVP. Intermediary virtual prototyping can enable powerful decision-making, management of uncertainty and revealing the contradictions and unwanted latent dispositions by providing an interaction field for knowledge creation and recognition of problems, as was explained in the

"social value" chapter. IVP provides for getting feedback from internal and external customers by enabling the transfer of tacit knowledge to organisational learning which is a core competence of a company.

The social systems such as product development organisations are increasingly complex, causing situations where grey zones of management may occur without a holistic view of the contradictions of the activity system. Getting a grasp on the total activity system requires an expansive shift from single actions to activity orientation. This shift requires organisational learning, which is particularly important in a world of changing production paradigms. The participatory co-creation paradigm adds value to product development, simultaneously increasing the complexity. In the dynamic market with changing demands, the flexible variant production paradigm is competitive, but even more complex with management of changes in the social networked system. A strategy that builds on human knowledge and creativity seems to fit the variant production paradigm. From this perspective, and based on the experiences in the case study, IVP seems to be a means for improving the competitive edge by providing an opportunity to involve human stakeholders in the early product design and development phase, and to expand the design object from a technical system and single actions to a total activity system including the product context and lifecycle. Additionally, IVP enables making the mistakes and learning with immaterial prototypes compared to trial and error in conventional physical value chain, which reduces the cost of physical prototyping. The most potential business impact of generic virtual engineering consists of holistic management of product development and product data with up-front product validation and quality (Ovtcharova, 2010).

In the knowledge economy, it is crucial to understanding how the knowledge as a core competence and people as competence carriers can be mobilized. In the short run, a company's competitiveness derives from the price and performance of current products, but in the long run competitiveness depends on an ability to build the core competences. IVP could contribute in balancing between everyday businesses and maintaining or increasing future flexibility and core competences by facilitating knowledge creation.

Unfortunately, these above-mentioned advantages and value propositions can hardly be reached without impacts on many areas of the business, namely processes, organizational structures, management, technology. These impacts will be discussed in the next chapter. The most significant conclusions about IVP value for business and management:

- *Value is created when IVP is used and combined with the skills and knowledge of its users in product design and development*, but only part of it can be estimated as monetary exchange value, e.g. decreased cost.
- IVP enables *balancing* the daily performance and long term core *competence* by contributing to knowledge creation in the company
- IVP contributes to improved *decision making, management of uncertainty* and *revealing the contradictions and latent dispositions*
- *Early feedback* from internal and external customers, thus shorter *time-to-market*

- IVP contributes to the *co-creation and variant production paradigms* by in-volving human creativity in an early product design and development phase, thus increasing the flexibility
- IVP should be considered as a *strategic investment* that will produce in-come in the long run

The previous chapters 7.1–7.3 have been discussing the value of IVP based on the empirical case study findings, and by reflecting them with the theoretical framework in the dimensions of product design and development, social aspects, and business management. The fourth dimension, namely technical features of VP were discussed in the chapter 4 and 6. However, it was understood, that the value propositions require investment, as was stated in the last bullet above. The next chapters will discuss how IVP impacts the company.

7.4 Impact on the company – prerequisites for realizing the potential value of VP

This chapter discusses the impact of VP on the company. The impact means the prerequisites that need to be established for realizing the potential value of VP. First, the impacts are discussed on a general level, and reflected with the litera-ture. Later, the more detail findings from the case study are discussed in the di-mensions of processes, people and technology. These are the main dimensions of common generic PLM models. Thus, it is also recommended that IVP should be considered as part of company's PLM model and architecture.

It is tempting to believe that new technologies are solutions to any given problem. Even though virtual environments is not a new thing anymore as it has been stud-ied since the 1960s, it is still a piece of technology that people easily get excited about, and start imaging all the potential it offers. However, it would be an inflated conclusion that the observed and discussed benefits and value of intermediary virtual prototyping can be gained without compensation. On the other hand, as discussed in the previous chapter, in order to create value a good or service has to be put into activity of consumption and managed by the users (Grönroos, 2008). Therefore, when evaluating a potential investment in a new technology, potential disadvantages should be considered at least as carefully as potential advantages (Fox, 2008). Furthermore, it is important to begin from the needs where this tech-nology would be applied and define the requirements for the system (Kalawsky, 1993). According to Rehfeld (2010), the initiatives for introducing VR is mostly driven by design and engineering departments ignoring the needs of product crea-tion process and the IT infrastructure, but some visionary industry leaders have realized that virtual prototyping must be fully integrated into the PLM backbone and processes in order to achieve good return on the investment.

The case study revealed that, besides the benefits and value for design, people and business, implementation of virtual environments-based virtual prototyping also causes other types of effects in a company. As Zimmermann (2008) noted in his study of the automotive industry, the success of virtual reality-aided design requires both technical and organizational prerequisites including skilled employees and committed users and managers. Zimmermann (2008) continued that, in order to enable virtual reality technology as a productive tool besides VR technology, data acquisition and management, change management, system interfaces and usability are also important factors. Also, Ovtcharova (2010) argued that generally speaking, "virtual engineering" or any IT system cannot lead to a significant improvement as such when put to existing processes. Ovtcharova concluded that the idea of virtual engineering should refer to a range of scientific, technological, organisational and business activities using advanced information management, and for instance immersive visualisation and "human-machine-human" approach.

The research for this thesis can confirm these conclusions surely. In some cases, investments in companies in their own virtual environments facilities have been come-downs because they have not been integrated into the business processes (Aromaa et al., 2012). Aromaa et al. (2013) proposed a "virtual prototyping implementation maturity model (VIRMA)" that could be a decent framework for systematic evaluation of companies' preconditions and development targets for IVP implementation. The model was developed in case studies with two other large Finnish manufacturing companies.

This chapter discusses the importance of balancing positive and negative factors of a new technology. However, typically hype about new ICT technology almost ignores factors such as the additional hardware and training required, that enables the claimed positive effects, but which also incurs new costs (Fox, 2013b). The adoption of IVP is proposed to increase the potential for creativity, innovation and productivity by improved communication and collaboration. However, it will also impact processes, people and organisation besides the technology. This kind of change will raise management challenges and, therefore, companies must accept their overhead cost (Alves et al., 2007). Consequently, investment evaluations need to be balanced by making explicit an assessment of these positive and negative factors (Fox, 2008).

Planning of investments for a new technology includes a lot of uncertainty. Effective management of uncertainty should entail a comprehensive consideration of costs and benefits for reducing, maintaining and increasing uncertainty (Grote, 2014). Maintaining the status quo may reduce uncertainty to some extent, while for instance adoption of a new technology such as VP may simultaneously increase uncertainty but bring some benefits as well. Additionally, a new technology should be evaluated in the context of organizational strategy, because without being aligned to strategy, positive effects will probably not be gained (Fox, 2013b). Instead of the peripheral actions of the micro context (e.g. technical user interface), ICT should be studied within a macro context including the interaction within the whole activity system (Allen et al., 2011). This approach was also discussed

interestingly by Putkonen (2010) with the notions of microergonomics and macroergonomics in the product development process and work system context.

Major causes of underperformance or rejection of new technology are putting them into existing business processes and organisation devoid of understanding that the benefits are commonly leveraged through organisation change rather than the technology's functionality (Doherty, 2014). On the other hand, since organisations can be considered to be complex systems, change or intervention in one part of the system might affect other aspects of the system as well (Davis et al., 2014).

Changes in organisations may go through evolution, i.e. incremental steps, or sometimes through a revolution. In the long run, evolutionary change is not enough in order to sustain success, and sometimes even destruction of existing structures and processes are needed for instance in the case of implementing totally new technologies (Tushman & Reilly, 1996). For instance, Ovtcharova (2010) reasoned that generally good adoption of virtual engineering (including virtual reality technology) causes redefinition of the overall product development process, and integration of information systems, tools, the network of processes and the whole product lifecycle view.

The observations and discussions within the case study can confirm these statements in the literature. There are these kinds of general statements in the literature, and even some specific examples of how e.g. integration of VR and product data management can be arranged. However, these aspect of VP or virtual engineering generally are company-specific, and the case study of this research aims to reveal some concrete findings about how VP impacts or will impact the company and business when it is fully adopted. Some changes have already been made, some aspects need further research and development in the ongoing and future projects. The chapters following aim to clarify these findings.

Firstly, when the focus of virtual prototyping expanded from the first technology demonstrations into real new product development projects it was understood that it would have a wide impact on processes, organisations and technology infrastructure such as product data management. Small gains can be achieved locally through incremental steps, but the major benefits can be achieved only when the product life and business is regarded as a whole. This can be considered as a systemic and revolutionary paradigm change.

The most remarkable change, based on the observations, is the way of organising and managing new product development projects and digital data and information as well as product knowledge between organisational functions and product life stages. They must be genuinely and systematically integrated and concurrent, involving all stakeholders from engineering designers to factory and maintenance workers and from product managers and project managers to human factors experts and marketing. The limited case studies prove this approach to be valuable, but when IVP is implemented and scaled to an everyday paradigm it will cause changes that will be further discussed in the chapters following.

This chapter discusses the challenge of building IVP as a core competence of the firm, from the organisational design perspective. As discussed in the previous chapter, the intermediary virtual prototyping contributes to value

creation as part of knowledge creation, which is a core competence of companies. On the other hand, it can be seen that IVP itself is a knowledge-intensive asset and a core competence. It is a complex system.

Core competences are complex systems that cannot be easily copied by competitors (Prahalad & Hamel, 1990). Building and maintaining core competences require developing a systematic and companywide strategic architecture and implementation plan including resource allocation, culture change and commitment, management and leadership. Kimpimäki (2014) has proposed such a business leadership approach and the main elements of an enterprise architecture including the levels of business, information systems and technology. That kind of reference model would be a good framework for implementing IVP systematically so that it takes into account business demands instantly.

Directors and managers are the architects of the organisations, meaning that they are responsible for designing their units to best fit the strategy (Tushman & Reilly, 1996). Therefore, managers have to first understand the potential advantages and value of IVP, and then establish programmes in order to implement IVP systematically on every level and dimension of enterprise architecture. On the other hand, according to Grote (2014), new technology can be considered either a predictable causal agent that produces planned and managed impacts to organizations, or an unpredictable agent when systematic interventions are not possible. In the latter case, responsibility for effects cannot be assigned and no one has really overall picture of the impact. However, this should not relieve anyone of responsibility but quite the contrary makes everybody responsible (Grote, 2014).

When observing the intervention of a new technology as a holistic combination of it in an organisation and culture, it holds a certain kind of spirit that is manifested (Grote, 2014) by the system features, how they are named and presented, how it is introduced and instructed. This spirit has an influence on how the technology will actually be used in the organisation. Leino and Pulkkinen (2012) described a preliminary PLM framework model within the case study that explains how bidirectional product lifecycle communication, collaboration and knowledge sharing can be enhanced by the utilization of virtual environments and virtual prototyping. Although VP techniques have already proved their usefulness, there are still many challenges and areas to be further developed.

Findings and conclusion of impacts from the case study

The chapters following discuss and conclude how IVP did change, or will change the case company when it is implemented extensively. The impact is discussed in the dimensions of processes, people, and technology.

The new successful manufacturing paradigm is oriented to the optimization and value creation of products during their whole life, and this success is mainly based on high diversity and skilled personnel at all business levels (Westkämper, 2007). The previous chapter has explained how IVP contributes to the product lifecycle, and especially to involving people from all stages of product life and from different

segments of business organisations. However, the capture of the proposed IVP value also demands many kinds of preconditions and prerequisites in the organisation. Therefore, IVP impacts (Figure 68) companies in the form of process, organisation and technical infrastructure development as the major dimensions of a generic PLM model.

During the case study, it was concluded in the case company that virtual prototyping as a methodology and virtual reality as a technology must be seen as part of their PLM model and architecture, because they are the framework for managing virtual product processes and digital information. Also, Rehfeld (2010) concluded from their research on the automotive industry that a growing demand for visual simulation and progress of PLM systems drives the firms towards rethinking product processes and making functional and visual simulations integral parts of the PLM strategy. It is also important to ponder when the digital and physical worlds meet, i.e. how the product system can be designed more widely on the virtual side. Therefore, IVP should be integrated on the dimensions of processes, technology and data management and, people and organisation when scaled and implemented in full scale as part of businesses. It was anticipated that implementing such a change in the organisation will also require good leadership, educating people, culture change and justification of the advantages beyond status quo[14].
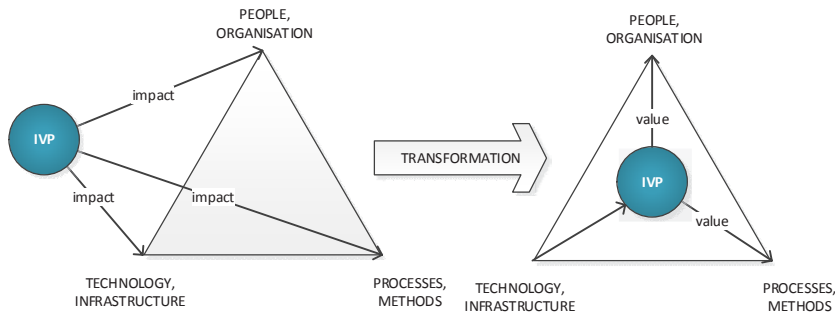
Figure 68. Adoption of IVP impacts PLM model in the dimensions of people, technology and process.

Activities, such as product development, are open systems, which means that, when the firm adopts a new element from outside (for instance IVP), this often leads to a secondary contradiction where some old element (for example, the rules or the division of labour) collides with the new element (Engeström, 2001). Figure 68 is a simplified illustration of how IVP firstly disturbs and impacts the dimensions of people, processes and technology. The value will be created in the

---

[14] The existing state of affairs, especially regarding social or political issues (www.oxforddictionaries.com)

long run when the contradictions have led to the new kind of activity system. This kind of technological contradiction generates disturbances, but is also an innovative attempt to change the activity (Engeström, 2001).

The Cultural Historical Activity Theory (Vygotsky, 1978) and Theory of Expansive Learning (Engeström, 1987) were utilized in explaining the proposed value of intermediary virtual prototyping in a social and organisational context. Identification of activity systems and contradictions within the systems have also been utilized successfully in the implementation and analysis of information systems in large organisations leading to expansive learning and more advanced activity systems (Allen et al., 2013). The concept of activity enables an analysis of the role of technology on the level of individuals as well as groups in organisations within one united system (Norros, 2013). Based on this research, it can be recommended that future implementation of IVP would be supported by activity theory approach.

Organisational learning and knowledge management were reasoned to be the core competences (Prahalad & Hamel, 1990) of companies. Therefore, it is reasonable to consider these aspects as part of the PLM concept as well. (Ameri & Dutta, 2005) saw PLM as a knowledge management system, which improves the learning capacity of the organization and consequently increases the rate of knowledge accumulation in the corporate knowledge base. The Dynamic Theory of Organizational Knowledge Creation by Nonaka (1994) was also supported by the work of Ameri and Dutta (2005) and Newman[15]. They see that the four knowledge conversion modes (socialization, combination, externalization, internalization) can be supported by PLM. However, existing and reported PLM models are usually thin (focused on items and drawings) and/or high level without real reference to practice (Leino & Riitahuhta, 2012).

Based on the experience in the case study, and also a wider discussion with industry, knowledge management is a popular topic but also quite an abstract concept. On the other hand, the observations of the case study show that the knowledge system in the company is constituted from personal tacit knowledge and common explicit knowledge that can be stored and shared in databases and files, such as EDM/PLM systems. However, as the tacit knowledge is dependent on the personal mental model, the explicit knowledge in databases is dependent on the information model, i.e. the framework that links the pieces of data and information together so that it can be shared, retrieved and interpreted correctly. In PDM, which is the backbone of PLM, the product structure is normally the main framework that constitutes the information model. Therefore, VP and related data, information, documents should be referenced with the product model in order to contribute to the knowledge management. For instance, the feedback from VP-based design reviews is knowledge that is transformed from tacit mode to explicit knowledge and stored in PDM. This requires a virtual prototype baseline structure to which this knowledge can be related. The VP baseline means that the exact configuration including structure; bill of materials (BOM), item revisions and model

---

[15] Newman, B., (2002), "An Open Discussion of Knowledge Management, The Knowledge Management Forum", http://www.km-forum.org/ what_is.htm

versions must be stored together with feedback and other information in the PLM system. Currently, this is not supported by the case company's PLM, but it has been recognized as one of the main development targets in an ongoing project. As Weber et al. (2003) stated, PDM/PLM systems typically handle data, not knowledge, and they proposed a principle that establishes relations between product characteristics and properties. This would be an interesting approach to enable links between tacit human knowledge and explicit knowledge in databases.

The chapters following will explain how the impact of virtual environments-based virtual prototyping was observed in, or anticipated by, the case company in order to capture the potential benefits and value of IVP. The impacts will be introduced through the three dimensions of product lifecycle management (PLM) model (see e.g. Grieves, 2005, Stark, 2006), namely processes and methods, people and organisation, and technology – tools and systems. General elements and embodiments of the PLM model, as well as application as a knowledge management platform were introduced in Leino and Pulkkinen (2012).

Discussion of the impact dimension of processes and methods

The objectives of developing processes can be distinguished by strategic global objectives that involve the complete business process, and operative objectives that are more local and related to one or a few key processes (Gomes de Sa & Zachmann, 1998). Developing PLM can be considered as a strategic objective, while inside PLM there are operative processes. PLM processes (see e.g. (Grieves, 2005, Stark, 2006) defining what and when will be done by whom. Engineering change management (ECM) is an example of a typical PLM process. A process has also pre-defined inputs, e.g. 3D models, and outputs, e.g. ergonomics analysis documents. A method explains how process transactions will be conducted and supported by suitable tools and applications. A process, for instance, defines when (what point of a product process) a virtual product review will be set up by whom, and who are the participants in the review. A method related to virtual product review explains, for instance, how a certain product review will be executed. In the case studies, methods include e.g. product assembly and maintainability design review. (Leino & Pulkkinen, 2012)

In the literature, it has been often stated that virtual prototyping shortens product development and the whole time-to-market period. This can be justified (Zimmermann, 2008) by the fact that virtual prototyping is a frontloading product process, meaning that single sub-processes and milestones can be accomplished earlier and parallel because there is no need to wait for physical prototypes. In the chapter 7.1, it was discussed how this was manifested in the case study.

As mentioned earlier, IVP is a process that should involve stakeholders and HF/E discipline as widely as possible. In turn, challenges will occur (Norros, 2013) both about how HF/E should be integrated early in design processes and projects from a design object viewpoint, as well as how HF/E approach should change the processes and work organisation. Additionally, the co-operative process around an intermediary object such as a virtual prototype requires specific management

principles (Boujut & Laureillard, 2002). This challenge was visible especially during the first sub-case studies, and it is a common problem that we have still encountered more widely in industry. The cause of the problem is two-fold. On the other hand, the mind-set of HF/E expert is more analysis-oriented than synthesis (design)-oriented, as was stated also in the literature review. This means that it seems to be natural for HF/E experts to evaluate concrete designs, but a definition of HF/E related requirements is difficult. Thus, virtual prototypes enable early HF/E involvement, because the experts can evaluate them in the early process phase.

On the other hand, the traditional product process has been "end-loaded" so that HF/E aspects are evaluated with an almost ready product when it is way too late to make major changes. This is a very critical issue related to management and process changes in order to gain the value of IVP. There have been clear indications in the case company in this direction. However, in the end this comes down to the personal capabilities and attitudes of managers and engineers, which can be only enhanced with good leadership. Furthermore, this change also requires technical preconditions that are discussed in the chapters following. However, the organizational processes are complex and fragile (Nonaka & von Krogh, 2009). Therefore, when designing new business processes, it should be carefully considered (Zimmermann, 2008) whether the new process is able to replace existing process and whether it is able to offer additional benefits, and to involve (Edwards & Jensen, 2014) managers as socio-technical system designers. It is important to see whether the new process supports and secures management decisions.

This chapter discusses the implications and impacts on product design and development processes estimated by the case company in the (Roundtable discussion on the thesis research, 2013). Adopting IVP and scaling up to cover daily product processes should cause a paradigm change in design and product development, as was described in the chapter 7.1. Firstly, it should be ascertained systematically what kind of prototypes and how many are conventionally used in product development, and for what purposes. Because the NPD projects and products are different and they may be carried out by different people or organisational units the processes and procedures may vary. The adequate design maturity and level of details of 3D-models for virtual prototyping, e.g. for assembly simulations in internal productization, should also be considered. Conventionally, even the detailed 3D-models are ready weeks before the manufacture drawings are generated and parts ordered from suppliers. If the virtual prototyping of internal productization were conducted with draft 3D-models, there would be savings of weeks of calendar time compared to the conventional process.

The earlier the feedback and validation from downstream functions, e.g. production, can be gathered, the more potential for savings exists. Leikko (2012) reasoned that in the case company there is an intent towards earlier involvement of productization to NPD process, but it may be difficult for workers to comment on abstract product concepts. IVP can make this bridge easier. The demand for a frontloaded and changed design process and re-thinking the design maturity was

also reported in the literature. Gomes de Sa & Zachmann (1998) argued that normally CAD data do not meet the requirement of VR, and new CAD models should be created with virtual prototyping in mind. (Tseng et al., 1998) concluded that preparation and representation of the product model must meet the needs of decision making and other product process stakeholders. Rehfeld (2010) requested the frontloading of the preparation of virtual prototyping material in order to achieve the benefits.

All these statements from the literature were recognized clearly in the case study as well. On the other hand, it was envisioned that these changes are not easy, but they must be addressed before virtual prototyping can be effective. It was assumed during the research that at least many product layout level plans could easily be evaluated with low level of detail 3D-models. It was concluded that at least there would be a huge potential for savings if the manufacturing drawings and documents were generated only after the design verification and validated 3D-models by using the intermediate virtual prototypes. Consequently, there would be earlier and better quality decisions and many fewer engineering change loops with the physical product. Major savings could be achieved when a "no-go" decision (i.e. terminating a product development project) could be made without building a physical prototype. Sometimes directors may demand savings in product development which may, for instance, cause omitting one or several physical prototypes. In these cases, virtual prototypes could compensate for the need of testing and verifying design solutions before starting standard production.

In order to achieve the same risk level and potentially reduce costs in a product development project, it should be explicitly defined (Zimmermann, 2008) how a virtual prototype will partly replace a physical prototype, what the possible new project milestones are, and when the design maturity is sufficient for building the first physical prototype. In Appendix A is an exemplary illustration of how product development processes can change when IVP is adopted in the case company. These kind of functional process models were created in simulation games of the ManuVAR project. On the right side (to-be) process it can be seen that one virtual prototype was removed because the virtual product phase was extended, but in turn there are new roles and technological prerequisites that affect the PLM model.

This chapter highlights the importance of product design reviews, and the role of IVP. A virtual environments-aided product review was a particular process in the case study (see the section 5). The case study indicated that the product review is one of the most potential virtual environment applications in the research context. Product review is an important milestone of a product development project (Huet et al., 2007). Product reviews enable managing risks within product development, and they can be categorised (Unger & Eppinger, 2011) as strict reviews (gates) or flexible review that allow parallel work on the project. From the risk and uncertainty management viewpoint, there are two approaches (Grote, 2014) for designing the product processes: A mechanistic project management and risk-minimizing approach, and a more creative approach that is open for novel solutions but which includes more uncertainties in order to achieve innovation. However, Ovtcharova (2010) argued that using VR technology mainly in design

reviews is too limited a task in the product development. This is also a finding from our case study. Perhaps the value of VP is difficult to understand if it is seen just as a sophisticated visualisation in design review meetings. However, this research aims to conclude that the concept of intermediary virtual prototyping is more widely integrating people, processes and information. It should also be used for other purposes beyond design reviews, although reviews were the main applications of virtual prototyping in the case study as well. Therefore, the creative approach mentioned by Grote (2014) should be emphasized.

Product review procedures and good practices are described in the literature, e.g. (Huet et al., 2007); however, there is a challenge in how to implement these good practices within a company's own business processes. Furthermore, virtual prototyping and virtual environments impact these procedures beyond a conventional way of doing daily work. In the case study, it was for instance clear that members of a VE- aided product review board might need instructions and training in virtual environments in order to fully understand the system and to be able to work with it (Aromaa et al., 2012). Consequently, in order to gain all the benefits of virtual environments-aided product reviews, systematic procedures (Aromaa et al., 2012) and roles (Zimmermann, 2008) for preparing, coordinating, conducting and post-processing reviews are required (Aromaa et al., 2012). In order to prepare and post-process VE-aided review meetings efficiently, the interface between the product data management (PDM) system and the virtual environment is crucial. This is not a trivial task today. In fact, especially translation of engineering changes and notifications back to PDM and CAx is one of the most important research targets (Seth et al., 2011) in the virtual prototyping community. Nowadays, feedback from product review meetings is usually recorded only into participants' minds or personal notes, and reported to the engineering designers and managers verbally or through an email. This leads to insufficient communication and knowledge sharing within the organisation (Aromaa et al., 2012).

Preconditions for maximising benefits of virtual prototyping are discussed in this chapter. During the case study, it was understood that establishing a good interface between virtual environments and product data management impacts the PLM model deeply, for instance the specific virtual prototype and product assembly structures, access management, and engineering change management. Products, both new products and released products, are continually changed in respect of their items, attributes, geometry, components, structures, materials, documents (Kariniemi, 2014).

In an NPD project, changes are happening frequently. If the NPD processes are frontloaded with use of VP, it must be integrated into the engineering change processes, and revision/version management. Of course, processes must be agile and the bureaucratic engineering change management of the released product are not needed in an NPD project. Parallel product structures or views of a central product structure have been proposed during the case study as an approach to manage feedback and changes. For instance, Kariniemi (2014) proposed that changes to a sequence can be made directly with a parallel assembly structure without touching the engineering structure. Also, Kissel et al. (2012) have pro-

posed product structure management as a way to increase the transparency of existing solutions, thus more Lean decision making.

The relation of virtual prototype to product structures was seen as one of the major enablers of effective IVP in the case company. However, the implementation of such structures will be the subject of other research. Ideally, virtual prototyping should enable concurrent engineering (CE) and must therefore allow simultaneous product exploration and collaboration by various engineering teams already when the design is in the early maturity phase (Zorriassatine et al., 2003). The VP structure together with other parallel product structures would enable this CE paradigm. On the other hand, there is recent evidence (Ovtcharova, 2010) that overlapping activities of CE may lead to additional expenses of development rework which may outweigh the benefits. To minimise this risk, Ovtcharova suggests clear iterative process definitions and integration of tools, data management, processes and organisations.

The demand for a virtual prototype structure was discussed in the chapter 7.1. In the case company, design models that were not released to production were managed in EDM (Engineering Data Management) systems, to which other departments (e.g. production) did not have access during the first years of the case study. However, this is an example of a PLM process that was changed during the case studies since now development engineers of internal productization have access to EDM and the possibility to see design models that are under construction.

Vehviläinen (2014) studied the utilization of AR and VR in the ManuVAR project inside the case company. He concluded that digital 3D-models have been used for a while, for instance in assembly review meetings. However, he reasoned that those design reviews have been ineffective for several reasons. Firstly, they have been arranged so late that, in practice, any major engineering changes were possible before building the physical prototype. Secondly, the design reviews were arranged in a normal meeting room using normal 2D-projectors without any possibility to interact with the product model. These technical deficiencies were reported also by Di Gironimo et al. (2014) in their research. They concluded that the limitations of representation of design features and lack of interaction cause difficulties in the interpretation of the design by non-experts. Thirdly, there was no clear agenda or decent documentation from the review. Thus, it was concluded that, in order to improve the effectivity of virtual design reviews processes and procedures together with the new technology must be developed (Vehviläinen, 2014).

Additionally, there should be clear responsibility for coordination, documentation, camera/video recording, assessment of different product aspects including such as assembly, maintenance, safety, and ergonomics. Despite the demand for systematic product review procedures, there should be enough time for discussions and brainstorming. At the end the meeting should be clearly summarized and conclusions should be drawn. Documenting VE-aided product reviews and sharing information and knowledge within the organisation is important. Experiences from these meetings, both good and bad solutions and ideas should lead to

expansive (Engeström, 2001) learning. The process implications in relation to value propositions in the three dimensions are summarised in Table 13.

Table 13. Summary of process implications in relation to value propositions in the three dimensions

Value proposition dimension	Precondition or impact : processes and methods
For product design and development	
Shifting form product part domain towards organ domain, and linking organ domain and part domain of the product perspective with the process domain of production perspective	• Change of product design and development process • ECM implemented in NPD projects • Establish a virtual prototype as early as the first 3D drafts and product structure become available • Re-think the process of how design maturity progresses in respect to the needs of other product life stakeholders • Enable parallel product structures and views (EBOM, MBOM, BOP, etc.) early – consider where they are established and maintained (EDM, PDM, ERP, or some other system) • Change management of parallel structures • Change management of virtual prototypes: updates, items, revisions/versions
IVP is means for investigation and revealing unwanted dispositions	• Improve integration or organisational functions and concurrence of NPD processes • Enable more agile NPD processes compared to standard products • Establish capability to design and plan engineering changes earlier • Establish capability to produce alternative product structures and solutions quickly and cost-effectively • Integrate systematic and frequent virtual product design reviews involving a wide range of product stakeholders
IVP is particularly beneficial in manual work intensive variant production	• Wide Involvement of product stakeholders: Designers, developers, production, assembly and service workers, project managers, product managers, customers, etc.

Improves communication between people, and collaboration within organisations, thus earlier feedback from downstream lifecycle	• Establish systematic collection and processing of feedback from product stakeholders • Establish systematic virtual design review meeting, goals, processes and procedures including documentation templates, agendas, video/audio recording • Establish processes, VP structures and PLM workflows for managing the feedback between the product stakeholders
Saved time and resources by decreased number of physical prototypes and engineering changes	• Frontloaded NPD project • Early involvement of internal productization, production, product life stakeholders
For people	•
Collaborative virtual prototyping is an intermediary object that enables shared mental models, organisational learning and knowledge creation crystallized in the product and services	• Establish systematic processes that involve stakeholders in a NPD project • Enable better transparency and provide stakeholders for seeing each other's viewpoints and changes to the product from the beginning • Establish IVP facilities at the company NPD proximity
IVP enables expanding the object of activity system improving the expansive learning and knowledge creation	• Establish processes and methods to create models including context models, operations, constraints, material flows, etc.
IVP is also an organisational interaction field that provides for modelling the context and actions related to the product and involving widely stakeholder of the product life	• Establish processes and methods to create models including context models, operations, constraints, material flows, etc.
The expanded object enables revealing contradictions and latent dispositions within the product life	• Establish capability to create assembly- and other instructions from virtual prototypes •
For business and management	•
Value is created when IVP is used and combined with the skills and knowledge of its users in product design and development, but only part of it can be estimated as monetary exchange value, e.g. reduce cost.	• Guarantee continuous process development • Measure or evaluate process maturity
IVP enables balancing the daily perfor-	• Establish processes that capture all

mance and long term core competence by contributing to knowledge creation in the company	deviations and change requests to systematic ECM and PLM • Document decisions and engineering changes to PLM through VP and product structures: Good and bad decisions, reasoning of decisions. • Consider CM II approach
VP contributes to improved decision making, management of uncertainty and revealing the contradictions and latent dispositions	• Systematic organisation of VP based design review meetings • Establish clear NPD project process with allocated VP based design reviews both at gate decisions and between them • Describe clear agenda and goals for design reviews: what is assessed and evaluated, what will be decided
Early feedback from internal and external customers, thus shorter the time-to-market	• Ensure early involvement of internal and external customers • Systematic and careful documentation of feedback • Consider how an NPD project differs from standard production and delivery projects • Understand how NPD and IVP contributes to time-to-market and value
IVP contributes to the co-creation and variant production paradigms by involving human creativity in the early product design and development phase, thus increasing the flexibility	• Early involvement or product stakeholders to NPD projects • Consider how IVP contributes and differs in respect to product portfolio (standard, partially configurable, engineering to order projects), and processes (NPD, delivery projects, standard production, product upgrades) • Understand the different operations, cultures, and goals of organisations
IVP should be considered as a strategic investment that will produce income in the long run	• Establish IVP-related processes so that they are independent of specific commercial tools, and systems • Establish IVP as part of enterprise architecture and PLM model development

Discussion of the impact dimension of people and organization

Product design and development is described in the literature as a process or set of processes. A product development organisation is the social system and environment in which the design and development work is carried out. Thus, decisions need to be made concerning team staffing, incentives, performance monitoring, and investment in productivity-enhancing tools and processes (Krishnan & Ulrich, 2001). However, sometimes it may be forgotten that people with different roles execute the processes. The product design and development can also be observed on different levels of abstraction, e.g. on the level of the NPD project or focusing on an individual engineer (Krishnan & Ulrich, 2001). So it is important to consider the correct level when analysing and developing the processes. On the other hand, people may take shortcuts if the processes appear cumbrous, which is of course not the intention.

When discussing organizational learning, organizations should be seen as systems of interrelated roles where the roles tell us where to look for appropriate information and how to process the information (Simon, 1991). When organisations change their strategies, they must also change their organisational structures and processes, which is a revolutionary change (Tushman & Reilly, 1996). It should also be understood that the processes inside the company are principally different; thus, it needs also different staffing and management.

Typically, manufacturing firms are organized into functions which are beneficial for managing stable products, but the task of developing new products is a more challenging and dynamic process (Krishnan & Ulrich, 2001). Observations in the case study infer that sometimes management may not see the difference clearly or do not know how to react. In the literature (Krishnan & Ulrich, 2001) a common approach for tackling this problem is to establish teams including people from various organisational functions to a NPD project, which was also proposed by (Nonaka, 1994).

VP should be positioned in these different type of processes, and also design the organisations and roles around it. It is also important to remember that, in this research, the focus is only on one type of virtual prototyping and a limited set of processes. However, Allen et al. (2013) argued that actually social activity is relatively autonomous from its organisational structure. This can again be referred to the hypertext organisation of Nonaka et al. (1992), where a discussion is going on between social activity and formal organisational structure. The latter is needed to maintain continuity and adequate stability from a management viewpoint. However, successful companies rely on strong and balanced social controls which are simultaneously tight and loose, meaning that bureaucracy is minimized, management is decentralized, leadership is systematic, teamwork is encouraged, people are trusted, procedures are flexible, knowledge is shared and decisions are made close to operations and customers (Tushman & Reilly, 1996).

In redesigning a socio-technical system, the following aspects should be given special attention (Edwards & Jensen, 2014): What are the boundaries and scope of the system; who should participate the redesign and change process; what kind

of knowledge is needed, avoiding over simplification of the complex system, and performance management and leadership both from productivity and well-being viewpoints. These aspects seem sometimes too difficult for engineers who tend to consider socio-technical systems, i.e. organisations and processes, as causal and mechanistic systems rather than complex and open systems. There is, for instance, an asymmetry between people and technology and how they process information (Nardi, 1996), because only people (nowadays) have motives and consciousness.

In this research context, IVP should be considered both as an independent and dependent variable (Grote, 2014) since it changes the organisation but it is also changed by the organisation. This kind of information technology intervention does not work itself, but the actions of individuals and the total activity system contribute to the intervention success. The socio-technical system design should draw on design science by undertaking more predictive work and making predictions about the anticipated consequence of design decisions (Davis et al., 2014).

Organizations that wish to change in order to differentiate the need to estimate the cost of instilling the knowledge, beliefs and values in members of the organization for implementing the new goals (Simon, 1991). Virtual environments and virtual prototyping could be utilized in many milestones of a product development project. Nevertheless, so far in the real world they are not utilized as widely as might be possible for two major reasons (Zimmermann, 2008): lack of acceptance by users and management, and the imperfection of the virtual environment itself. Naturally, the latter is at least partly behind the first reason, but beyond that there are also higher level factors.

This chapter discusses the challenge of designing IVP as the core competence. It also needs good leadership, appropriate mind-set, and necessary know-how. In earlier chapters, it was reasoned that improved collaboration, knowledge transfer, and organisational learning can be the core competence of the company supported by IVP. However, organizational knowledge creation is very sensitive to social context, such as the organizational processes, timing of activities, physical proximity of people, and peoples use of technology (Nonaka & von Krogh, 2009). This sensitivity must be taken into account in order to establish and support a culture that encourages and stimulates collaboration and knowledge sharing. The knowledge and ideas must flow laterally through and between organizations and their cognitive boundaries in order to learn for instance about a new product under design and development (Simon, 1991).

Building and abandoning core competences must be recorded and appreciated in the organizational memory so that it can be recalled as a fair activity (Prahalad & Hamel, 1990). The essential precondition for accumulating organizational memory is the representation of the organization itself including definition of roles of the organization members (Simon, 1991). On the other hand cultivating this kind of core competence requires that stakeholders understand that they do not belong in any particular business line, but they contribute to the whole company's success (Prahalad & Hamel, 1990). People need to be motivated because often so called "NIH – not invented here" syndrome (Simon, 1991) hinders the collaboration. The

NIH syndrome includes both knowledge and cost dimensions between organization groups. In other words, IVP combined with organisational knowledge should be seen as a core competence which enables design, development and production of all the products and services in the company's portfolio. Therefore, the end products should be seen as embodiments of the core competences (Prahalad & Hamel, 1990).

Organisational change management, leadership and learning are critical factors because engineers may resist (Nonaka & von Krogh, 2009) the use of virtual prototypes because they do not believe in their performance or they may even feel threatened by them. In some cases, the changed mind-set of users is needed for effective exploitation of IVP. For example, designers should allow assessment of their unfinished drafts as early as possible. In co-operative work, people should share and build knowledge in order to create a common understanding of the situation instead of traditionally sharing only the results of the work attitude (Boujut & Laureillard, 2002).

At the higher level of the organisation, business unit managers or product managers may be reluctant to share their competence carriers due to competition. However, effective utilization of core competences is dependent on the dynamics of the competence carriers (Prahalad & Hamel, 1990). Leaders and managers must develop an appreciation of societal needs, understanding of the true basis of company productivity, and the ability to collaborate across boundaries in order to create shared value (Porter & Kramer, 2011). The change may be difficult and costly because of the structural (complexity and interdependence) and cultural (institutionalized and embedded expectations, informal norms, values, social networks, myths and stories) (Tushman & Reilly, 1996). However, the organisational culture is a key to success, but it can also be a cause for especially long-term failure because of resistance to necessary changes (Tushman & Reilly, 1996).

In order to create value with a new good or process, it needs to be implemented and used, which may need new skills and know-how of new or existing resources of the company, or external human resources (Grönroos, 2008). The new virtual prototyping methodology requires know-how, skills and understanding about how to use IVP effectively, how to build virtual environment models and simulators, how to run a virtual product review meeting session, how to apply design methodologies such as user-centred design and participatory design, and how to capture, transfer and save tacit and explicit knowledge for wide usage during a product lifecycle. For instance, CAD provides designers with representation of their design problems, but effective use of these capabilities requires a better understanding how people actually extract information in order to enhance human performance in design tasks (Simon et al., 1987).

The chapter below discusses the estimated implications and impacts by the case company (Roundtable discussion on the thesis research, 2013). It was anticipated by the case company that sooner or later virtual prototyping will revolutionize the way of organizing product design and development. Therefore, it is better to prepare readiness for virtual prototyping. However, according to Tush-

man and Reilly (1996), the benefits of proactive change are clear, but only a small minority of firms initiate revolutionary changes before a performance decline.

Communication and understanding. As was explained in the chapter 7.2, intermediary virtual prototypes enable communicating real life experiences to other participants. On the other hand, it was claimed that real life experiences are necessary for understanding virtual environments correctly. For instance, designers should visit the actual working sites of the machines in order to really understand the activity and conditions. This experience allows them to build a mental model which enables understanding virtual prototypes and activities correctly in virtual environments.

The intermediary virtual prototype may also be a medium for knowledge transfer between a senior and novice designers. On the other hand, experienced assembly workers in internal productization can utilize their mental models when performing with a virtual prototype in a virtual environment. They can complement the virtual product model with elements of their own mental model. This is why it was observed in the case study that the senior assembly and maintenance workers often realized the benefits of VP, i.e. they know more about the potential problems that may occur in production or maintenance work. Prahalad and Hamel (1990) called these actors "competence carriers". On specific aspect discovered was related to maintaining the core competence of manufacture and assembly knowledge: When manufacturing is outsourced, IVP could be a means for communicating and sharing knowledge. If the competence carriers are not given exciting opportunities to use their competence, it begins to fade (Prahalad & Hamel, 1990).

New roles and responsibilities. In consequence, intermediary virtual prototyping may result in new kind of roles in product development. For instance, some assembly workers and foremen may be specialized in virtual prototyping, though they would still be part of a physical production system. The success in this kind of role is very much dependent on the attitude and openness to new technologies and ways of working. Therefore, core competences should be seen both from the internal and external customer's viewpoint (Prahalad & Hamel, 1990). However, if the organisation is conceived only as a set of business units, it may be the case that nobody feels responsible for maintaining core competencies (Prahalad & Hamel, 1990).

The case study indicated (Internal company report on virtual environments pilots in ManuVAR project, 2012) that using the same people in VE-based review meetings repeatedly leads to a situation where the new technology becomes familiar and easier to use. Consequently, the quality of the discussion is improved because it is focused on the product review topics (not on the VR technology itself). Familiarity with the VR technology combined with the mental models of participants may enable participants to ask even things that are not present in the virtual environment model but which they can imagine to be there.

The automotive industry is one of the early adopters of virtual environments-aided virtual prototyping (Zorriassatine et al., 2003), (Rehfeld, 2010), (Gomes de Sa & Zachmann, 1998), (Weidlich et al., 2009). There the adoption has resulted in

establishing "VR centres" that provide expertise and service for e.g. data acquisition, conversion, virtual environment preparation, and maintenance of the necessary equipment and software (Zimmermann, 2008). The main reason for this is that today normal engineering designers are not sufficiently familiar with the VR technology. On the other hand, a new "IVP manager" role is needed, because it is estimated to require so much effort that it cannot be done in addition to the main activity. In the case study, this service was mainly provided by VTT experts. However, it was anticipated by the case company that real implementation of IVP in the company would require establishing this kind in-house facility and service.

Generally speaking, virtual prototyping requires mastery of the software used and an ability to configure and integrate systems and to interpret the virtual prototyping results. Therefore, it is important to understand that implementing virtual prototyping and VR technology is much more than purchasing software and hardware – it requires a great deal of human involvement (Zorriassatine et al., 2003). This was understood by members of the case company, who participated in the research projects. Therefore, it is important to systematically study these impacts and compare them with the assumed benefits and value of IVP.

The characteristics and capabilities of IVP and virtual environments also enable improved involvement of special expertise such as safety and ergonomics. Generally speaking, IVP facilitates improved team work and collaboration by demonstrating the context, activity and environment in addition to the actual technical system. Changing the processes, work and organisation can be difficult because sometimes management is not interested and other stakeholders such as designers and workers might not see the necessity for change or even only anticipate problems and increased costs (de Jong & Vink, 2002). Therefore, these stakeholders should also be involved in designing new processes, work procedures and organisational structures that address their real demand both from a productivity and a well-being point of view. Besides the knowledge and communication medium, cooperation is also a question of attitude (Boujut & Laureillard, 2002). The organisational implications in relation to value propositions in the three dimensions are summarized in Table 14.

Table 14. Summary of organisational implications in relation to value propositions in the three dimensions

Value proposition dimension	Precondition or impact : people and organisation
For product design and development	
IVP enables shifting form part domain towards organ domain, and linking organ domain and part domain of the product perspective with the process domain of production perspective	• Establish increased transparency between product stakeholders through IVP and PLM
IVP is particularly beneficial in manual	Education of engineering designers about

work -intensive variant production	human factors/ergonomics and IVP
For people	
Collaborative virtual prototyping is an intermediary object that enables shared mental models, organisational learning and knowledge creation crystallized in the product and services	• Establish and develop IVP know-how among the company personnel • Pick the responsive early adopters for IVP pilots • Educate specialised IVP roles representing product stakeholders (e.g. experienced sheet metal workers, welders, assemblers, service experts, etc.), VP technical experts, designers, and managers • IVP must be introduced supportive and mature enough from a wider audience in the company in order to avoid rejection • Capture explicit knowledge to PLM • Enable necessary information and knowledge availability for all stakeholders through PLM
IVP enables expanding the object (product) of activity system (product development) improving the expansive learning and knowledge creation	• Notification of engineering change requests, comments, response – recording them to PLM with relation to VP structure • Engineering designers and managers expand their view to product activity system beyond the product functions and characteristics
IVP is also an organisational interaction field that provides for modelling the context and actions related to the product and involving widely stakeholder of the product life	• Recognition of product stakeholders including also suppliers • Establish clear map of roles of who communicate with the stakeholders • Understand the importance of frequent face-to-face and digital communication
The expanded object enables revealing contradictions and latent dispositions within the product life	• Consider how to transfer knowledge from NPD and IVP to production and product lifecycles • Enable modelling product context, activity (e.g. material flows, processes), actions (e.g. lifting heavy parts)
For business and management	
Value is created when IVP is used and combined with the skills and knowledge of its users in product design and development, but only part of it can be estimated as monetary ex-	• Appropriate "CAE-type" usability of IVP tools • Educating and motivating the product stakeholders about IVP, removing resistance to change • Directors and managers must understand

change value, e.g. decrease cost.	• and respect the different views, needs, and contributions to product process and business success by different stakeholders and individuals • The company management must understand how to capture, share, and utilize product knowledge, and how IVP can help in this • Establish required new roles and jobs for the re-designed IVP based product development
IVP enables balancing the daily performance and long-term core competence by contributing to knowledge creation in the company	• Understand value of the holistic and integrated product development system beyond the organisational functions • Understand the dynamic interactive organisation system • Remove the partial optimization within the organisational functions • Consider IVP as a knowledge hub that integrates daily knowledge and accumulates it for the future decisions
IVP contributes to improved decision making, management of uncertainty and revealing the contradictions and latent dispositions	• Recognition and Involvement of all product stakeholders: Engineering design, productisation, production, suppliers, purchase, service, project managers, product managers, etc.
Early feedback from internal and external customers, thus shorter time-to-market	• Internal functions and stakeholders should be considered as a strategic business network as well • Remove the "PLM-silos", i.e. organisational, process, and information barriers between functions, stakeholders, and persons
IVP contributes to the co-creation and variant production paradigms by involving human creativity in the early product design and development phase, thus increasing the flexibility	• Organisational culture change is demanding for leadership, but it must be accomplished in respect of IVP • IVP implementation must be carried out in parallel with daily work without jeopardizing business • An open- minded attitude is needed as part of IVP culture, e.g. willingness to show draft designs, and willingness to give constructive feedback • The culture change requires common

	concepts and terminology • All stakeholders and persons must respect each other's work and opinions • There must be enough discipline to obey rules and processes, without losing agility – the processes and rules must be designed together
IVP should be considered as a strategic investment that will produce income in the long run	• The added value of IVP should also be estimated or calculated quantitatively based on well planned business cases • IVP investment and implementation projects should be shared between departments because all stakeholders will be both contributors and beneficiaries • IVP must be planned so that it can be scaled up in a global company – e.g. remote design reviews • There must be sufficient resources for creating and maintaining virtual prototypes and product structures, for managing virtual design reviews, and for documentation • The value of IVP and organisational functions like productization should be understood although they do not belong directly to product value chain (making money)

Discussion of the impact dimension of technology

The potential positive effect of technological innovations is often dependent upon inter-relationships between many other technological components (Fox, 2013b). As a potential technology innovation, Fox (2013b) mentioned augmented reality for maintenance work support that is dependent on a well-structured database, wireless network, information design, small data files and ergonomic and usable devices. In the case of VP, product data management systems should for instance support a fast and reliable process of building and post-processing virtual environment sessions (Zimmermann, 2008). This includes converting data into an appropriate format, sometimes with required metadata as well. For practical utilization of VR/VE, it is important that existing models – 3D geometry, but also kinematics, behaviour, metadata – can be imported into a VE system, taking into account the purpose of VE (Kalawsky, 1993). Also, Gomes de Sa and Zachmann (1998) reasoned over fifteen years ago that VR will not become a widespread tool in the manufacturing industry before it can be completely integrated into the existing IT infrastructure. Nevertheless, (Ovtcharova, 2010) concluded that VR-based

solutions are still inadequate at least in the dimensions of integration with IT infra-structure and product processes, and the methodology for selecting the appropriate technical options for a set of specific task. Especially the backward propagation of information from VR, for instance from a virtual design review meeting to PDM is still a problem (Di Gironimo et al., 2014). These challenges were very much visible in the case study when the research progressed from single VR demonstrations to realistic NPD use cases.

Previous chapters have discussed the importance of understanding human capabilities compared to a purely technical approach. In design, human experts generally have better heuristic capabilities and a larger vocabulary and set of concepts, while computers have "brute force" for computational speed beyond human ability (Simon et al., 1987). Simon et al. mainly discussed artificial intelligence (AI) expert systems, but this comparison of human and technical capabilities can also be seen in managing data and information related to IVP, while humans bring the tacit knowledge dimension.

It may seem obvious that all virtual prototyping and VR data should be administered in the PLM backbone, making data management automated and data available to all stakeholders (Rehfeld, 2010). Generally speaking, and specifically in this research context, there is lot of business potential which can be reached by implementing the PLM landscape more widely. Besides the new or re-designed business and supportive processes and practices, this requires defining supportive information models, meta-models, system architectures and integrations (Koudal & Coleman, 2005), (Srinivasan, 2011).

From the process viewpoint, future PLM should integrate all downstream lifecycle stakeholders and related processes, such as customers, end-users, design and development, manufacturing, documentation, maintenance, after sales service, quality management, etc. within early lifecycle stages (Abramovici, 2007), (Srinivasan, 2011).

Information models, meta-data models and processes need to be developed in order to support multi-discipline systems engineering, intelligent mechatronic product models, simulation-based engineering, knowledge management, besides the current core mechanics design focus (Abramovici, 2007), (Srinivasan, 2011). Utilization of the PLM backbone for virtual prototyping requires a dedicated VR data model to be developed in the PLM system with an interface to workflow support, revision control, update management, access rights control, collaboration and conferencing (Rehfeld, 2010). However, general accepted industry standards for PLM meta-data models and for PLM processes are still missing (Abramovici, 2007). Accordingly, in practice product data management is still focused on managing conventional product development and design data, and the methods used to collect product data from middle and end-of-life phases are incomplete (Abramovici, 2007). The relevant feedback information from the field cannot adequately be obtained and utilised for later product design versions. Based on the case study participatory approach combined with suitable virtual prototyping, tools and methods enable acquiring feedback from downstream lifecycle phases already in the virtual product development phase. In this way, virtual environments

enable "on-line" knowledge transfer as an intermediary object while "off-line" knowledge management should be enabled by PDM/PLM systems (Leino & Pulk-kinen, 2012). Obviously, both social interaction through IVP as a medium, as well as a rationality approach enabled by PLM are needed. This requires knowledge transfer as (Nonaka, 1994) proposed.

Horváth et al. (2010) proposed how knowledge could be captured in order to establish intelligent content in product models with the functionality of industrial PLM systems. Furthermore, Horváth and Rudas (2009) have also proposed a structure of a virtual prototyping space. Expandable product models in PLM systems may support an increasing number of engineering processes, design objectives, decisions, and consistent model data (Horvath & Rudas, 2007a). Nevertheless, stakeholders' attitudes to sharing knowledge is central to the success of knowledge management practices (Ameri & Dutta, 2005). Therefore, methods, tools and systems are useless without sufficient organisational leadership and change management.

Implications and impacts estimated by the case company (Roundtable discussion on the thesis research, 2013). Based on the experiences on the case study, three main technology dimensions were discussed by the representatives of the case company: configuration and use of the virtual prototype, usability (user interfaces) of the virtual environment and virtual reality, and data management capability. It is very important to know the baseline of the product model and virtual prototype, but it is also necessary to pay attention to the actual configuration of the virtual environment (e.g. visualization, motion capture, haptics, other user interfaces, etc.), and the version or revision of the investigated virtual prototype model. This is important mainly for two reasons: traceability and learning. Traceability is important in order to be sure which model configuration was used for instance in a certain safety analysis. The learning aspect refers to improving knowledge about what kind of virtual prototyping configurations are suitable for certain purposes, i.e. in the development of the virtual prototyping itself. This information should naturally be in PLM, but currently how to do it reasonably is only under research.

The efficiency of the bi-directional model pipeline i.e. the data (model) process from design and engineering tools (like CAD) to virtual prototypes and virtual environment, is essential in effective virtual prototyping. In the case study, virtual environments were built at the VTT laboratory, and the digital models needed were mainly downloaded from the company EDM and transferred on a memory stick or similar type of media to the VR system. However, some tests were carried out during the project with a direct VR/EDM interface, but due to limited time and resources, this aspect was left as a subject for further research. However, it was understood that this capability also requires the development of agile processes, workflow and information models of PDM that support it. It was reasoned that the virtual prototype would need its own and parallel product structure in the same way production function needs an assembly structure. The VP structure baseline would be the frame where information and knowledge e.g. from design reviews can be related to. This information and knowledge typically includes engineering

change requests and arguments, ergonomics analysis reports, free comments and development proposals, virtual prototype and VR-equipment configurations, meeting notes, video- and audio-recordings.

The product stakeholders are interested in the product in different ways (Kariniemi, 2014), and they need different views on the product model. At the time of this research, in the case company, Kariniemi discussed the requirements and possibilities of parallel product structures, which should improve the holistic understanding of the product from several stakeholder perspectives, and made some demonstrations in the CAD/PDM environment. Generally speaking, product structures are needed in databases like EDM, PDM, ERP to represent the hierarchical relations between data objects, and in particular parallel structures are required because the engineering structure (EBOM) in EDM does not optimally serve production and other lifecycle stages. The biggest difference between EBOM and MBOM is the existence of subassemblies in production (Kariniemi, 2014), (Leikko, 2012). This means that some engineering product module structures are split into several subassemblies (see Appendix B). When IVP is also used for this productization aspect, an appropriate VP structure is needed together with the required functionality.

In the case company, the product structure of production (MBOM) is in PDM, and the assembly routing is in ERP system. On the other hand, ERP does not contain the actual real work flow of manufacturing and assembling a physical product (Lee et al., 2011). Therefore, this information cannot be used in NPD, at least not at the beginning of an NPD project. This is, of course, not a universal state of affairs, but it is a significant finding in the case company. The actual product assembly or maintenance (repair) procedure should be available at the virtual prototyping. This may be referred to as Bill of Process (BOP), which states how, for instance, the MBOM, i.e. manufacturing bill of materials is transferred as subassemblies and a complete product. However, the work of (Kariniemi, 2014) was mainly focused on standard production, but it gave good insights into developing support for early NPD project, productization and utilization of IVP.

The MBOM must be revised constantly and up-to-date. Similarly VP must be up to date, and there is also a demand for an "as-built" virtual prototype structure, i.e. a VP baseline, where for instance a design review can be referred and feedback knowledge recorded. Kariniemi (2014) discussed that the concept of "Digital manufacturing" (DM) could help in integration between designers and production department, because it provides a methodology and tools for transforming engineering structures to production structure including the realistic simulation of manufacturing and assembly activity (Kariniemi, 2014). Also Lee et al. (2011) have reasoned that DM would support integration of information and knowledge between PDM and ERP. Kariniemi envisaged that DM would add value by producing material for production and maintenance instructions, and content to the Manufacturing Execution System (MES).

Some commercial PLM vendors (e.g. Siemens PLM and Dassault Systemes) today offer solutions and central data management that enable the DM concept (Westkämper, 2007). However, they are not "plug and

play" tools, and they need quite an extensive configuration in respect to data models, processes and integrations besides the new paradigm of product development as has been discussed before.

The VP structure must be configured and simplified for a certain virtual prototyping purpose. For instance, when new product assembly and/or maintenance work is evaluated in the virtual environment, an appropriate model, i.e. product structure, must be configured. Because real-time simulation and interaction with the model is required in the virtual environment, the model must often be optimized by omitting features that are not needed in order to evaluate the product properties. It is essential to carefully ascertain the necessary configuration of the virtual prototype model and VE in respect of the nature of the task, but it is at least as important as ascertaining the sufficient quality of VE configuration from the human user viewpoint (Ferrise et al., 2013). A natural and intuitive human mindset and behaviour should be designed for the VE, taking into account human cognitive processes (Ovtcharova, 2010).

The VP structure is different from the hierarchical product design structure (EBOM), which is mostly built based on product functions. It is also different from the actual (physical) assembly structure (MBOM), because it is a simplified and restricted model for the real-time virtual environment. Additionally, the VP structure should support the design process and design maturity in the embodiment design phase, where the organ structure (principles for establishing the structures that implement the product functions – basic structure, form and dimensions) meet detailed part structure (quantified structure in Tjalve's terminology). For instance, in the early NPD project phases draft 3D-models and scarce product structure is enough for evaluating the main principle from the production perspective (Leikko, 2012).

Also, Kissel et al. (2012) have proposed a central product structure model as an organisational and temporal hub and information backbone in concurrent engineering design and development, and in particular for frontloaded early project phases. Their approach was argued to facilitate concurrent work between design and other stakeholders in earlier design domains and interplay between the domains. The paper by Kissel et al. (2012) did not show detailed practical implementation of this approach, but it is very interesting. Also, some commercial PLM vendors (e.g. Siemens PLM, Dassault Systemes) seem to develop their offering towards this kind of approach, also called systems engineering. This is the point of considering the strategy between one vendor and their data model, and a neutral data model (e.g. ISO-standard based) and several independent solutions. Additionally, Kissel et al. concluded that the product structure management requires significant effort and a new mindset. This is naturally an important aspect to consider in respect of IVP benefits.

IVP offers a medium for communicating and transferring tacit and explicit knowledge between e.g. workers and designers in real-time. Nevertheless, the knowledge should be captured and saved in a certain data format digitally in order to be usable in a PLM system during the product development and lifecycle. Saving and managing such knowledge in a PLM system requires a mature and rich

data model. Management of virtual prototype models, task models and context models, as well as management of different product structures for product design and development, for production and service require capability to manage parallel product structures and configurations.

One root cause for many communication- and knowledge-sharing defects is poor non-integrated and overlapping IT architecture and poor PLM implementation strategy without an understanding of real PLM drivers (Leino & Pulkkinen, 2012). IT systems are created around functional organisations without compatible information models. Virtual Engineering initiatives are typical examples of inadequate PLM process implementations. Therefore, for instance interfaces and procedures are needed for data conversation from CAD to VE and onward back to PDM, as well as integrations in order to transfer metadata between systems. Virtual prototypes together with sophisticated PLM support could be seen as an instance of "design prototypes", i.e. schemas (Gero, 1990) for representing generalized heterogeneous knowledge elements derived from similar design cases bringing all the requisite knowledge to the design situation.

The third technology dimension of VP was related to the price versus quality/usability ratio, which was often assessed as relatively low. On the other hand, during the nine-year case study significant development was seen in technology maturity with simultaneously lower prices. Probably the relatively high cost of VR hardware and software may be caused by minor competition in the segment. However, the entertainment and gaming industry may have an impact on the prices in the future. Already at the end of the case study, the company concluded that the adoption of virtual reality technology is more dependent on the prerequisites than the VR technology itself. However, technology development (hardware and software) in the market will improve the realism of virtual prototypes and usability of the technology. It is also an issue where companies who wish to purchase commercial off-the-shelf (COTS) tools have little influence, but what they can do is to establish preparedness for this technology in the form of processes, interfaces and product data models. Companies should also understand that the cost of this kind of technology should not be allocated just to one department because they are used and provide benefit in interfaces between organisational functions and product life stages (Kariniemi, 2014).

The study by Vehviläinen (2014) in the ManuVAR concluded that the most appreciated VR feature was the improved visualisation, perspective and interaction compared to the conventional CAD-model and 2D-projection. However, the users interviewed concluded that VE-based virtual prototyping would be even more effective if there is a possibility to include tools, equipment and environment, as well as dynamic functionalities within the product and environment that are used in the real assembly and maintenance work. These aspects were discussed already in the section 5.

As was mentioned previously, VR applications are not utilized as widely as could be for two major reasons (Zimmermann, 2008): lack of acceptance from users and management, and the imperfection of virtual environments themselves. The lack of acceptance is so far mainly caused by a lack of real knowledge and

understanding, and also attitudes to the relatively new and exotic technologies. The imperfection of VR technology itself can be divided into three categories based on the three interfaces of virtual prototyping:

- *To the product model*: It is still not possible to simulate all required product properties and characteristics sufficiently: mass, forces, touch – haptics. Also, a digital human model (DHM) was lacking. Therefore, it was not possible to see the user's own body
- *To reality*: VE-EDM/PDM interface, not possible to feedback information to EDM, not up-to-date models, not early enough in design process, measuring tools, etc.
- *To VE*: usability and user-friendliness of the UI devices, lighter devices, wireless devices, quality of visualisation, navigation at virtual environment, CAE type user interface, measuring tools, etc.

The technological implications in relation to value propositions in the three dimensions are summarized in Table 15.

Table 15. Summary of technological implications in relation to value propositions in the three dimensions

Value proposition	Precondition or impact : tools and systems
For product design and development	
IVP enables shifting form part domain towards organ domain, and linking organ domain and part domain of the product perspective with the process domain of production perspective	- VP traceability: VP baseline, item and information revision, version management, upgradeability - Item codes and metadata visible in VE - Parallel product structures - VP structure that is capable of providing for virtual prototyping, and capable of relating knowledge to the database - Access to data for necessary stakeholders - Bill of process (BOP) – how work is done, bill of materials – subassemblies, components
IVP is means for investigation and revealing unwanted dispositions	capability for modelling the dispositions: Needed product structure, properties and characteristics, context model, activity model
IVP is particularly beneficial in manual work-intensive variant production	VE properties, characteristics that support HF/E
Improves communication between people, and collaboration within organisations,	Ability to handle information, knowledge, feedback technically – to integrate them

thus earlier feedback from downstream lifecycle	into PLM • VP baseline model • Explicit knowledge management – Enriched product model that collects the information and knowledge • Ability to relate information and knowledge with the VP – especially the geometry • Automation of information and knowledge management
Saved time and resources by decreased number of physical prototypes and engineering changes	• Virtual prototyping integrated to ECM process • Automated or semi-automated model conversion and simplification pipeline
For people	
Collaborative virtual prototyping is an intermediary object that enables shared mental models, organisational learning and knowledge creation crystallized in the product and services	• Virtual prototype baseline structure • digital human model • User friendly VR technology
IVP enables expanding the object (product) of activity system (product development) improving the expansive learning and knowledge creation	• Modelling tools, equipment, kinematics, more details like welds, electric wire, hydraulics
IVP is also an organisational interaction field that provides for modelling the context and actions related to the product and involving widely stakeholder of the product life	• Local VR-laboratory at the company • Ability to arrange virtual design reviews on factory floor or at customer site (e.g. augmented reality) • Large enough VR-laboratory • Logical user interface • CAE type usability and logic • Data and information security
The expanded object enables revealing contradictions and latent dispositions within the product life	• Ability to illustrate product module interfaces, restrictions
For business and management	
Value is created when IVP is used and combined with the skills and knowledge of its users in product design and development, but only part of it can be estimated as monetary exchange value, e.g. decreased cost.	• User-centred development of IVP: All stakeholders

IVP enables balancing the daily performance and long term core competence by contributing to knowledge creation in the company	• Continuous development of technology and processes
IVP should be considered as a strategic investment that will produce income in the long run	• IVP should be seen as a user interface to product knowledge, and as a hub where product knowledge is cumulating: requires

Dynamic impacts on business

Figure 69 aims to illustrate the difficulty of quantifying the benefits and value of IVP in an industrial context. It is tempting to approach value and impact as a causal and deterministic phenomenon where IVP and the target system are static and solid. This approach can be characterized with a metaphor of billiard balls. However, the real world is more complex. Actually both IVP and the target system, i.e. business and design are dynamic, like metaphorical amoebas. A business organisation has to be treated as an open system, having fuzzy boundaries with inputs, outputs and wide range of other environmental factors including financial, market, regulatory and technical developments (Eason, 2013). IVP is a framework which is configurable and changing all the time, whereas the business system is complex including lot of cross-dependencies and uncertainties. The causality between IVP and business value is difficult to prove. Therefore, it is more reasonable to adopt a qualitative approach and investigate the opportunities that IVP has in the complex environment.
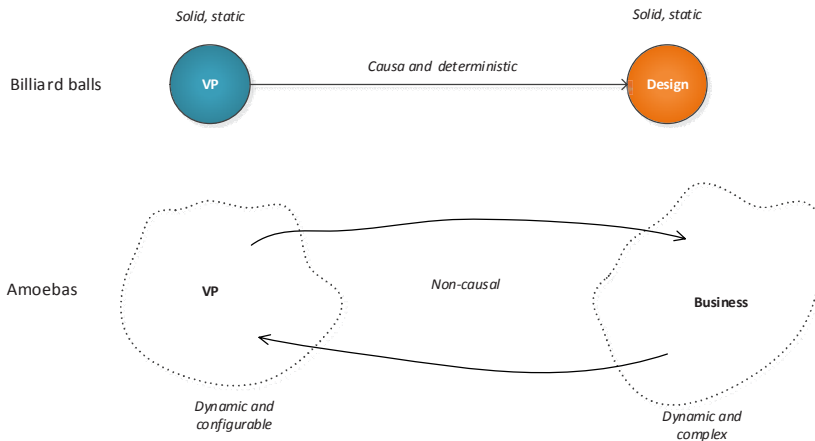
Figure 69. Value of virtual prototyping is difficult to be quantified because the dynamic and changing nature of virtual prototyping entity and the dynamic and complex nature of target system i.e. business as well as non-causal relationships between them.

Anticipated impacts and challenges in the case company (Roundtable discussion on the thesis research, 2013). Utilization of virtual prototypes and environments is a natural step toward a holistic product lifecycle management (PLM) framework. However, this step is challenging because it requires changes in many processes, organizations and infrastructures, as was discussed in the previous chapters. The boundaries between product management, product design, production, and other departments must be cut across. These technologies and methodologies must integrate these organizational functions and stakeholders. It should be understood that virtual prototyping and virtual environments are not just tools any more, while product design review meetings should be seen more as continuous interaction between the stakeholders and transactions for creating and transferring product knowledge rather than just occasional meetings. Therefore, it is not just a matter of tools and methods but also the development of existing processes and the creation of new ones besides change of attitudes and habits. So it is foreseen as a great culture change in the company.

As described in the previous chapters, IVP has potential value propositions for the dimensions of technology, product design and development, people and organisation (social) and business, as well as impacts in the form of necessary prerequisites for capturing all the value dimensions mentioned. Additionally, many of these dimensions or elements of them are changing over time. Consequently, these dimensions and elements form a dynamic system which can be illustrated and visualized as a model in Figure 70 below. The model is qualitative and by no means perfect or comprehensive, but it intends to illustrate how, for instance, implementation of IVP increases cost in one place and decrease cost in some

other place. It is remarkable that these costs and saving occur with a very different time scale. On the other hand, IVP adds value in form of increased core competence which can mainly be assessed only qualitatively.
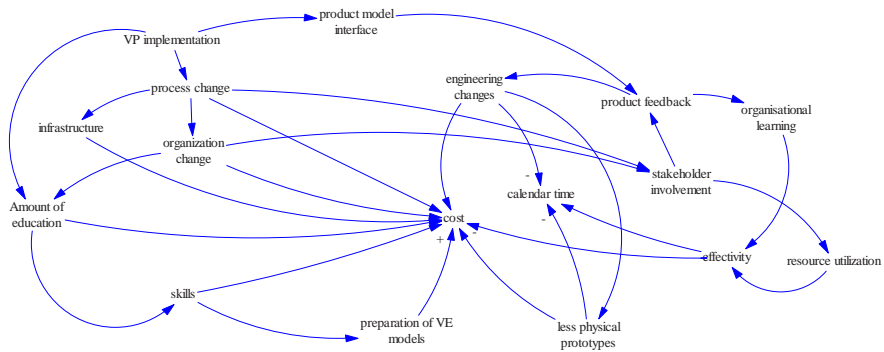
Figure 70. Two sides of a coin. Realization of virtual prototyping value needs certain prerequisites and investments.

In principle, dynamic system models can also be quantified, but quantification of IVP benefits and value is very challenging because of the system complexity. On the other hand, quantitative data was not available for this research. Value consists of tangible and intangible elements. Some tangible value elements can be quantified and even monetized, but there are value elements that can be assessed only by qualitative measures and use value (Grönroos, 2008). In respect of knowledge creation, the nature of value estimation is multiple and qualitative rather than simple and quantitative (such as efficiency, cost and return on investment (Nonaka, 1994). Enterprises including product development and production functions are complex organisational systems, where a causal chain of reasoning is difficult if not impossible. On the other hand, coping with this complexity is proposed to be one of the main sources of value of IVP.

Conclusion on IVP impact on the company

New technology is often underperforming or rejected because it is put into existing business processes and organisation. However, the real benefits are usually captured through organisational change, and new ways of doing things. Therefore, the anticipated benefits of new technology should be balanced with the impacts on the organisation. Thus, IVP should be studied in a business organisation macro context instead of just technical micro context. IVP affects the PLM model in the dimensions of people, processes and technology. It is forecast that sooner or later IVP will revolutionize the way product development is organized in manufacturing companies. Therefore, it is better to start building a foundation for this major change.

IVP does not work itself, but the actions of individual and the total activity system contributes to value. The success of IVP requires prerequisites including skilled people and committed users and managers. Building the foundation for IVP requires leadership, education of people, a change of culture and the mind-set of people, and justification for advantages beyond the status quo. People should be open to sharing their work and knowledge, and willing to learn new things. IVP need to become familiar to the users, and the learning curve brings the benefits in long run. It is probable that there will be new roles in the organisation specialized in IVP with the required skills, experience and mind-set. They can be seen as competence carriers or node points in a hypertext organisation. Through IVP special expertise from other areas of the organisation can also be involved. IVP strategy changes the organisation, but on the other hand IVP processes may be autonomous from the organisational structure. In the hypertext organisation, it should be understood that people do not belong just to one position or business line. Thus oversimplification of the complex IVP organisation should be avoided. Stakeholders should be involved in organisational design in order to balance productivity and well-being.

IVP interrelates with many other technologies and processes. In order to become an everyday asset and integral part of business processes, it should have an interface with product data management systems. The data pipeline should be bi-directional, meaning that models can be retrieved from the database and put back, maintaining the required metadata. The virtual prototype model version and change management and configuration management were seen to be essential apart from the model pipeline and usability of IVP. These capabilities require supportive information models, architectures, integrations, and agile processes. IVP can be seen as an on-line knowledge transfer capability of PLM.

Effective IVP requires paradigm change in engineering design and product development. The process should be re-engineered, taking into account the appropriate design maturity. This produces new milestones to product development projects. However, there should be a trade-off between strict project milestones and flexible parallel design processes. In order to capture the major value of IVP, all relevant stakeholders should be involved in the processes. Their feedback and knowledge is the most important contribution to IVP value. To put process work effectively, good practices and a proper amount of systematics is required. For instance, a design review meeting requires a clear goal, structure and documentation.

Adoption of IVP causes contradictions and disturbances to the organisations which change their whole activity system, but simultaneously it is a potential source for innovation. IVP itself is a core competence and complex system which requires knowledge and strategic thinking. It is difficult for competitors to imitate. However, the benefits are difficult to quantify because the business organisation is an open and complex dynamic system with fuzzy boundaries. IVP increases cost in one place and reduces cost in another place with a different time scale. Furthermore, the value of IVP has tangible and intangible elements that are multiple and qualitative rather than simple and quantitative. Value is created when IVP is used.

7.5   Summary and conclusion of the section

This section of the thesis discussed and reflected the constructed VP value model with theories from the literature. The ultimate purpose of this research was to resolve the main problems, namely a lack of knowledge of the value of virtual prototyping and especially virtual environments in manufacturing industry, and thus problem of slow adoption in industry. This problem was derived as the three research questions: 1) How value of virtual environments-based virtual prototyping can be framed, conceptualized, evaluated and justified, 2) How empirical value of intermediary virtual prototyping can be observed, concretized, and described, and 3) How and by what means the intervention of VP impacts the case company.

These questions were approached firstly by proposing a hypothetical "Phenomena model" synthesising the theory of engineering design and theory of virtual reality and virtual environments. The case study data was then reflected upon with the hypothetical theory model. The analysis of data revealed that virtual environments have advantages related to virtual reality technology (perception, interaction) and justified by the better user interface with the product model and the digital representation of it. VE enables real 3D representation of 3D digital models, instead of just 2D representation on a computer screen. However, the analysis revealed also that there are value propositions beyond these technology-related features. The value propositions were categorized as dimensions of product design and development including aspects of design object and design process, social including individual and organisational aspects, and business value dimension. Consequently, the preliminary phenomena model was extended to these value dimensions and the literature was studied in order to find theories that enable explaining them.

Resource-based view. As a starting point, the concept of value was studied more deeply with the in the light of the case data. This step initiated a strategic approach because that explains what actually contributes to business value. Generally speaking, assessing or measuring value is a challenging task because of its abstract nature and strong context-dependency, including subjective and objective components. The literature (Prahalad & Hamel, 1990) revealed that people and their knowledge is the essential core competence of companies. Thence the resource-based view of the firm and value models and theories that include intangible and subjective value elements in business value chain models, and highlight the value of human skills, knowledge, experience, motivation, etc. were endorsed. For instance, the knowledge-based view emphasizes the social aspects apart from the pure economic aspect (value chain) (Nonaka, 1994) by considering knowledge as a business asset and competitive edge.

Strategic approach. On the other hand, value conversion is one of the most challenging questions for those trying to understand creating value from intangibles (Allee, 2008). Nevertheless, the value configuration theory together with the

dynamic knowledge creation theory enabled putting VP into a business organisation context and systematically analysing the mechanism of knowledge conversion. In the model, VP is positioned as a strategic asset within value network and value shop configurations that have their own logic and processes related to value chains.

Dimension of product design and development. The value of VP in engineering design dimension was divided into design process and design object aspects. On a higher level, value was justified by a frontloaded product process, meaning that VP facilitates integrated product development and concurrent engineering. It is possible to evaluate new product specifications with a virtual prototype and acquire early feedback from production and other downstream lifecycle stages. This leads to a smaller number of engineering changes in physical products, and therefore time and cost savings. Additionally, engineering change management could become proactive since it is possible to study the effects of engineering changes with a virtual prototype and with several product variants. Therefore, the risks of product development can be reduced by catching unwanted dispositions, i.e. unwanted consequences, between different product lifecycle stages or organisational functions. This aspect also refers to the improvement of internal quality which also contributes to end customer quality and price. From the design object aspect, VP enables examining product properties and phenomena in different design domains which can be related to the Theory of Dispositions. Additionally, virtual environments enable a subjective evaluation of product properties (such as ergonomics) and a better understanding of human factors. Furthermore, VP enables testing aspects such as safety which are not necessarily possible with physical prototypes or end products. In all virtual environments facilitate an improved involvement of users and customers (both internal and external) in product design and development and therefore better quality of products.

Social value dimension. The social value dimension of VP was divided into individual and organisational aspects. From an individual stakeholder viewpoint, virtual environments enable easier involvement in the design process by an improved understanding provided by the more natural user interface to product model, and therefore an improved participatory approach. It enables exploring and observing the product model together with the activity and context, and therefore improved understanding of unfamiliar models and specifications. This stimulates dialogue between stakeholders and gives real-time feedback which consequently improves knowledge conversion and transfer. Virtual environment is a place for on-spot-isms, i.e. learning by doing. VP gives opportunities to make mistakes and learn with immaterial prototypes compared to the trial and error in the physical value chain. From these advantages, social value can be derived in the form of improved design for human factors and ergonomics.

From the organisational viewpoint, virtual environments-based virtual prototyping can be seen as an intermediary object which enables building a shared mental model and interaction field for knowledge creation and organisational learning which is one of core competences of today's companies. The new concept of intermediary virtual prototyping (IVP) was established in order to emphasize the

dimensions of VE based virtual prototyping. The common interaction field enables involving stakeholders with different biographies, which increases the creativity of the organisation. On the other hand, it may also reveal dispositions, i.e. contradictions, between the stakeholders which is the seed of expansive learning. Expansive learning may result to process innovations besides product innovations.

Business and management dimension. From the business and management viewpoint, IVP may enable better identification of correct problems and give diverse views and opinions on the problems. Therefore, it may reduce uncertainty and risk, therefore coping with product, process and organisation complexity. Organisational learning and knowledge management were recognized as one of the major value elements of IVP. However, in a knowledge economy intangibles must be seen as assets of companies and setting them into motion in unique value conversion networks is a strategic investment which will produce income in the long run (Allee, 2008). IVP should be treated as such a strategic asset investment that includes holistic impacts also on organizations, processes, procedures and infrastructure in order to enable the value capture of IVP. Nevertheless, the value of IVP depends on enterprises business models, product types, organisations, maturity levels, etc. Therefore, holistic and systemic value configuration modelling should be initiated first (Leino et al., 2013).

Core competencies should be difficult for competitors to imitate, which can be based on complexity and organisational learning (Prahalad & Hamel, 1990). Understanding the strategic value of IVP combined with organisational knowledge, and the proper implementation of it into a company's processes and infrastructure could still be such a core competence, accounting for its role in improved knowledge transfer and conversion, and therefore better utilization of resources and intangible value (Leino et al., 2013).

In future, the proposed model will be used as a reference in empirical studies. It will be iteratively improved and concretized in industrial strategy development projects. The aim is that VP business value modelling facilitates better adoption of VP, and reduces incredulous attitudes in manufacturing enterprises.

Based on their literature survey (Melville et al., 2004) summarize IT business value models: "*If the right IT is applied within the right business process, improved processes and organizational performance result, conditional upon appropriate complementary investment in workplace practices and organizational structure and shaped by the competitive environment.*" This also crystalizes how the value of IVP should be approached and what type of enablers should exist.

8. DISCUSSION ON THE RESEARCH PROCESS

This section covers the discussion on the research approach and process, research content and results, the way in which results were achieved, interpretation of the results, and generalisation and limitations of the research. For a thesis committee, mastery of the methodology and theoretical issues, along with an indication of the care with which the research was conducted, is important (Yin, 2009).

The research problem emerged from the insufficient knowledge and justification of benefits and value of virtual environment-based virtual prototyping in a manufacturing industry context, both in practice and in scientific publications. Moreover, the methodology for assessing the value of virtual prototyping is narrow, as well. This problem was approached from the science base by formulating a theory framework for value evaluation, and from the problem base by an empirical case study in one manufacturing company. Based on the dialogue between theory and practice, the research resulted in three types of new knowledge: 1) a theory framework for value evaluation, 2) knowledge of value of virtual environments-based virtual prototyping in practice, and 3) knowledge of the impact of virtual environments-based virtual prototyping in the company. The virtual environments-based virtual prototyping concept as the research subject evolved during the research. The research resulted the new concept of intermediary virtual prototyping (IVP), which combines the dimensions of technology, product design and development, social aspects, and business management. In this thesis, the shorter term "virtual prototyping" (VP) refers to the virtual environments-based virtual prototyping.

In this research, the value of VP was studied in the context of engineering design and product development in the manufacturing industry. The goal of this research was to solve the research problems by creating new knowledge of the value and impacts of VP in a manufacturing industry context. To be solved, this goal required methodology for evaluating and modelling the value. The problem was approached from a design science perspective, aiming to justify value also for business management.

Our three research projects during nine years (2006–2014) enabled observation of the progress of implementation and adoption of virtual prototyping and virtual environments technology and methodology. Thus, it was possible to obtain relatively wide and rich data, but only in one company. The long time period also enabled observation of progress of understanding, changes in procedures, and maturation of technology.

At the beginning of the first project, the focus was mainly on testing different kinds of techniques and assessing their usability. Later on, when the technology was developed and validated, the focus shifted towards development of methods, procedures, processes, and product data management. Virtual prototyping became a method that could be used in real product development projects. Nevertheless, the use cases were still demonstrations and pilots that aimed to recognise the benefits and development targets. It was understood that VP holds great potential, but also big influences on the organisational processes and social aspects.

New technologies, like virtual reality, often face prejudice and uncertainty in companies. For instance, the survey study by (Engelbrektsson & Söderman, 2004) concluded that engineering designers' and product developers' perception of the usefulness of different product representations (e.g. hand-made sketches, drawings, mock-ups, scale models, 3D-CAD, virtual reality) is not necessarily equal to the actual experience of the product representation itself, but they consider more how the representations may affect the product development process. This was explained by the tendency to focus on the time and cost-related efficiency of product development rather than product quality aspects. VP was considered to be an expensive and difficult-to-use methodology. It is obvious that new technology, such as VR, must not impair the efficiency of the product development process. On the other hand, it should be understood how to improve effectiveness, as in better product quality by better understanding of the internal and external customer demands. Therefore, integration with company processes, knowledge, and infrastructure is essential in order to spread the use of VP.

8.1   Success of the research approach and process

Research design

A research design is the logic that links the data to be collected and the conclusions to be drawn to the initial questions of study (Yin, 2009). Here, the strategy for the research design for this thesis is discussed. According to Neville (2007), there are two principally different research philosophies: positivistic and phenomenological philosophies, which may also affect the selected and appropriate research approach and method. The positivist approach to research is common in natural science, where controlled experimental studies are typically used. However, for instance, human behaviour is not as easily measured as phenomena in natural science (Neville, 2007). Therefore, a phenomenological approach that

emphasises description and interpretation of the subjective experiences of humans may be more suitable when people are involved. For instance, case studies, action research, and grounded theory are typical methods in the phenomenological approach (Neville, 2007). Typically, phenomenological research also has a qualitative approach. This research obviously had a phenomenological approach, since the observed phenomena were very much related to human behaviour, and quantitative measurements were not included. Additionally, controlled experimental studies were not conducted. It was found more meaningful to observe the true-to-life activity in the projects and aim to make conclusions about them. Naturally, this kind of approach is impossible to repeat, which is the supposition in the positivistic approach, and there is more space for coincidence in the research process.

Grounded theory and abductive approach. Traditionally in the philosophy of science, the research approach has been categorised as deductive or inductive. Deductive research moves from general ideas or theories to specific and particular situations, while inductive research moves from particular situations to make or infer broad general ideas or theories (Neville, 2007). The third approach that is getting more acceptance in practical philosophy is the abductive approach. This research is mostly abductive, but there are also inductive traits.

The case study in one company is a particular situation, but some of the conclusions can be generalised based on the types of products and business of the company. Harnesk and Thapa (2013) clarified the abductive philosophy in the context of constructive research, information systems, and management science: the abductive method is an iterative cycle of deduction and induction, which, as an inferential procedure, creates conjectures that would contribute to the understanding of an ill-structured problem of the world when they were correct. Research may begin with an initial artefact, but the complexity of contextual circumstances infers uncertainty about the nature of the problem. Therefore, the abductive method is reasoning about the real-world problem, taking into account and analysing also subjective opinions of the social world, to develop the richest possible understanding. The initial "Phenomena model", which integrated the engineering design theory and the theory of virtual environments and virtual reality, can be considered as the initial artefact. However, it turned out to be insufficient for explaining the findings of the case study. Hence, the theory frame was expanded. In IT and management science, the abductive method has been typically used in studies of technology adoption with constructive interventions, rather than building technology. Furthermore, the abductive method typically represents the view of continuous stakeholder participation together with the researchers, resulting in an emergent perspective.

In abduction, formulated conjectures are shaped into sharp propositions. Another phenomenological research method is grounded theory. Grounded theory emphasises the generation of theory from data. Thus, theory is generated from observations made rather than decided before the study (Neville, 2007). This is reasonable, because the researcher often finds out during the research what they are actually looking for. Grounded theory seems to fit together with case study and

action research, as well as the abductive approach. This thesis research combines these approaches. This kind of approach seems to include the risk of a diffuse and lack of coherence. This was obviously a visible risk in this research when the dimensions of the VP value were expanded and new theories were selected to explain the case study findings. However, it is argued that, despite the risk of being diffuse, this research succeeded in structuring and conceptualising the complex phenomena, and establishing links between the theories and dimensions. It is not claimed to be perfect or the only possible frame, but at least it is argued to be an eligible starting point for research in this relatively new area.

The goal of this research was to solve the research problem and answer the research questions by creating new knowledge on the value and impact of VP in the manufacturing industry context. To be solved, this goal also required a methodology for evaluating and modelling the value. The first research question required a theoretical framework conceptualising, evaluating, and justifying the value of VP. Therefore, the constructive research approach and phenomenological philosophy were selected as an appropriate strategy. Additionally, the approach was qualitative, because the aim was to understand the intangible nature of the unit of analysis.

Constructive approach. The constructivist epistemology emphasises the fact that scientific knowledge is constructed by scientists with the help of "cognitive tools" and theories. In this context, the cognitive tools are concepts, notions, and models that help the researchers to express their thinking, findings, and conclusions for other researchers, in a scientific manner. The constructivist approach is the opposite of the positivist epistemology, which sees scientific knowledge as discovered in the world. For a classical positivist, scientific facts are discovered, and the connection between the world and the fact is unique. On the other hand, constructivism entails that there is no single valid methodology for the construction of scientific knowledge, so no unique prescription to establish "the facts" or provide the data, and no guarantee of a consensus (Crnkovic, 2010).

The scientific approach includes systematicity and interventions based on theoretical considerations, while refining the methodological tools during the research process (Crnkovic, 2010). In this research, existing theories and models of literature were used as cognitive tools that supported thinking and transferring the researcher's mental model about research data and findings to the constructed value evaluation model. As stated before, the constructed model is not claimed to be perfect or the only possible one. However, it succeeded in explaining the case-study findings in a scientific manner, and in establishing links between the concepts and notions between the dimensions of VP technology, product design, and development, social aspects, and business management. Thus, the constructive approach can be seen as appropriate for this research.

Exploratory study and unit of analysis. The constructive approach was also exploratory and expansive. The exploratory approach is typical when the problem is ill-defined. Thus, as the starting point of this research, a hypothetical theory frame "Phenomena model" was used, and it was expanded towards several dimensions as understanding about the research unit increased. Sometimes the unit

of analysis may have been defined one way, even though the phenomenon being studied actually followed a different definition, as in confusing a new technology with the workings of an engineering team in an organisation (Yin, 2009). At the beginning of this research, the unit of analysis was focused more on the new VP technology, but as the research proceeded and understanding progressed, it was shifted towards organisation, process, and management levels. The exploratory approach has been criticised for the possibility to draw solid conclusions about the research. This aspect was taken into account when drawing conclusions about this research. In particular, it has been considered how the conclusions about the one case study can be generalised. Anyway, it is argued that the problem and angle were new, so the exploratory approach can be seen as appropriate.

Interventional action research. Besides being constructive, non-experimental, and qualitative, this type of research can be characterised as interventional. Interventional means that the study was not purely observational or ethnographical, but the action research method was used. That is to say, the researcher was participating in the cases, and observing the case subjects, and simultaneously involved in developing the use of VP in the case company. Action research involves an intervention by a researcher to influence change in any given situation, and to monitor and evaluate the results. The researcher enters the situation, for instance by introducing new techniques, and monitors the results. This research requires active co-operation between the researcher and client, and a continual process of adjustment to the intervention in the light of new information and responses to it from respondents (Neville, 2007). Aiming to reduce challenges in product development, VP was introduced in the case company during the research projects. VP was utilised in several true product development projects.

The research takes place in real-world situations, and aims to solve real-world problems, so it has a social dimension, too. Action research enables the gathering of deep and diverse material, but there is a risk that involvement in developing work jeopardises objectivity in the research. However, action researchers do not try to remain objective, but recognise their bias to the other participants (Crnkovic, 2010). The risk of bias can also be managed using methods like triangulation, meaning the use of parallel sources, theories, methods, and researchers, and four Master's theses were written during the research period in the case company. In this research, bias was reduced by triangulation between literature, empirical study, and discussions with other experts and researchers.

The nature of non-experimental action research is such that statistically significant quantitative data is difficult, if not impossible to gather, and it is not even pursued. Thus gathered data was qualitative. Though qualitative data is typically richer than quantitative data, by means of decent analysis methods it may lead to a deeper understanding of the phenomena (Yin, 2009). As the case studies were conducted during nine years, while continually developing usage of VP, it was possible to have a retrospective perspective of action research, as well. Therefore, adoption of VP proved to rise from being a technological gadget towards a business-level strategic asset. The case study as a research method enabled the gathering of data in relatively realistic settings, thus the virtual environments la-

boratory was outsourced to a research institute (VTT). However, the case studies were related to actual new product development projects in the case company. This validates the findings related to design and product development phenomena. Modelling is one method of analysing case study data (Yin, 2009) and constructing new knowledge (Crnkovic, 2010). In this concept, modelling means conceptual modelling, meaning making a composition of concepts that are used to help people understand the subject the model represents. Furthermore, according to Sheridan (2014), scientific modelling is performed in conjunction with the scientific method by a sequence of the following steps:

1. Make informal observations and consider one or more questions on what is observed. An incipient mental model may already form in the observer's head;
2. Gather information and resources (formal observation);
3. Form a predictive or explanatory hypothesis in terms of independent and dependent variables. This is where a conjectural model begins to take shape;
4. Test the hypothesis by performing an experiment and collecting data in a reproducible manner. The experimental design will have a large effect on what model might emerge;
5. Analyse the data, preferably using appropriate statistical methods;
6. Interpret the data and draw conclusions that serve as a starting point for a new hypothesis. This is where the model is refined and formalised;
7. Publish or otherwise communicate the results to peers, rendering the model in a form that best summarises and communicates the determined relationships;
8. Retest and refine the model (frequently done by other scientists).

This research followed mainly the above scientific modelling method by forming first an explanatory hypothesis, which was tested in the case study and expanded and refined after the data analysis. The data analysis was not done by statistical methods, due to the nature of the data being only qualitative. This thesis is the way of publishing and communicating the research result to peers.

Research strategy

This chapter discusses first the success of the entry point into research. Second, the elaboration of research questions is discussed. Third, the success of the selected research approach and research questions in solving the research problem is discussed.

The main scientific school and paradigm of this research is research in the engineering design field. This entry point was reasoned from two viewpoints. First, engineering design theory provides for conceptualising and clarifying the research problem area. Second, this area of scholarship is the home base of the researcher. In the engineering design theory research can be scoped to design object knowledge and/or design process knowledge (Hubka & Eder, 1996). Later, when the theory frame expanded, the notion of design/designing was also considered more widely, as described, for instance, by Herbert Simon. Design is thinking,

deciding, and solving problems (Simon, 1969). Besides technical systems, the object of design may also include businesses and organisations.

From the engineering design viewpoint, the research was specifically scoped to include the manufacturing industry and partially configurable product variants. The observed business process was new product development in the case company. More specifically, sub-cases were related to embodiment and detail design in internal productisation (i.e. preparation for (serial) standard production; sub-case 3 and sub-case 6), and maintainability design (sub-case 2) of a new product/module, as well as to the concept design phase (sub-case 4 and sub-case 5). Another specific area within the scope was design for manual work, because the nature of production includes lot of manual assembly and maintenance tasks. The product in focus was a complicated mechatronic system for the mining and construction business. The research unit of analysis was the impact and value of VP within the process, at product and business level.

The overall research strategy can be characterised in respect of Design Research Methodology (DRM), described by Blessing and Chakrabarti (2009). Within DRM methodology, the research was focused on evaluation of existing design support, namely virtual environment-based virtual prototyping methods and tools. The evaluation strategy was based on reflecting empirical case data to the constructed theory framework from the dimensions of engineering design, economics and management, and social sciences. Formulation of research problems and question was described in introduction (Section 1), and answering to the questions and solution to the problems will be discussed in Section 9.

Selection of theory basis

This chapter justifies the selection of the theories, and describes how the selected scientific theories contribute to the research questions, and the areas to which this research makes a contribution. Possible scarcities of the existing theories are discussed, as well.

For case studies, theory development as part of the design phase is essential, whether the ensuing case study's purpose is to develop or to test a theory. Theory development prior to the collection of any case study data is an essential step in doing case studies (Yin, 2009). This research investigates the value of VP from several aspects: virtual prototyping as a piece of technology, product design and development, and organisational and business management, while the main contribution is n design science. Engineering design theory was a natural basis, because VP was studied in the context of product design and development. This research contributes to the field of engineering design. In that field, the Theory of Technical Systems (TTS) (Hubka & Eder, 1988) is an essential theory that clarifies the concepts of designing and developing technical products, and the concepts and properties of a product (socio-technical system) itself. The concept of value within design was also defined in the TTS. However, there are several base theories and schools within the engineering design community. The TTS can be seen

as the root of the research, where the author has his home base. This is the main reason for selecting the TTS as the starting point in this research. The hypothetical theory model for case study was based on synthesis of the TTS and the Theory of Virtual Environments and Virtual Reality (Kalawsky, 1993).

Analysis of the case study data revealed that the hypothetical model had to be expanded towards the dimensions of engineering design, social science, and business management. Based on this categorisation, the literature was reviewed in order to find new theories that support virtual prototyping evaluation. The selected theories cover a wide and *multi-disciplinary approach*. The selection of the theory basis followed the research process introduced in the Introduction section, Figure 9.

Virtual environments and virtual reality were the particular technology used in virtual prototyping. Therefore, the science of virtual reality and virtual environments was a self-evident choice. The science of virtual reality and virtual environments contributes to the research by delivering the multi-disciplinary knowledge foundation about virtual environment concepts and technology. The well-established scientific conceptualisation compared to much other virtual reality literature was the main reason for selecting the theory (Kalawsky, 1993). It classifies virtual environment elements from various aspects and describes the capabilities that possibly benefit design and value creation processes. Anyhow, the theory proposes utilisation in industry, but does not describe the connection, for instance, to design in detail. It is also proposed that industry and other possible users of the virtual environment should contribute by stating needs and requirements for the theory and technology development.

The Theory of Technical Systems (TTS) contributes to the research by describing the life-cycle of a technical system in which value is created, and explaining the purpose of models and prototypes within design processes. The TTS also contributes to the research by describing the properties and performance of a technical system that should be simulated by virtual prototyping. The TTS describes a model of a socio-technical transformation system, in which human beings have their important roles. Nevertheless, the human aspect is not treated very deeply. Additionally, the socio-technical transformation model is described as a rather causal process. Anyway, human beings usually make systems complex and non-causal. Although the TTS was published in the period when computer-aided tools and methods were relatively immature and rare, it discusses the role of such design support. Hubka and Eder (1988) argued that the development and introduction of such tools and methods should not be driven ad hoc by hardware and software, but by the needs of the design process. The TTS was supplemented with newer literature on the area, which also describes links from engineering design theory towards virtual prototyping (e.g. Weber & Husung, 2011).

The Theory of Dispositions (Olesen, 1992) contributes by describing mechanisms between the parameters of a product and the parameters of the systems that are realising the product and that the product meets during its lifetime. The Theory of Dispositions helped to explain mechanisms in which VP is an asset in identifying and communicating hidden issues within complex value networks. On

the other hand, disposition models could serve as means for recognising critical VP targets, because it is self-evident that not everything can be examined in virtual environments. The Domain Theory (Andreasen, 1980) enabled the linking of a virtual prototype to concepts of the design object. Domain Theory contributes by describing different views and abstraction levels of a socio-technical system model from the system use viewpoint (process domain) to the component structure level. This approach helps in connecting virtual prototype models with the design transformation process, especially in the case of human-machine systems where humans and their activities have an essential role. Thus, Domain Theory reveals both benefits of virtual prototypes and impacts of virtual prototyping for the methodology, processes, and infrastructure of manufacturing companies. Models of product development processes, like Integrated Product Development (Andreasen & Hein, 1987), incorporated models of managing product development in companies.

The Theory of Intermediary Objects (Boujut & Laureillard, 2002), drawing from psychology and cognitive science, enabled an explanation of the interface between the VP and human aspects. The Activity Theory, Theory of Expansive Learning (Engeström, 1987), and Theory of Dynamic Knowledge Creation (Nonaka, 1994) aided in the explanation of the meaning of VP in a wider organisational and social context. Cognitive science has concentrated on the representation and propagation of information, while Activity Theory is concerned with practice, as in doing and activity (Nardi, 1996). The Theory of Expansive Learning, built on Acitivity Theory (Vygotsky, 1978), gives social concepts to explain the complex activity of product development and virtual prototyping both from individual and organisational viewpoints. The basic triad of subject, object of activity, and mediating artefact enables clarification of how virtual prototypes and virtual environments create value in the human dimension. The theory can be used as a "lens" in analysing empirical research results. It is also a comprehensive framework that could be used to build bridges between the concepts of engineering design theories, virtual environments theory, social theory, and management theory. This was challenging because of the very different terminology of the theories.

Business management and value theories contribute to the research by clarifying the concept of value, and the mechanisms of value creation, transfer, and capture. In order to study the business value of VP, the context, meaning the business, should be modelled as well. The value chain model by Porter enables the positioning of design and virtual prototyping in the business context. In the classic value chain model, product development is considered as a support activity, but according to Olesen (1992), design and product development are functions that are part of product manufacture, and they should be seamlessly integrated with marketing and production. Virtual prototyping should be positioned in this later configuration. Additional value configuration models (value networks, value shops) contribute to the research by describing organisational frameworks and processes that help the justification of value creation, transfer, and capture. When the concept of "value" was clarified, value configuration and value network analysis turned out to be appropriate models for structuring and reflecting the case study material,

because in the end, value is created and captured in the business of companies. Value configuration analysis and value network analysis models contribute to the research by structuring business and organisations from both tangible and intangible asset viewpoints, and by explaining value creation, transfer, and capture mechanisms. Value networks analysis also offers principles for evaluating the value of an asset in practice. On the other hand, Stabell and Fjeldstad (1998) stated that, for instance, the evaluation of a firm-level value advantage in the value shops is more difficult than the evaluation of cost, because the relative cost of an activity and its relative value contribution are not necessarily related (Porter 1985).

The above-mentioned value theories and models also refer to the resource-based view and knowledge-based view to the firm, which explain well the empirical findings of the research study, and construe them as knowledge about value from an organisational and management point of view. The Resource Based View to the Firm (Wernerfelt, 1984) contributes to the research by explaining the elements and mechanisms in value creation. In their resource-based theory research, Bowman and Ambrosini (2000) emphasised that especially the perceived use value of an asset has both internal (enterprise) and external (customer) parts. They also stated that the tangible and intangible (e.g. knowledge) are inanimate, so they need to be activated by the intervention of people in order to create new use value. Therefore, labour is the only source of new use value, which can be captured as exchange value and profit. Bowman and Ambrosini also introduced a model of the value creation process that could be utilised in this research, in order to analyse the case studies.

The value-in-use approach (Grönroos, 2008) and the theory of core competence (Prahalad & Hamel, 1990) enabled argumentation of VP value as a strategic business asset. Business management theories are needed because product development is essentially a commercial function (Krishnan & Ulrich, 2001). The notion of value-in-use proposes that value is not embedded in goods or services (value-in-exchange), but value is rather created when goods or services are used and skills and knowledge of users are added to the value creation process (Grönroos, 2008). Therefore, goods and services are value propositions and foundations for value created by the consumers. When VP is understood as a combination of goods and services, and both internal and external customers are considered, it creates value only when combined with the skills and knowledge of the product design and development process. Sometimes part of the value can be measured in short-term financial terms, like cost savings, but value always also has an attitudinal component, such as trust, affection, comfort, and ease of use, whose impact can be assessed only in the long term (Grönroos, 2008).

Knowledge theories, especially the Dynamic Theory of Organisational Knowledge Creation by Nonaka (1994), contribute by introducing the concepts and framework that help to justify the value of VP from individual, organisation, and management viewpoints. The theory of Nonaka also has analogies with value configuration models (value networks, value shops), value in use theory, and the resource-based view. Thus, it emphasises the social aspects and cultural perspective of business, compared to pure economic aspects like the value chain model.

The theory contributes to organisation science by explaining organisational creativity, change, and innovations, and so aims to serve organisational development and management (Nonaka & von Krogh, 2009). Redundancy of information and knowledge within self-organising, multi-disciplinary, and cross-functional teams were seen as essential in the theory. The significance of VP could be explained with the concepts of the dynamic theory (like the use of metaphors and prototypes, bodily experience, rhythm of management) of organisational knowledge creation. The theory also justifies the importance of both communication content and communication line in joint knowledge creation, and gives some practical references to product development in the manufacturing industry. The theory was derived from the analysis of Japanese industry and its success.

These theories were selected based on dialogue between empirical data and the literature. They were proposed as elements of the value evaluation model, which established links between these theory concepts. They are not claimed to be the only or the perfect set of theories. Nevertheless, they were adequate for the goals of this research. One of the major contributions of the selected theories is gained by clarification of the similarities and differences between the concepts and terms 'virtual prototype', 'virtual prototyping', 'virtual environments', and 'virtual reality'. They are studied from different theory aspects, and a link to design theory, as well as value and organisation theories, is established.

Selection of empirical research methods

This chapter justifies the selected research methods and their suitability for the selected research strategy and contribution to the research. In this research, the research methods can be put into three main categories: a) empirical research methods, b) data-gathering methods, and c) data analysis methods.

Case study. Case studies have been made about decisions, programmes, the implementation process, and organisational change (Yin, 2009). In all these situations, the distinctive need for case studies arises out of the desire to understand complex social phenomena. The case study method enables investigators to retain the holistic and meaningful characteristics of real-life events. Four types of designs for case studies (Yin, 2009) are: 1) single case (holistic), 2) single-case (embedded), 3) multiple case (holistic), 4) multiple-case (embedded). This research was a single case, meaning that it was conducted only in one company. However, there were several sub-cases during the six-year period, and the approach was holistic, aiming to understand the complex phenomena in a real-life situation. The relatively empirical research and the richness of the material is proposed to be one of the strengths of this thesis, because empirical knowledge of VE-based virtual prototyping is relatively narrow in the present literature. Additionally, it was a very interesting and meaningful approach for the author.

One rationale for a single case is when it represents the critical case in testing a well-formulated theory. A single case can confirm, challenge, or extend the theory. A third rationale for a single case is the representative or typical case. The case

study may represent a typical project, a manufacturing firm believed to be typical of many other manufacturing firms in the same industry, at least in Finland. A fourth rationale for a single case study is the revelatory case. A fifth rationale is the longitudinal case: studying the same single case at two or more different points in time (Yin, 2009). The single case can be given a rationale because it was used in theory extension. Additionally, the case company represents a typical case in the Finnish manufacturing industry. Therefore, the generalisation of results must be based on characterisation of the company and its products and processes. Furthermore, the case was longitudinal, studying the single case over six years, at several points, revealing new layers of VP and its benefits.

Data-gathering methods

Literature analysis. A literature review was used for several purposes during different phases of the research. First, a comprehensive review was made during the clarification of the research problem and focal concepts, and as the basis for constructing the hypothesis. The literature was also consulted later, in order to find theories and models that help in the interpretation of empirical findings and in expanding the construction of new scientific knowledge. At first, it was challenging to figure out how to delimit the survey, but progress in the research focused the approach, and in tandem the necessary literature. Anyway, the multi-disciplinary nature of the research made the literature survey challenging, because so many new areas of knowledge had to be consulted. The result of the survey could be better, but with the limited time and resources, it had to be limited. Anyhow, the aim was to recognise the significant publications and draw conclusions together with the case study material.

The research was focused on the context of product design and development, and particularly on manual work during productisation and product life. Therefore, theories, concepts, and models from engineering design science were chosen as one of the scientific foundations. Second, virtual prototyping and virtual environments were focal concepts of the research that were clarified and reflected using the concepts of engineering design theory. Value was another focal concept of the research. The analysis of the value concept within the research context guided the study of the meaning of value from the business perspective. The aim of the next phase was to investigate existing knowledge about the utility of VP. The analysis and interpretation of empirical case study material led to an extension of the literature review towards social, management, and economic concepts and theories.

Sources of evidence

Case-study evidence may come from six sources (Yin, 2009): documents, archival records, interviews, direct observation, participant observation, and physical artefacts. Some overriding principles are important to any data collection: the use of multiple sources of evidence, a case-study database, and a chain of evidence. In this research, empirical data sources included interviews, questionnaires, direct

and participant observations, workshops, design review meetings, simulation games, documentation, and discussions with experts and other researchers. Questionnaires, workshops, and simulation games can be seen as sub-categories of interviews. Interviews were held a couple of times during the case study, but observation and documentation were done all the time during the project work. The interviews and questionnaires were firstly targeted at getting understanding about the situation and operations in the company, and later about feedback on VP. Structured interviews and questionnaires were used to get an overview on a specific topic and to gather wider data, while unstructured interviews and questionnaires enabled drilling into deeper details. One of the most important sources of case-study information is the interview: an in-depth, focused, survey (Yin, 2009).

Workshops were organised in order to study and discuss some specific issue or problem, and simulation games were used to model certain as-is or to-be processes, information flows, and organisational aspects. The as-is and to-be models supported recognising the benefits, enablers, and challenges of VP implementation. The simulation games were recorded in the form of process models, meaning so-called "swim-lane" models. Both workshops and simulation games included participation by members of several functions of the case company, as well as the researchers. The systematic methods (structured interviews and questionnaires, simulation games) enable the collection of material that is comparable and structured. However, it was difficult to define good questions for the interviews and questionnaires when the unit of observation was shifting as the understanding improved during the case study. On the other hand, the unstructured methods, like observation and discussion, seemed to give richer material, but the challenge was in documenting them. Therefore, the author adopted the habit of writing down notes about all remarkable situations in the case study.

Unit of observation and analysis. In research design and case-study planning, it is important to pay careful attention to what the case, meaning the unit of analysis, actually is. This, of course, affects what kind of data should be collected. The scope of data collection should distinguish data about the subject of the case study (i.e. the phenomenon) from the data external to the case, or the context (Yin, 2009). On the other hand, the unit of analysis should be distinguished from the unit of observation (Savioja & Norros, 2012). This means that in this research, the unit of analysis is about the value and impact of VP, while the unit of observation is individuals and groups of people. Figure 71 aims to illustrate the relationships between the research context, case study, unit of analysis, and unit of observation. Each case study and unit of analysis either should be similar to those previously studied by others, or should innovate in clear, operationally defined ways. In this manner, the previous literature can also become a guide for defining the case and unit of analysis (Yin, 2009). A study of the literature was conducted first in the research clarification phase, in order to clarify the concepts and gather understanding of the field. Later, when the research progressed and the theory framework expanded, the literature was summarised intermittently, when new aspects were identified, and studied inter-disciplinarily. Scientific databases were

searched for relevant theories and the state-of-the-art. Anyway, the exploratory and abductive nature of the research caused a changing unit of analysis, which made the observation, data collection, and analysis sometimes difficult. However, the concept-mapping method helped to establish and keep coherence with the material and analysis.
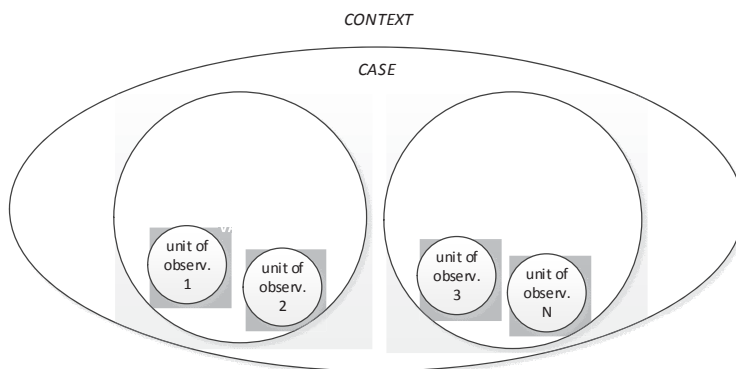
Figure 71. Relationship between the unit of analysis, unit of observation, and context.

Case-study database. Properly done, data collection is likely to lead to large amounts of documentary evidence in the form of published reports, publications, memoranda, and other documents. For case studies, the researchers' own notes are likely to be the most common components of a database, and it is good to point out the self-reported nature of data (Yin, 2009). The database of this research includes published papers and reports, project deliverables, company internal reports, meeting minutes, and notes about the observations and workshops and simulation games made by the researcher and his colleagues. The database was structured during the research and is maintained on the VTT server. Part of the raw data is confidential, thus permission is needed from the case company before investigating the data. However, the conclusions of the research can be traced back to the raw data. The mixed nature of the database made the analysis more laborious, but on the other hand, it was richer than, for example, pure material from a questionnaire. Additionally, it can be seen as a way to triangulate and discuss the validity of the research.

Chain of evidence

Data analysis. Case study data collection is not merely a matter of recording data in a mechanical fashion, but interpreting the information by examining, categorising, tabulating, testing, or otherwise recombining to draw conclusions as it is being collected (Yin, 2009). Data analysis in case studies consists of examining, categorising, tabulating, testing, or otherwise recombining evidence, to draw empirically

based conclusions. Five specific techniques for analysing case studies are pattern matching, explanation building, time-series analysis, logic models, and cross-case synthesis (Yin, 2009). The data of the case study in this research was analysed by means of categorisation and conceptual modelling[16]. The analysis method reflected the gathered data and observations against the existing theories and models in literature.

The conclusions and main statements of the research results were made by logical interference and reasoning, analysing the data using concept-mapping techniques. The concept maps show the links between the technical features of VP and advantages and value in design and business at organisational and individual levels. As a conclusion, data was derived as factors and perspectives that guided the formulation of a VP value model.

Theory development prior to the collection of any case-study data is an essential step in doing case studies (Yin, 2009). In this research, first a hypothetical theory model was constructed by synthesis of engineering design theory and the theory of virtual environments and virtual reality. The collected empirical data was analysed using conceptual modelling, and reflected against existing theories that helped to conceptualise and structure the data, and to understand the phenomena from several aspects of technology, design, economics, and sociology. This interplay aimed to construct a model for the value evaluation of VP. The strength of the conceptual mapping was the ability to clearly establish the links between elements of VP and scientific concepts. However, for others, it may not be so clear, due to different educational backgrounds, experience, and mental models. Hence, the wide area of used literature is justified for grounding the findings and conclusions in the existing scientific knowledge, which is also the purpose of scientific research. The conceptual mapping is anyhow a decent means for making one's thinking visible.

Model construction and analytic generalisation. The process of data structuring is inherently constructive. In science and engineering, this process is present in the construction of a model or an artifact. Typically, there is a starting point in the existing background knowledge, models and artefacts that present important constraints in the process of construction. In the research process for the design of an artefact, of central interest is how this designed construction evolves and how the artifact relates to its users. (Crnkovic, 2010)

Construction of the VP value model was founded on the discussion of empirical case data and identified scientific theories. Gathered and analysed material was synthesised with existing theories and models, in order to structure the VP value model. This part of the research aimed to give answers to the first research question: How can the value of virtual environment-based virtual prototyping be evaluated and justified? The created models were validated by comprehensive discussions with experts in industry and other researchers in several workshops and

---

[16] "Conceptual modeling is the activity of formally describing some aspects of the physical and social world around us for the purposes of understanding and communication." (Mylopoulos, 2008)

scientific conferences (ICED11, ICED13, DESIGN10, DESIGN12, TMCE12, TMCE14). In social science, most field experiments will not be able to include the participation of a sufficiently large number of communities to overcome the severity of the subsequent statistical constraints. The role of theory has been characterised as "analytic generalisation" contrasted with "statistical generalisation". A fatal flaw in doing case studies is to conceive of statistical generalisation as a method of generalising the results of the case study (Yin, 2009). This research and case study was about engineering design and virtual prototyping. Both are social by nature, when the resource-based view was taken, and the unit of observation is people, while the unit of analysis is value and impact. Thus, theory was used in analytic generalisation and the results are qualitative.

The research results were derived from the literature, theory basis, and analysis of empirical case studies. The results include three main types of knowledge: 1) a proposed theory framework model as a scientific foundation for evaluating the value of VP in the case company in a manufacturing industry context; 2) knowledge of benefits and value, as well as drawbacks of VP, in practice; 3) knowledge of the impact of adopting VP in industry. These results are discussed and reflected against the literature in one section of this thesis, and the quality of the results is discussed after that. Some results of the research projects and case studies were published during the projects, and the articles were one source of material for this research. The researcher was one of the authors in many of those papers.

8.2 Results – Discussion on research content and validity

Depending on the phase of the Design Research Methodology (Blessing & Chakrabarti, 2009), categories of research results include: new scientific knowledge and insights, theoretical frameworks, models, design supports (concept or realisation), or support evaluations (Blessing & Chakrabarti, 2009). The results of this research are based on evaluation of existing support (i.e. VP) in the industrial context. The results appear in the form of new knowledge of the value and impact of VP, and how the value can be evaluated based on the constructed theory frame. The results are related to the research questions. Answers to the research questions and the original research problems are described in the section 9.

Scientific evaluation of the research

The philosopher Karl Popper asserted that a theory can never be proven correct by observation, but can only be proven incorrect by disagreement with observation, thus scientific method is about falsifiability (Sheridan, 2014). This philosophical statement is reassuring, since the abductive approach of this research aimed at the best possible explanation of the studied phenomena, but it does not claim to be universal truth. Testing the constructed model and knowledge and possible

falsifiability will be the task of other researchers. The American Association for the Advancement of Science asserted, in a legal brief to the U.S. Supreme Court[17] (1993), that "*Science is not an encyclopedic body of knowledge about the universe. Instead, it represents a process for proposing and refining theoretical explanations about the world that are subject to further testing and refinement*" (Sheridan, 2014). The scientific justification of research shall be based on the following criteria (Airila & Pekkanen, 2002): the novelty, publicity, truth-likeness, and universality of the knowledge, and the publicity, criticalness (researcher) of the research, and autonomy (stakeholders) of the research.

The novelty and publicity of the knowledge. The novelty of the produced knowledge during the research was assessed by comparison with the existing literature, and discussions with researchers and experts in other companies, research institutes, and universities. The results were presented and discussed at several scientific conferences in the field of engineering design (ICED11, ICED13, DESIGN10, DESIGN12, TMCE12, TMCE14). The major novelty of the research springs from the adoption of a strategic business view of VP, and assessing its value from engineering design, social, and business capability viewpoints, as well. The novelty is also argued by the empirical study in industry. The new knowledge was disseminated through public research projects. The main results were presented, discussed, and published at scientific conferences during the years 2010–2014.

The truth-likeness of the knowledge. Truth of new scientific knowledge is too hard a requirement (Airila & Pekkanen, 2002). Therefore, for knowledge to be truth-like is a sufficient attribute. Indeed, in social empirical science, only approximate truths are aspired to, because it would be an illusion that a single formula for capturing the whole truth could be found (Simon, 1979). The models of product development research are, at best, coarse approximations of the phenomena, unlike the models in the physical sciences (Krishnan & Ulrich, 2001).

Truth-like means that new knowledge is approximately true (Airila & Pekkanen, 2002). The better new knowledge models reality, the more it is truth-like. There are normally two approaches for modelling a phenomenon in reality (Airila & Pekkanen, 2002): 1) defining better parameters for an existing model, 2) creating a new model and its parameters.

In this research, the phenomenon in reality is approached by proposing a new better model and its parameters for VP value modelling. In order to validate the research, four types of triangulation are proposed to exist when doing evaluations: 1) triangulation of data sources (data triangulation), 2) triangulation among different evaluators (investigator triangulation), 3) triangulation of perspectives of the same data set (theory triangulation), 4) triangulation of methods (methodological triangulation) (Yin, 2009). The truth-like requirement of this research was evaluated in several ways. There were several data sources, including reports, publications, notes, deliverables, which were made by several people. The interpretations

---

[17] U.S. Supreme Court Proceedings,1993. Daubert v. Merrell Dow Pharmaceuticals, Inc, p. 509. U.S. 579, 590.

and models of the data were discussed several times with other researchers and company people, and they were presented at scientific conferences. The same data set was analysed and interpreted using theories from the dimensions of virtual environments, engineering design, social science, and business management. Furthermore, several methods were used for data collection and analysis.

The universality of the knowledge – generalisation. The case study is not the best method for assessing the prevalence of a phenomenon, because a case study would have to cover both the phenomenon and its context, yielding a large number of potentially relevant variables (Yin, 2009). Argumentation on the universality of the new knowledge created in this research is based on characteristics of the case company, product, business model, product process stage, production mode, and reasoning on how the results can be transferred to companies with similar types of characteristics. The constructive generalisability (Lukka & Kasanen, 1995) proposes that linking the solution in one case to the literature justifies the supposition that it can also be valid in similar situations in other companies. The constructive research approach is a heuristic process based on deep knowledge of the problem at hand and of existing theory (Lukka, 2006). The reasoning process is abductive (Piirainen & Gonzalez, 2013). Additionally, the fact that there was only one case company limits generalisation of the results. General criticism about single-case studies usually reflects fears about the uniqueness or artifactual conditions surrounding the case (Yin, 2009). However, it was a conscious decision to focus on just one company and study it more deeply. Generalisation of the results was justified by describing the characteristics of the company's business, including characteristics of products and product processes, as well as settings of the case studies. This enables the transfer of knowledge to other companies with similar types of characteristics.

The publicity, criticalness, and autonomy of the research. The research process itself was public, since the research was accomplished in publicly funded research projects. Nevertheless, no research can be fully critical or autonomous, because of the bias and opinions and preconceptions of researchers and the environment. This had to be considered, especially because the action research method was used, meaning that the researcher was simultaneously developing the virtual prototyping methodology in the case studies, and observing the possible advantages and value of VP in the industry. Case-study investigators are especially prone to bias, because they must understand the issues beforehand (Yin, 2009). Actually, as scientists are real people, they are always biased by their initial knowledge and interests, status and physical location, and available tools of observation, which affects what observations are made and what questions are asked (Sheridan, 2014). Anyhow, the researcher was eager to get true knowledge on the real value or lack of added value from the business perspective. However, the original hypothesis was that VP would bring some added value and benefits for design and business. Additionally, the researcher was neither influenced nor rewarded by any stakeholders in the research.

Constraints and limitations

The research was limited to real, new product development cases in just one case company and at one factory site in Tampere. Therefore, generalisation of the results, especially the knowledge about value and benefits, has to be related to typification of companies, products, business models, and production modes. VP has proven value in complex integrated product development and in collaboration between design and production of complicated products. Anyhow, VP value capture requires a paradigm change in the way product development is organised around VP. On the other hand, the proposed method of VP value estimation in industry is a generic framework that should be configured for a specific company or network, case by case.

Researcher's role and learning process

The researcher has been working as a researcher in a research institute for about fifteen years. The work has been mainly applied research and practically oriented. The research has been related to development of industry products and processes, specifically human-machine interfaces of machines and production systems. Research topics have been related to several types of virtual prototyping methods and techniques, for instance multi-body dynamics and kinematics simulations of mechatronic machines, and real-time virtual environments of human-machine systems.

During his career, the researcher has been shifting his perspective from technology issues to product design and development processes, and utilisation of VP technology. This has been happening naturally in conjunction with technology and methodology maturity and industry interest. The researcher believes that the total value of VP has not been captured in industry, because of a lack of understanding of its opportunities and preconditions. Product design and development interest has led naturally from engineering sciences more towards design sciences, which have been the main subjects of the doctoral studies. Additionally, interest also grew towards social and business management science during this research.

Generally, the doctoral studies and dissertation work have taught scientific thinking and the scientific research method. The results of this research were gathered in three large research projects in cooperation with several other researchers. The role of researcher in this study was related to emphasising engineering design and process viewpoints, as well as industry benefits and impact.

9. SUMMARY AND CONCLUSION

The research problem emerged from insufficient knowledge and justification of benefits and value of VP in the manufacturing industry context, both in practice and in scientific publications. There has also been a gap between scientific literature of engineering design theories and theories of virtual reality and virtual environments. Moreover, the methodology for assessing the value of VP has also been narrow. In the literature, the perspective to VP has been very technical, but with loose connections or evidence of business value. This problem was approached from the science base by formulating an expanded theory framework for value modelling, and from the problem base by empirical case study of one manufacturing company. Based on the dialogue between theory and practice, the research resulted in three types of new knowledge: 1) a theory framework for value evaluation, 2) knowledge of VP value in practice, and 3) knowledge of the impact of VP in the company.

In this research, virtual prototyping is defined as a methodology that refers to the activity of prototyping. In virtual prototyping, virtual product models, meaning computer simulation models of the product, are used instead of or in addition to physical prototypes. A virtual prototype is a computer simulation model of the product prototype that is used in the virtual prototyping activity. This research is focused on real-time interactive models that are manipulated in virtual environments. A virtual environment is a real-time user interface to a virtual prototype model in the virtual prototyping activity. It provides the user with a natural feel of presence in a three-dimensional computer simulation world, and interaction with the 3D objects in that virtual environment. Virtual reality refers to the technology that enables the creation of virtual environments. In this research, the latter meaning is used. *Intermediary virtual prototyping (IVP)* is a new concept resulting from this research. It underscores the many layers and dimensions, from the technical advantages of virtual reality to the expanded mediating object of a product development activity system.

In this research, the value of VP was studied in the context of engineering design and new product development in the manufacturing industry. The industrial study was focused on low-volume configurable products and manual, work-intensive variant production. The product development was considered as a business process of the case company. The goal of this research was to solve the

research problems by creating new knowledge on the value and impact of VP in the manufacturing industry context. To be solved, this goal also required a methodology for evaluating and modelling the value. The problem was approached from the design science perspective, aiming to justify value also for business and management. However, it was obvious that engineering design theory does not provide sufficient concepts for business value modelling. Thus, as one result, this research proposes what theory dimensions need to be supplemented to the core engineering design theory.

Summary of the research process

Answering the main research question was based on comprehensive case-study research in one large manufacturing company over nine years (2006–2014). The case study included six sub-cases that were related to new product development projects in mobile rock crushing and screening equipment. More specifically, the sub-cases were focused on manual assembly and maintainability in concept design and internal productisation, that is, preparation for standard production.

The research approach was constructive, exploratory, and abductive, meaning that new knowledge was constructed by analysing and reflecting qualitative case data with the hypothetical phenomena model. The exploratory approach means that, during the case study and data analysis, the theory framework was expanded towards new theories and concepts that were explored from the literature, in order to find better interpretations, explanations, notions, and concepts for the findings in the dimensions of technology, design, social aspects, and business management.

The abductive method is an iterative cycle of deduction and induction that contributes to the understanding of ill-structured problems of the world. First, when the focus of virtual prototyping expanded from the first technology demonstrations to real, new product development projects, it was understood that it will have a wide impact on processes, organisations, and technology infrastructure, like product data management. Small gains can be achieved locally through incremental steps, but the major benefits can be achieved only when the product life and business is regarded as a whole. This can be considered as a systemic and revolutionary paradigm change. The research progressed as an expansive dialogue between the theory base and empirical case study material of a manufacturing company over nine years.

No direct methods for holistic value modelling in the manufacturing industry context were found in the literature. However, the value of general information technology to firms has been modelled based on the resource-based view (RBV) in the literature. The RBV is a strategic management theory that defines a firm's resources as tangible and intangible assets that could be thought of as strengths or weaknesses of a given firm. RBV was adopted as a starting point for expanding the theory frame from engineering design theory and the theory of virtual environments, in order to explain the case-study findings. Management and social science theories complemented the synthesis, since social dimensions and manual

work tasks were essential in the case study, and they provide for justifying the value of VP.

The definition of value in the context of products and services was described as equal to the cost of the product or service plus a subjective part of the value. Additionally, value is not embedded in the products or services, but it is created when they are used. In general, value theories aim to understand how, why, and to what degree people value things. Virtual prototyping was briefly defined as the opposite to physical prototyping, utilising interactive and real-time computer simulations of a product.

The validity of the contribution was made by triangulation between the literature, empirical study, and discussions with other experts and researchers, and four Master's theses were written during the research period in the case company. However, validity is restricted to the nature of the business, where products are partially configurable in manual, work-intensive variant production mode with relatively low volumes. Based on this research, the value of VP is manifested by utilisation by people as a core competence of the company.

The main propositions. The main propositions are derived from the proposed concept of intermediary virtual prototyping (IVP):

- IVP as an intermediary object of an activity system enables shared mental models, organisational learning, and knowledge creation that are crystallised in new products.
- IVP enables expansion of the product, or an object of a complex product development activity system.
- IVP enables revealing latent and unwanted dispositions by shifting from the product part domain towards the organ domain, and linking the organ domain of the product perspective with the process domain of the production perspective.
- IVP is particularly beneficial in manual, work-intensive variant production, where human skills and knowledge contribute to the flexibility of the production system.
- Value is created when IVP is used and combined with the skills and knowledge of the users, thus only part of it can be estimated as a monetary exchange value.
- IVP enables balancing the daily performance and long-term core competence by contributing to knowledge creation in the company. Therefore, IVP should be considered as a strategic investment that will produce income in the long run
- IVP creates value in use, but in turn it affects the company in all the mentioned four dimensions. Thus, the perspective into the adoption of IVP should be widened from technology to PLM strategy and organisation design.

Answering the research questions

In research, asking good questions is to understand that research is about questions and not necessarily about answers (Yin, 2009). Although good questions are perhaps even more important than good answers, this chapter aims to explain how the original research questions were answered. However, this thesis aimed to contribute to science also by seeking new perspectives to the given subject, thus also inventing good questions. The research questions were formulated in order to study the research problem from three different research aspects: 1) prescribing a theory foundation for value modelling, 2) describing empirical value, and 3) describing the empirical impact of VP. From these aspects, the following research questions were formulated:

1. How can the value of virtual environment-based virtual prototyping be framed, conceptualised, evaluated, and justified?
2. How can the empirical value of intermediary virtual prototyping be observed, concretised, and described?
3. How and by what means does the intervention of VP affect the case company?
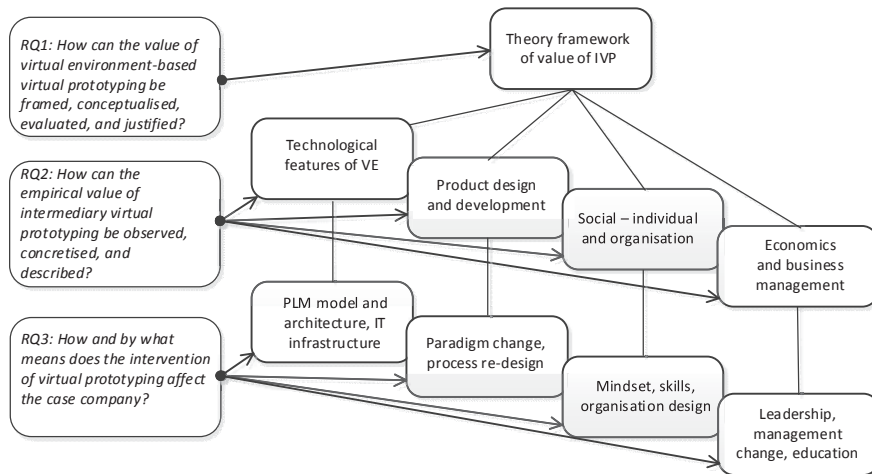
Figure 72. Answering the research questions and relations between the question and answers.

Figure 72 illustrates how the areas of new knowledge contribute to the research questions, and what the relationships are between the questions and new knowledge.

1) How can the value of virtual environment-based virtual prototyping be framed, conceptualised, evaluated, and justified?

The literature review of this thesis did not reveal coherent and extensive models or theory for the evaluation of virtual prototyping or a definition of the value of virtual prototyping. Therefore, theory and models for the evaluation of generic ICT were selected as a starting point from the business value angle. Reflecting case data with the Resource-Based View of the Firm led to the inclusion of other management theories, such as the Theory of Dynamic Knowledge Creation. From the opposite angle, the Theory of Technical Systems and the theory of virtual environments were the starting point for analysing the empirical data. The dialogue between case data and theory expanded the frame to social science, which built the bridge to management models. The new concept of intermediary virtual prototyping was proposed to integrate the four dimensions.

As a result of the research, a theory framework was constructed as a basis for the evaluation of VP. The framework recognises four main dimensions of value: 1) virtual environments and virtual reality technology as an improved interface to system models, 2) product design and development from process and object viewpoints, 3) the social dimension, including individual and organisational aspects, and 4) economics and management. The theory framework establishes links between the concepts of these dimensions and a logical path from virtual reality technology to business value, meaning justified evaluation of VP.

The framework adopts a strategic approach because that explains what actually contributes to business value. Value models and theories that include intangible and subjective value elements into business value chain models, and highlight the value of human skills, knowledge, experience, motivation, and so on, were endorsed. The value theory section of the research revealed that people and their knowledge is the essential core competence in companies.

2) How can the empirical value of intermediary virtual prototyping be observed, concretised, and described?

The value of VP appeared to be difficult to estimate in terms of money or such quantitative currency. There are normally too many variables affecting the benefits and cost of VP. Furthermore, resources create value when they are put into use and combined with skills and knowledge. Therefore, only part of value can be measured in money. Instead of calculating quantitative value, the proposed theory frame includes factors and a logical chain from VP technology to qualitative value

components. Empirical data can be reflected with the constructed frame, which enables concretising and describing the value of VP. The case study of this thesis describes how value elements can be observed and discussed with theory.

The main proposition of the research states that the value of VP is manifested by its position as an intermediary object and a medium for improved communication and knowledge creation. IVP improves communications and the systemic view of complex systems by expanding the design object. Therefore, IVP should be considered as a strategic asset for firms, improving the utilisation of resources and core competence. Understanding the strategic value of IVP and proper implementation of it in a company's processes and infrastructure (like PDM and PLM) could be seen as a core competence accounting for its role in improved knowledge transfer and conversion, and therefore better utilisation of resources and intangible value. Therefore, positioning IVP within the value network is essential.

The added value of an intelligent VP value network is derived from the facilitation of necessary human interventions and the opportunity to make mistakes and learn with immaterial prototypes based on intangible assets, compared to trial and error in a conventional physical value chain. Setting the intangible human assets into motion must be seen as a strategic investment that will produce income in the long run.

Quantifiable objects on the potentially value-adding side could be, for instance, the number of engineering changes, the costs of physical prototyping, the calendar time of product development and productisation projects, ergonomic aspects like the number of safety problems, and levels of occupational well-being. The more problems can be identified and changes made with a virtual prototype, the fewer changes and problems occur within the physical prototyping and serial production. Thus, the internal quality of the product will be better. Similarly, the increased cost side of the IVP could be quantified, including, for instance, the cost of creating virtual prototypes and virtual environments, investments in the infrastructure, processes, and competence. At the end of the day, it is a matter of comparing the added value and cost when decisions on investments and funding are made.

3) How and by what means does the intervention of virtual prototyping affect the case company?

The value of VP has been justified in four dimensions, described in questions one and two. In turn, implementation of VP seems to have systemic impulses to the processes, organisation, and infrastructure of the company. The anticipated benefits of VP should be balanced with the impacts on the organisation. IVP affects the organisation in the dimensions of people, processes, and technology, meaning the PLM model of the company. The people dimension requires skilled and committed users and managers, and probably also new roles and competencies. Stakeholders should be better involved in the organisation design. IVP interrelates with many other technologies and processes. An interface with product data management system and product structures that support IVP are the essential precondi-

tions for effective IVP. IVP also requires a paradigm change in engineering design and product development. The NPD project should be frontloaded, and the way in which design maturity progresses and virtual product models are produced should be changed.

The impact is difficult to quantify because business organisations are open and complex dynamic systems with fuzzy boundaries. Furthermore, the value of IVP has tangible and intangible elements that are multiple and qualitative instead of simple and quantitative. However, the impact of IVP can be modelled qualitatively as a dynamic system, which helps in recognising the affected existing elements or the required new elements of the system. It also helps in assessing the anticipated advantages and cost.

Solution for the research problem

The lack of practical evidence in industry and the knowledge gap in the literature concerning the benefits and value of virtual environment-based virtual prototyping was formulated as a practical research problem:

How can the adoption of intermediary virtual prototyping be propagated in manufacturing industry by justifying its value and usefulness in complex business environments?

and a scientific research problem:

How should research on virtual prototyping and virtual environments be integrated with design science research?

The second problem was reached by establishing links between the concepts of scientific disciplines as part of the theory framework, which also enabled the solution of the first problem by providing a framework for value justification. The research progressed as a dialogue between the practical and theory problem base. The complexity of the practical problem induced to the expanded theory frame with the four dimensions. However, the practical research problem can be considered only partially solved, because it was treated only qualitatively. Especially directors and sponsors of the industrial companies are predominantly interested in quantified results, like saved money or time. It was not possible to get quantified data within the period and scope of this research. However, in the ongoing project, the principles for quantified value modelling have been proposed based on comparing past and ongoing NPD projects and their costs and time. Anyway, as was theoretically reasoned before, only part of the VP value can be quantified, while part of the value is subjective. On the other hand, the approach of creating first the theory frame for structuring a possible later quantitative analysis is reasonable.

Scientific implications and contribution

The importance of this research arose from the absence of knowledge and evidence on the industrial value of virtual environment-based virtual prototyping. This causes retardation of its propagation, because companies need evidence of value as a basis for investment decisions in new technology. The value of VE-based virtual prototyping is insufficiently proposed in the present literature. The literature is either scarce or old, or very technically oriented. On the other hand, value is touched upon in many publications from other VE domains like training, learning, and psychology.

This research considers virtual prototyping from a business viewpoint, because it is a way to ultimately justify value in business. Business means, in this context, both the logic of making money, and the resources needed for running a business effectively in the long run. Results include knowledge on how value can be described scientifically, and how it can be evaluated in industry. This research contributes to more holistic understanding about virtual prototyping and its value, both in academic world and industry. Value of this research emerges specifically from the relatively long empirical study in industry reflecting the data with the created theoretical frame.

This research contributes to design science in the form of new knowledge of how the value of virtual environments (VE)-based virtual prototyping can be described and modelled in the context of the manufacturing industry and product development. The new knowledge includes a theoretical foundation for VP value modelling. The contribution and novelty are manifested by constructing an expanded theory framework for virtual prototyping value modelling in four dimensions, with causal justification from virtual reality technology to business value elements that led to the *new concept of Intermediary Virtual Prototyping (IVP).*

One form of the contribution appears in the form of conceptualising virtual prototyping and virtual environments with respect to engineering design theory. The engineering design theory frame was expanded towards virtual environments, in social and management theory dimensions. The research fills the gap in literature, which is the missing link between concepts of virtual environments and concepts of engineering design. The research also creates knowledge of the virtual prototyping value in practical industrial settings that was narrow in the literature. Utilisation of the constructed value model contributes to knowledge of practical advantages and value, as well as criticism and impacts, of VP in the manufacturing industry. Thus, the original research problem "*How can the adoption of intermediary virtual prototyping be propagated in manufacturing industry by justifying its value and usefulness in complex business environments?*" can be considered to be solved.

The research was limited to real, new product development projects in just one case company. Therefore, generalisation of the results has to be related to a typology of companies, products, business models, and production modes. VP has proven value in complex integrated product development and collaboration between design and production, and other stakeholders in complicated products.

Anyhow, VP value capture requires a paradigm change in the way product development is organised around VP.

The scientific novel contribution of this thesis is as follows:

1. The construction of a theory framework for modelling the value of real-time and interactive virtual environment-based virtual prototyping was proposed and discussed. The proposed framework enables structured and qualitative analysis of the virtual prototyping value in industry. The novelty of the framework emerges from the ability to justify how technical elements of virtual prototyping logically contribute to value in the dimensions of engineering design, social aspects, and business management.
2. Contribution to engineering design theory by integrating virtual prototyping, human factors, and business management. The thesis discusses unifying theoretical concepts between the domains of engineering design, virtual prototyping, social science, and business management. The discussion resulted in the proposed new concept of intermediary virtual prototyping (IVP), which integrates the four dimensions. IVP as an intermediary object expands the product development activity system.
3. Reflecting empirical case data with the proposed theory framework produces new practical knowledge of the value and impact of IVP, and contributes to theory in the four dimensions, by validating their utility as means for analysing and explaining empirical data.
4. The empirical results are discussed with the anticipated benefits of the literature. The discussion was made from the perspective of partially configurable products and manual, work-intensive variant production mode. This perspective is novel compared to the majority of virtual prototyping and virtual environments literature.

9.1 Conclusion

The most important conclusion of the research is that the virtual environments-based virtual prototyping (VP) must not be considered only as a piece of technology, but a combination of technology, methodology, processes, and infrastructure in relation to the technology, people and organisations, and management. The value of VP can be described in four dimensions, but it also changes them. The value cannot be captured without a holistic view of VP. The research results consist of three types of knowledge. Firstly, the scientific theoretical foundation was elaborated for initiating the value modelling of virtual prototyping and virtual environments. Secondly, new knowledge of the value of virtual prototyping and virtual environments within new product development was created in an industrial case study. Finally, the conclusions on how VP impacts the company were reported. The analyses of case-study findings led to four categories and perspectives of value: virtual reality technology, product design and development (design object,

design process), social (individual and organisational), and business and management.

Both VP and the target system, meaning the company and product development, are open, dynamic, and complex systems with very many variables. Therefore, pure causal and quantitative value and impacts are impossible to model in practice. Additionally, the time scale of impacts is long, and the influences can be seen only after months or even years. Therefore, the qualitative research approach was selected, aiming to frame and structure the VP value elements and impacts on the company.

9.2 Conclusion on the VE and virtual prototyping technology

The main conclusions on the benefits of VP technology are: VP has an interface of a virtual prototype (experience) and an interface of a virtual environment, which benefits in the form of interaction and perception that are directly connected to the technology. VE enables a true 3D experience and perspective compared to 2D representation using a conventional technique, like 3D-CAD and video projector or drawings. Two levels of user interfaces in virtual environments can be seen: the technical interface that enables manipulation of the virtual environment, and a higher-level interface that is related to perceiving and observing the product model in the virtual environment. In VE, a user can see the product and context in actual dimensions. The user can interact with the model and understand its functions more easily than with 3D CAD. Stereo-graphics visualisation and user motion tracking enable an improved sense of depth, understanding of scale, and perspective of 3D models.

Virtual environments enable improved interaction and navigation with a model. However, there are benefits beyond them. Therefore, the study of VP was expanded in the dimensions of technology, engineering design (object and process), social (individual and organisation), and business and management.

Concerning the level of VE technology maturity, it can be concluded that especially the computer science literature, where the majority of VE publications exist, gives too optimistic a reflection on the usability and quality level, often based on loose argumentation related to practical benefits. The gaming industry and movies increase the over-optimistic expectations of novice users. In the engineering design literature, a lack of interfaces to product data management is frequently reported as one of the main utilisation barriers, as was also concluded in this research.

The used virtual environments technology still has some deficiencies. The used technology in the case study represented a good industry standard, but it was not high end. The technology was rather defined to represent a cost-efficient configuration that companies could afford to purchase. From a usability and quality point of view, the used virtual environment configurations of this study were not very highly appreciated. The usability of devices and software is partly unsatisfactory.

Personal user demands are challenging, and the use of virtual environments may even cause symptoms of simulation sickness. On the other hand, it was also understood that new tools and systems need learning, as well. However, the VE technology maturity is progressing all the time. Therefore, it is more useful to discuss the findings of higher -level benefits and development targets. The visualisation quality of the head-mounted display was the biggest inadequacy. The field of view and visual quality (resolution) of head-mounted displays are still inadequate for long-term usage. From the usability viewpoint, users demanded similar types of user interfaces and functions that are available in CAE tools, such as measuring tools.

Other major imperfections were related to a lack of a digital human model (DHM), and appropriate physics simulations and haptics. In principle, it would be possible to provide these features in the used VE platform, but within the given resources in the research projects, it was not possible. Haptics (force feedback) and digital human models were found to be needed in conducting and analysing manual work tasks in virtual environments. Therefore, not all real-world phenomena, like lifting and mounting heavy parts, can be analysed in virtual environments. It was also understood that virtual environments need to be supplemented with physical objects, like tools, product parts, and boundaries, that represent the limited spaces in the environment.

An important conclusion about VE technology development was that it must be user driven. The technology is often developed by computer programmers who do not necessarily understand the holistic requirements of product design and development. On the other hand, virtual environments enable the analysis of some aspects that cannot be done with a physical prototype, for instance going inside a machine or conducting actions with high safety-risk levels.

9.3   Conclusions on VP value for product design and development

Besides the technical advantages, virtual environments add value for product design and development in the dimensions of the design object and design process. The improved user interface with the product model enables various stakeholders, from assembly workers to human factors experts, designers, and managers, to understand the model in the same way. Virtual prototyping and virtual environments were applied mainly in design review meetings where participants from many functions and organisation levels were involved. It was concluded in this research that product design reviews are the most important application area of VP. This participatory design approach improved the systematic and holistic view from the perspectives of many stakeholders during a product life-cycle. On the other hand, design for human principles can be followed more easily when designers can better understand the perspectives of workers and other stakeholders. The holistic organisational and product life-cycle perspective, aided by the ad-

vantages of virtual environments, enables the revealing of unwanted dispositions. Virtual prototypes enable the analysis of production and maintenance process domains already in the design phase. Design solutions can be verified and validated before manufacturing physical parts.

The main conclusion on the VP value in the product design and development dimension is the capability to observe virtual representations of product properties of physical artefacts in a similar way as in non-virtual world. All product stakeholders benefit, because designers learn about required external properties (analysis) and their relations to design properties, or product characteristics (synthesis). Therefore, VP enables shifting product concept validation and internal productisation towards an earlier embodiment design phase. The internal productisation in respect of product assembly and maintenance can be done earlier, or at least in parallel with detail design, because components do not need to be fully detailed for manufacturing documentation. Thus, internal productisation can be shifted towards embodiment design, which means the allocation of functions and logical structure (organ domain) of a product concept to a basic structure and form of parts. Additionally, product assembly and maintainability can be analysed in the embodiment design phase virtually. In the design process dimension,

VP enables shifting from part domain and physical prototypes towards a product organ domain, where the characteristics of basic product structure, part form, and dimensions are determined. Thus, with a virtual prototype, feedback from production, productisation, and later product life phases can be gathered before making the detailed manufacturing documents and drawings. The design becomes more mature in the embodiment design phase before detail design and physical manufacture. Therefore, the whole product design and development time can be decreased.

In practice, VP enables better integration of human factors and an ergonomics (HF/E) approach into product design and development. VP combined with human-centred and participatory design methodologies enables more systematic and holistic taking account of HF/E aspects. Therefore, it is a means for early investigation and revealing of unwanted dispositions. Dispositions are relations between an engineering design and other product-life stakeholders. The disposition means that part of a decision made in one activity that affects the type, content, efficiency, and progress of activities within other functional areas.

VP is particularly beneficial in manual, work-intensive variant production, where human skills and knowledge contribute to the flexibility of production system. This can be justified by improved communication and understanding between people, and collaboration within organisations, and thus earlier feedback from the downstream life-cycle. VP extends the product model from the technical system to include operations, context, and human interaction. Thus, VP enables involvement by real product stakeholders, like assembly and maintenance workers, in the product design and development process. It also makes it possible to simulate and study phenomena that cannot be done with physical prototypes or CAD, like dangerous work tasks. Assembly or maintenance workers may influence and improve their work tasks, and contribute to HF/E design, safety, and well-being.

These advantages of VP contribute to the productivity of new product development through saved time and resources, by a decreased number of physical prototypes and engineering changes. This common claim in the literature was explained in this research with scientific concepts and models, and reflected and justified with the empirical case-study data. VP contributes to the Lean product development paradigm, by decreasing non-value adding work in the physical product phase. For instance, VP -aided internal productisation is an example of an organisational function that does not directly generate money for the company, but that contributes to productivity by decreasing time-to-market, production costs, and sharing of product knowledge.

VP enables getting feedback from production and other product downstream life-cycle stages already before the physical prototypes. Therefore, it enables the generation of engineering design changes in the early virtual product phase and a decrease in the number of changes in the detail design phase and with physical prototypes and production. Thus, engineering change management (ECM) was concluded to be one of the main drivers of developing VP in the case company. VP enables at least catching the most critical design flaws before making the manufacturing documents and physical prototypes. VP also provides for analysing the engineering change requests, change impacts, and validation of engineering change decisions. It was concluded in the case study that the other key processes among the ECM within product design and development that benefit and are influenced by the VP are: product requirements management (especially human factors), concurrent engineering, product design reviews, product feedback management, product data workflow management, internal productisation, design verification, and validation (product function, assembly, maintainability, safety, ergonomics, customer acceptance).

VP contributes to the product life-cycle management (PLM) paradigm by enabling better design and validating the product's downstream properties and processes, like production and maintenance, already in the virtual product phase, and sometimes already in the product concept phase, before the big decisions have been made.

Configurable products and variant production mode require flexibility, which leads to manual, work-intensive assembly tasks and production styles. VP enables the testing and investigating of several product configurations and variants compared to just one physical prototype. VP enables frontloading the NPD project, meaning more flexibility in the head of the NPD process, because engineering changes can be made before the physical product phase.

9.4   Conclusions on VP value for the social dimension

The social dimension was studied from the perspective of an individual person, and from the perspective of groups and the organisation. The empirical case-study data was reflected with social, cognitive, and psychological theories, and as a

conclusion, the new concept of intermediary virtual prototyping (IVP) was proposed. IVP is a mediating artefact of an activity system that is easy to understand. IVP is proposed as an improved user interface to product data, as a node point of the NPD activity system, and as a medium in the knowledge transformation process.

IVP improves the transformation between tacit and explicit knowledge, thus transferring and capturing tacit knowledge that, for instance, factory and maintenance workers, as well as designers, hold. IVP can be seen as a means for communicating and discussing human factor-related demands and requirements for designers, and for transforming them to formal requirement specifications. IVP is also a means for making implicit requirements, and knowledge in general, explicit because it enables the presentation of circumstances that are often missing from a product description. From a human factor viewpoint, design for a human approach improves understanding of human requirements, decreases safety risks, and improves ergonomics. The user interface of virtual environments, compared to normal CAD, enables, for instance, assembly or maintenance worker reachability and visibility analyses.

Besides this epistemological dimension (tacit-explicit), IVP also contributes to the ontological dimension, between individuals and the organisation. This is important because the product knowledge is dispersed around the organisation and business network. IVP brings together stakeholders, which is not so easy and common with a physical prototype. The stakeholders representing different organisational functions and roles in the company see the product in different ways. Thus, they have a different mental model concerning the product development. IVP as an intermediary object is proposed to enable shared mental models, organisational learning, and knowledge creation that are crystallised in new products. IVP enables improved communication for those stakeholders who are not so familiar with engineering design tools and product representations.

The virtual prototypes are models of a product, and virtual environments can be considered as interfaces to those models. IVP enables a view of a product seen through the eyes of others. For instance, workers can better understand design models, and designers can better understand how the products are really assembled and maintained, what the work system context is, and what possibly needs to be changed in the product. Because there are work tasks and restrictions that designers cannot know, it is important to involve those stakeholders who know them well.

Product design and development is a collective activity, and the viewpoint of a single designer is always restricted. The virtual product design reviews are the key elements for involving different stakeholders, and IVP improves the possibilities to actively participate and give real-time feedback about the design. IVP enables a genuine human-machine and socio-technical system view, and thus a more holistic design approach. This provides the potential for increased creative dialogue and innovations, by combining people with different biographies and mental models. IVP adds value for the stakeholders, because they can affect the design earlier, when it is still possible to make changes to the product description. People get

motivated when they have an opportunity to influence how their work will be de-
signed and organised.

From a social perspective, virtual environments add value because they enable
description and simulation of the actual socio-technical system, including the con-
text and activity, not just the technical product. IVP enables expansion of the
product, meaning the object of the product development activity system, by ena-
bling simulations of work tasks, operations, and the context of the product. IVP is
an organisational interaction field that provides for modelling and simulation of the
context and actions related to the product, widely involving stakeholders in the
product life. By expanding the product as an object, it enables a view of the total
object and the motive of the activity system, and therefore reveals contradictions
within the activity system and therefore latent dispositions during the product life.
From the social dimension perspective, the participatory approach enables im-
proved coping with complexity, because conflicting goals of different stakeholders
can be understood and dealt with together. The common object of the different
activity system, or the product, unites the stakeholders of the product life when
manifested in common processes, information management, and organisational
management. IVP improves the unity around the common object.

9.5   Conclusions on VP value for business and management

In the business management dimension, the main conclusion is that IVP is pro-
posed to be considered as a strategic investment that enables the balance of the
daily performance and long-term core competence of the firm, which will produce
income in the long run. IVP can support this balance between short-term efficiency
and long-term success, for instance, by cutting the cost of physical prototypes and
engineering changes, and can simultaneously add more value, capitalising on the
core competence by providing an interaction field for organisational knowledge
creation and capture. IVP improves future innovation management and creativity,
because more ideas can be tested in the early NPD phase.

Only part of the created value can be estimated as monetary exchange value in
the short term, but the whole value is beyond analytical and factual measure,
having multiple qualitative dimensions. Value is created when IVP is used and
combined with the skills and knowledge of the users. IVP should be seen as a
strategic asset that significantly contributes to value creation, but is simultaneously
a remarkable investment when adopted in business. It is also a remarkable in-
vestment because it is fairly expensive when all changes to the business enter-
prise are regarded, including organisational, processes, and information manage-
ment.

In the case company, the amount and importance of manual work and human
factors was an essential factor that justified added value. However, quantified
value in terms of money and time can be justified with the decreased number of
physical prototypes and with testing the new concept design earlier. Virtual proto-

types enable the testing of several product configurations. On the other hand, the safety and health of people are priceless. IVP provides for safer and more ergonomic products. Product manufacture, operations, and maintenance can be tested safely in virtual environments. IVP contributes to improved decision-making, management of uncertainty in NPD, and revealing the contradictions and latent dispositions, by enabling early feedback from internal and external customers, and thus a decreased number of major engineering changes in the physical product process, and a shorter time-to-market. An NPD project is a typical activity in which the knowledge is dispersed around the organisation and networks, and different stakeholders often have different goals and motives, which causes contradictions. IVP provides for a more holistic view of the product and activity systems.

IVP contributes to the co-creation and dominant design situations, where product variation is important, by involving human creativity in the early product design and development phase, thus increasing flexibility. In a business strategy that is based on product quality, product variability, and flexibility, IVP creates value because it enables better utilisation of the knowledge and skills of people. Therefore, IVP is particularly beneficial in manual, work-intensive variant production mode. From this perspective, intermediary virtual prototyping seems be a means for improving the competitive edge in the market, where product variation and flexibility is important, like in the case company and widely in the Finnish manufacturing industry. Time-to-market is one of the most common performance indicators of product development. However, if the focus is on holistic business success, perhaps a more important indicator is time-to-profit. IVP can improve time-to-profit by frontloading the NPD process, and decreasing physical prototypes and engineering changes in the physical product process. The case company estimated that 3–6 months can be saved in a typical NPD project by better utilisation of virtual prototyping. The saving of time, money, and other resources, and the decrease in non-value adding work, has been justified logically by reflecting the case-study data with scientific theories.

IVP should be seen as a strategic asset that enables better utilisation of company resources. It can also be an asset that supports strategic changes of business models, for instance shifting towards service business. The case company's strategy was also to increase service business. Therefore, product maintainability was also identified as a critical property, which can be analysed and developed together with the assembly properties given the usage of IVP. IVP can also provide for efficiency in producing high-quality production and maintenance instructions and documentation. IVP creates value in use, but in turn it affects the company in all the mentioned four dimensions. Thus, the perspective in the adoption of IVP should be widened from technology to PLM strategy and organisation design.

9.6   Conclusion on the risks of VP implementation

Conclusions on the risks of implementation of VP can be divided into the dimensions of technology, processes, leadership and management, and education. In the technology dimension, it should be considered whether the implementation strategy is based on commercial (COTS) applications or in-house development. Especially a COTS application by one vendor may lead to harmonised virtual prototyping and PLM platforms, but it may decrease flexibility. The in-house development strategy enables an optimised and flexible platform, but may lead to complex and hard-to-maintain architecture.

One risk is related to the maturity level of the technology. The introduction of unfinished tools with poor usability may lead to rejection. Another risk is related to finding the right application areas and methods of VP, where it really adds value. Anyway, it is a big risk to suppose that there are some generic virtual prototyping processes that can be just implemented, because the applications and processes should be tailored to fit every specific business and company. A major risk is to understate the significance of integrating VP in product data management and product processes. It is a great risk to think that this technology as such increases the efficiency of product processes.

It should be understood that a substantial part of VP value is manifested in the changed processes and organisation. Therefore, it should be considered what the risk of changing them is. The third risk dimension is associated with leadership and management: how the big picture of IVP and its value and dynamic impact are understood, who will be in charge of implementing IVP, and whether the resources are sufficient. The fourth risk dimension is also related to leadership. It is a risk if the education and training in IVP-related techniques, methods, and processes is neglected. The education should be based on common and well-defined concepts and terminology.

9.7   Conclusion on the effectiveness and optimal areas of VP

The main conclusions on the strengths and weaknesses of virtual prototyping compared to more conventional methods are described here. On the one hand, virtual prototyping is compared to physical prototyping, which it aims to partially substitute, and to CAD, where it aims to add features that add value to product design and development. Compared to physical prototypes, virtual prototypes has the following advantages: it is possible to test and compare more alternative design options and different product configurations; it is possible to investigate viewpoints and phenomena that are not possible using a physical prototype (e.g. dangerous tasks); and it is possible to test and evaluate product properties before physical manufacture, possibility involving more stakeholders in design and design evaluation. The cost of a virtual prototypes probably lower than the cost of a physical prototype when the focus is the type of NPD described in the case study.

Virtual prototyping can decrease the time-to-market and time-to-profit when the preconditions are adequate. Compared to physical prototypes, the realism of a virtual prototype is lower (e.g. forces) and not all product properties can be tested and evaluated.

Compared to CAD, virtual environments-based virtual prototyping is more illustrative and interactive, thus it is easier to perceive and evaluate the product models. VP extends better the product model from being technical system-centric to an actions and product context. Therefore, VP enables better subjective evaluation of product properties. However, the VP technology, including the infrastructure, processes, and data management, is, in most cases, more expensive and more difficult to use than common CAD tools. Attitudes towards VP are still often suspicious. The usability of VP as SW/HW (VR) is often poor compared to CAD. VR tools usually lack the capability to produce or modify geometry, which is an obvious capability of CAD. VR often has a limited interface to PDM/PLM. The reason for this is that these often originate (like the used Virtools in the case study) from the gaming industry or computer science.

Based on this research, VE-based virtual prototyping can be effectively used in early new product development where human aspects, like safety and convenience of manual work tasks and the viewpoint of many stakeholders, are significant. Early means the phase of an NPD project before manufacturing physical parts. It was concluded that VP is effective when combined with design approaches like participatory design and analysis methods like human posture and visibility analyses and risk analyses. The virtual design reviews were the most important application area of VP in the case study.

The case study included two main types of NPD projects: 1) Generation and evaluation of a totally new product or module functions and properties, and 2) internal productisation of new or updated product or modules. VP can create value for both types of projects. The validation and selection of product concepts are important in the concept design phase, while the efficiency of engineering changes and optimisation of product structure and geometry are important in the productisation phase. Especially early concept evaluation by internal and external customers is essential. In both project types, the capability of designing in 3D is important. VP increased the utilisation rate of 3D models. It was concluded that VP utilisation is effective when the product design and development is done using 3D CAD/CAE tools in a company, and VP adds value to them. However, there must be the capability to produce virtual prototypes efficiently, which requires integration with product design and development processes and product data management. Additionally, VP enables the production of instructions and documentation for production, service, and end customers.

Of course, the way in which virtual prototyping may create or may not create value depends on the nature of the business, business models, products and production modes, life-cycle phase of the product type (may be e.g. a facelift of an old product or a totally new product or module), and dominant design paradigm. The nature of the products and production of the case company are such that VP creates value by combining the core competencies. The case company still holds

the core product development and also product assembly inside. Service business, including upgrading old machines, is a growing business. Additionally, the capability to invent and offer new functions and properties for products or modules, and the possibility to test and validate the operation and maintenance of them early, is a competitive edge. On the other hand, the products are complicated, large mechatronic systems in which lots of components and functions are packed into a relatively small space, due to the mobility of the machines. This boundary condition, together with variability, flexibility, high reliability demand, and a tight time schedule, is demanding, and IVP helps design and development effectively. The investigation of interfaces between new and old product modules is important, because modules may be designed in several locations and the old machines may be modified during their life-time. The possibility to test several product configurations is a significant advantage in variant production.

9.8   Managerial implications

The six-year research also gave a retrospective view of development, from a virtual environment technology demonstration to the implementation of virtual prototyping methods and processes. Current technology deficiencies and the lack of virtual environment usability and realism will probably be relieved by general development in technology, especially in the entertainment sector, where the market is large and mature, though the demands of industry may be different. There are also many options for software and devices, and the PLM providers are also developing their products towards the capabilities of VP. Anyhow, it is clear that real benefits can be reached only when these tools and methods are integrated into companies' product processes and information management systems. Hence, it is more important to create and develop generic procedures and processes, as well as the data management architecture and information models that support them.

The product design and product development organisations should drive the development of virtual prototyping technology, instead of IT. Actually gaining the real value of IVP seems to demand a paradigm change in design processes and product development projects. 3D models and virtual prototypes should be prepared earlier and more efficiently, accounting for the demands of IVP. Virtual environments add value especially involving humans, working context, and activity in designing the human factors of socio-technical systems. Anyhow, design for humans methodology should be well defined, and tools and systems should support it. The paradigm change requires a re-design of the work tasks, processes, and organisation, and strong leadership in order to implement it in practice. People need to be motivated to do things in a new way, perhaps with a changed attitude.

There are lots of expectations concerning the business value of virtual prototyping. From a company viewpoint, prerequisites for real implementation of IVP include an affordable price, ease of use, and close facilities. IVP should also be seen as part of the PLM model development vision, including widening impacts in

every organisation and process level, as in Figure 73. Thus, IVP is a matter of organisation design and a wide area of competence, and it cannot be reduced to just technology. Because the adoption of virtual prototyping was reasoned to influence companies widely, it should be considered what kinds of impulses it may have on product and process innovations.
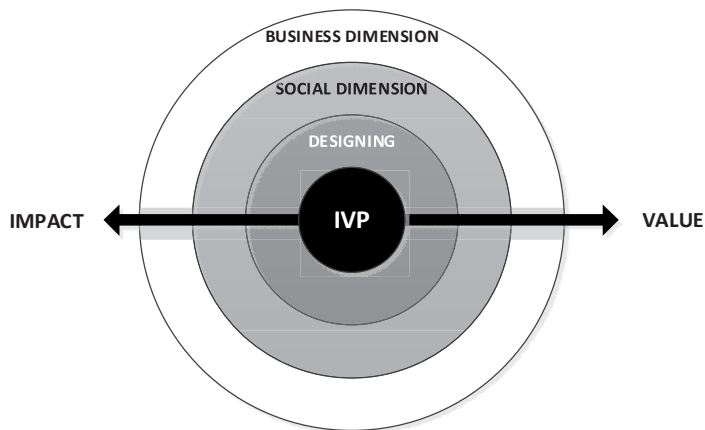

Figure 73. Widening the impact and value space. The value propositions are growing from the virtual prototyping technology simultaneously impacting the dimensions of designing, social aspects, and business

9.8.1 Process implications

It was concluded that effective utilisation and VP value capture requires a paradigm change in new product development. Virtual prototyping should be understood as a pivotal process within NPD and PLM. This means that the virtual product process phase should not focus on producing 3D models and manufacturing documents for the physical product process, but it should include the whole product life-cycle. The NPD project and process should be frontloaded so that, for instance, assembly and maintainability analyses and improvements can be done using the virtual prototypes. This process should be clearly defined, but naturally it will jeopardise the agility of NPD. The frontloading may increase the work and cost at the beginning of the project, but it may also decrease the engineering changes and the cost of physical prototypes in the physical product process phase. In the end, it may decrease the time-to-market and time-to-profit. It should also be understood that there is no "one size fits all" NPD or virtual prototyping process. Thus, it should be found out how VP should be configured and implemented in different NPD projects and different product portfolios.

The paradigm change also affects how the design maturity should evolve during the NPD project and process. The basic product structure and parallel view should be established already in the early concept phase, and it should be well consid-

ered how the structure will progress in order to support stakeholders, like production and service, widely. The necessary product data and models should be available and up-to-date for all stakeholders who participate in the NPD process. The way of producing CAD models should better serve VP.

The paradigm change also requires a holistic and systemic design approach, including the whole product life-cycle, the context of the product life, and the activity. The holistic and systemic approach also demands understanding of the different and often contradictory goals and demands among the internal and external customers. It is important to understand which product properties are valued by each stakeholder, and how they contribute to the success of the business.

The product design reviews are one of the most important application areas of VP, according to the case study. In order to effectively utilise VP, the virtual design review procedures should be well defined, systematic, and part of the NPD project, involving the stakeholders widely. The design reviews should be frequently arranged and the feedback from stakeholders should be systematically collected, documented, and managed as part of the NPD project and PLM. The goals and outcomes of the reviews should be clear. The virtual design reviews should be defined as part of engineering change management (ECM) within the NPD projects and processes. In order to maximise the value of VP, it should also be considered how the digital material produced in virtual prototyping could be effectively utilised during the product life-time.

IVP and NPD should be seen as part of the company's PLM strategy. VP should be integrated into the PLM architecture and information model. Processes and workflows that support virtual prototyping should be established in the PLM model, and the processes should be continuously maintained and developed. It is recommended to define the PLM architecture and information models in a neutral way, so that they are not completely vendor dependent. PLM development should have a champion who drives the high-level holistic development without boundaries or organisational departments and functions.

9.8.2   Organisational implications

The business management literature proposes that, when strategy and major business processes are created or re-designed, usually the organisation should also be re-configured in order to better support the new processes. It was also anticipated by the case company that, sooner or later, virtual prototyping will revolutionise the way in which new product development is organised. Therefore, it is wise to be proactive and establish up-front readiness for IVP as part of the PLM model, processes, and organisational capabilities.

It was concluded that one aspect in which IVP creates value is wide integration and involvement of stakeholders in NPD. Therefore, it is important to recognise and involve the stakeholders at organisational group level, but also at individual person level. It is essential to realise that product development is not just the same as the engineering design department. Instead, stakeholders in the whole product life-cycle should be integrated. It is also important to see that an organisation that

is optimised for a standard physical production and sales-delivery process is not an optimal organisation for an NPD project. Hence, it is suggested that NPD with IVP should be organised in dynamic teams, where all the needed stakeholders are involved.

On the individual person level, there should be new roles for implementing, developing, and operating virtual prototyping. These roles would include responsibilities like VR laboratory manager, virtual design review facilitator, virtual prototype data manager, virtual prototyping process owner, and human factors expert. Besides the VP technology and process roles, there is a need for roles that represent the product stakeholders. For instance, experienced assembly and maintenance workers who are interested in virtual prototyping would be very valuable for NPD. They are people who (Prahalad & Hamel, 1990) are called the "competence carriers". Additionally, there should be a "system engineer" who aims to optimise the product from the life-cycle and technical viewpoint.

The product design review meetings should have a clear agenda, structure, and systematic procedures. Additionally, there should be clear responsibility for coordination, documentation, camera/video recording, and assessment of different product aspects, including assembly, maintenance, safety, and ergonomics. Despite the demand for systematic product review procedures, there should be enough time for discussions and brainstorming. At the end, the meeting should be clearly summarised and conclusions should be made.

From the business management viewpoint, it should be understood that IVP does not belong just to a single organisational function, business line, or department, but that it is proposed to be a holistic system and part of product life-cycle management. This is important from both the utilisation and implementation viewpoints, including cost. Some of the case sub-studies were made to be more engineering design driven, while others were production driven. It was clearly seen that these are emphases on different aspects of product development. On the other hand, some of the participants in the case company represented PLM with a more holistic view of the product. The value of virtual prototyping is partly proposed to manifest from integrating different product processes and organisations, breaking the possible barriers between organisational units, and decreasing partial optimisation of product processes. Therefore, it is important to recognise and respect the internal customers in the company and value network, and to create a culture that encourages openness and knowledge sharing. This demands good leadership, an attitude change among stakeholders, motivation, rewarding, and readiness to share unfinished work and give constructive feedback. Education in IVP should be arranged for the company personnel, including virtual prototyping technology and methodology, and human factors demands. A clear terminology of IVP should be established in order to avoid confusion. Naturally, there should be sufficient financial and human resources available for the IVP implementation and utilisation. In the daily project work, it is proposed to consider how IVP is managed as an organisation and process on top of the formal organisation, and how it differs from the conventional management practice. There should also be enough discipline to follow the IVP processes as part of the learning curve. All these as-

pects should be understood as a core competence of the company that is difficult to imitate, because it includes a network of processes, knowledge, know-how, and organisations.

9.8.3 Technological implications

The effective utilisation of virtual prototyping requires bi-directional data and information flow between virtual environments (VE) and product data management (EDM/PDM) systems. During the case study, it was understood that establishing a good interface between virtual environments and product data management impacts deeply the PLM model, for instance in specific virtual prototype and product assembly structures, access management, and engineering change management. The interface between VE and EDM/PDM also requires a process of data conversion and simplification, which should be at least partly automated to be efficient. Conversion is often needed when the CAD/CAE software and VE software are from different providers. Conversion and simplification of CAD models for VE is the most important data process. However, the product structure (hierarchy), as well as metadata such as item codes and version and revision information, should be transferable bi-directionally. In the case study, it was reasoned that virtual prototyping as a methodology, and virtual reality as a technology, must be seen as part of the company PLM model and architecture, because they are the framework for managing virtual product processes and digital information. Therefore, it should be studied more how the capabilities of existing PLM systems and tools could support IVP. However, generally it is suggested that the strategy between in-house VP development and commercial (COTS) tools and systems should be considered.

Based on our research, a participatory and human-centred product design and development methodology, combined with appropriate virtual prototyping tools and methods, enables getting feedback from several life-cycle phases already in the virtual product development phase. This is one of the major value-creating areas of virtual prototyping. It was proposed that VE enables "online" product knowledge transfer, but "offline" knowledge management is also needed and enabled by PDM/PLM systems. In the case study, the possibility to make comments and give feedback directly on the virtual prototype model was one of the most desirable capabilities of IVP. It should be possible to link this information to the item information used in product design and CAD.

In this research, the need for parallel virtual prototype structures in EDM/PDM was recognised as one of the most important enablers for effective VP utilisation. The structures are the frames for producing virtual prototypes for different purposes and demands of different stakeholders, and they are also the frames for recording explicit product knowledge. However, it will be a question of future research: what kind of structures support VP? The parallel product structures are enablers for improved implementation of a truly concurrent engineering paradigm. For instance, the main principles of product assembly and maintainability can be validated already in the product concept phase, if the basic structure, main dimen-

sions and forms of parts, main interfaces between parts, and modules are available early enough.

It was concluded that, in the process dimension, new product development requires a paradigm change with a frontloaded virtual product process and re-thinking of the progress of product model maturity. For instance, the parallel virtual prototype structure and content with draft geometry should be available early for the analysis of the main assembly procedures using the virtual prototype. Therefore, the information model of EDM/PDM must support the design process and parallel structures. Additionally, the parallel structures should also support description of the product-related activity and context, for instance in production and service. From a technical multi-discipline viewpoint, the virtual prototype structure should, besides the mechanics, also support hydraulics, electrics, welds, and other such details that are important, for instance, for assembly and maintenance analyses.

In EDM/PDM, which is the backbone of PLM, the product structure is normally the main framework that constitutes the product information model. Therefore, VP and related data, information, and documents should be referenced with the product model in order to contribute to knowledge management. A virtual prototype "baseline structure" is proposed as the frame for explicit knowledge management, linking the tacit knowledge from stakeholders to PLM. It is proposed to manage the documentation, feedback, requirements, notes, and engineering change requests, for instance, from virtual design review meetings. Additionally, it would manage the traceability of the virtual prototype version, virtual environment technology configuration, item revision, and decisions made. The VP baseline means that the exact configuration, including structure, BOM, item revisions, and model versions, must be stored together with feedback and other information in the PDM system. Currently, this is not supported by the case company's PDM/PLM, but it has been recognised as one of the main development targets in an ongoing project. When the virtual prototype is understood also on a meta-level as a configuration of product data and product data structures, the tacit product knowledge can be made explicit in PDM/PLM. VP should be managed as an engineering change process, in order to stay up-to-date with design revisions and feedback. On the other hand, the engineering change management process was seen as one of the drivers for VP implementation in the case company. Other remarks on demands for virtual prototyping included: user-centred development of VP, CAE-type user friendliness of VP technology, a company VR laboratory in proximity to the factory, data security, and utilisation of digital human models in product design and evaluation.

9.9   Discussion on societal implications

The countries of the European Union, and especially Finland, are struggling with a challenging situation in the economy. Manufacturing has been traditionally one of

the three life-blood industries in Finland, alongside the forestry industry and lately the IT industry. However, all these major industries are now in trouble. Anyway, Finnish industry can survive in the global market with innovations, increased productivity, and flexibility. Digitalisation has been seen as one of the key enablers for successful manufacturing. Based on this research, IVP is proposed as one contribution to this digitalisation framework, when it is implemented in a holistic and systematic way. It was described in the case-study material how IVP can increase productivity and flexibility.

It is proposed that IVP creates value by improved involvement of stakeholders and their skills and knowledge in product processes. The "Shared Value" model of Porter and Kramer (2011) also emphasises "the importance of social benefits and capabilities, understanding customers, creating value for all stakeholders, and their non-material contributions to value creation and improved productivity". However, they argue that generally, strategic thinking has contracted and the time horizon of investments has shortened in business. Companies are seeking fast gains. Outsourcing has caused a gap between firms and stakeholders. This approach should be turned again to long-term strategic thinking. IVP requires it, too. (Ovtcharova, 2010) has argued that new technologies, like pieces of digital engineering, emerge every 3-5 years, but the adoption into business processes requires more time.

Castells and Himanen (2013) have summarised conclusions about the future sustainable development and competitive edge in Finland. They had a higher-level societal perspective, but their conclusions can be scaled to a specific industry or even to a single company. Castells et al. see information technology as the key enabler of better productivity, but it requires a systemic and revolutionary change, with a new leadership and especially working culture. The new working culture requires increased interaction, risk-taking, and trust among all stakeholders. Information technology enables new forms of organising work. Based on our research, these are the major issues that must also be focused on in IVP.

Castells et al. concluded that economic growth, especially in Finland, will be based on the spirit of innovation supported by clever utilisation of IT, re-organised networking, and less hierarchical work systems. Trust among people is still seen as a significant competitive edge among Finnish people. In the case study, this could be seen, for instance, in the relationships between the case company and their suppliers in NPD projects. Creativity is an essential premise for innovations. Creativity should be seen and respected widely, to include everything in which people can use their unique potential in a new or better way. IVP was proposed to create value by better exploitation of the skills and knowledge of all product stakeholders within product design and development and the whole product life-cycle. Anyway, the new culture and leadership require a common and holistic view of business, without partial optimisation, where all stakeholders know the common goals and also benefit from reaching them.

9.10 Recommendations for further research

This thesis proposes a theory frame for describing the value of intermediary virtual prototyping, meaning virtual environment-aided use of computer models in product design and development. Future research is recommended to use the theory frame as the basis for developing methods and even tools that support the value evaluation in industry. On the other hand, it is also recommended to do more empirical research in industry in other companies and other business areas, in order to validate and enrich the theory frame.

In this thesis, it was reasoned, based on the case study, what the enablers of the proposed value dimensions and elements of IVP are. These enablers should be further studied and developed. IVP should be better integrated with design methodology, processes, infrastructure, and organisations. This thesis reported the findings on the major targets, and recommendations on where they should be directed. For instance, connections with product concept design, requirements management, and engineering change management will be specific research topics in future projects.

Concerning product knowledge management, it is recommended that the product information and knowledge flow should be studied and modelled, starting from the demands of the product life-cycle stakeholders, and how IVP could best support the flow. This would contribute to the value of virtual prototyping, because it was proposed that unity of stakeholders and their knowledge is one of the main value propositions. Scientific research should also be done in order to develop improved information models and architectures that support knowledge management and VP integration with PLM systems. This should also support improved utilisation of created virtual environment models within the product life-cycle.

Today, there are many "hype" things on the table, like the Internet of Things, Digital Manufacturing, and Industry4.0. There is also a risk that they cannot proceed from the hype to being real and valuable assets in industry, similar to virtual environments. It is recommended that the relation between IVP and these concepts should be defined, and it should be studied how IVP could contribute to them. The relation of these concepts with other "virtual techniques", like augmented and mixed reality, should also be a topic of research. Anyhow, they are also concepts and technologies that require a revolutionary change in the relatively conservative manufacturing industry. Based on the case study findings, it is also a recommendation to investigate profoundly the capabilities of COTS tools and systems, and implementation within the PLM framework.

In future research, it is also recommended to further study how the Activity Theory could better support modelling and designing of work tasks, processes, context, and realism, and how it could be better synthesised and merged with design object models (technical systems). For instance, factory and production-line environments would add value, according to feedback from production development experts. The implementation and development of digital human models are required as well.

In the case company specifically, it is recommended to continue the research on IVP utilisation and to consider how the company should be changed in the dimensions of technology, processes, people, and management, for implementation of IVP. It should also be considered how IVP can be scaled to the global business, and how it can be utilised in other business lines, such as in individual machine upgrading. This thesis described how the value of IVP was qualitatively perceived in the case company. However, there is still a demand for quantitative modelling of the value, for instance in terms of time and cost.

References

Abramovici, M. (2007). Future Trends in Product Lifecycle Management (PLM). In The future of product development, Proceedings of 17th CIRP Design Conference (pp. 665–674).

Abramovici, M., & Schindler, T. (2010). Benefits of PLM in the Automotive Industry. Results of a Benchmark Study. In International Conference on Product Lifecycle Management.

Airila, M., & Pekkanen, M. (2002). Tekniikan alan väitöskirjaopas. Espoo: Teknillinen korkeakoulu.

Allee, V. (2000). Reconfiguring the value network. Journal of Business Strategy, 21(4), 36–39. Retrieved from http://vernaalle.com/images/VAA-ReconfiguringTheValueNetwork.pdf

Allee, V. (2008). Value network analysis and value conversion of tangible and intangible assets. Journal of Intellectual Capital, 9(1), 5–24. doi:10.1108/14691930810845777

Allee, V. (2009). Value-creating networks: organizational issues and challenges. The Learning Organization, 16(6), 427–442. doi:10.1108/09696470910993918

Allen, D. K., Brown, A., Karanasios, S., & Norman, A. (2013). How should technology-mediated organizational change be explained? A comprison of the contributions of Critical Realism and Activity Theory. MIS Quarterly, 37(3), 835–854.

Allen, D., Karanasios, S., & Slavova, M. (2011). Working With Activity Theory: Context, Technology, and Information Behavior. Journal of the American Society for Information Science and Technology, 62(4), 776–788. doi:10.1002/asi

Alves, J., Marques, M. J., Saur, I., & Marques, P. (2007). Creativity and Innovation through Multidisciplinary and Multisectoral Cooperation. Creativity and Innovation Management, 16(1), 27–34. doi:10.1111/j.1467-8691.2007.00417.x

Amaral, L.A.N., & Uzzi, B. (2007). Complex Systems – A new paradigm for integrative study of management, physical, and technological systems. Management Science, 53(7), 1033–1035.

Amditis, A., Karaseitanidis, I., & Mantzouranis, I. (2008). Virtual Reality Research in Europe: Towards Structuring the European Research Area. In D.

Talaba & A. Amditis (Eds.), Product Engineering – Tools and Methods based on Virtual Reality (pp. 3–20). Springer.

Ameri, F., & Dutta, D. (2005). Product Lifecycle Management: Closing the Knowledge Loops. Computer-Aided Design and Applications, 2(5), 577–590. doi:10.1080/16864360.2005.10738322

Andreasen, M. M. (1980). Machine design methods based on a systematic approach – contribution to a Design Theory. Lund: Lund Institute of Technology.

Andreasen, M. M. (2011). 45 Years with design methodology. Journal of Engineering Design, 22(5), 293–332. doi:10.1080/09544828.2010.538040

Andreasen, M. M., & Hein, L. (1987). Integrated Product Development (205 p.). Copenhagen: Springer-Verlag.

Andreasen, M. M., & Mcaloone, T. C. (2008). Applications of the Theory of Technical Systems – experiences from the "Copenhagen School." In AEDS 2008 WORKSHOP, 31 October – 1 November 2008, Pilsen, Czech Rebublik (pp. 1–18).

Argyris, C., & Schön, D. (1978). Organizational Learning. Addison-Wesley.

Aromaa, S., Leino, S., Viitaniemi, J., Jokinen, L., & Kiviranta, S. (2012). Benefits of the use of virtual environments in product design review meeting (pp. 355–364).

Aromaa, S., Leino, S.-P., & Viitaniemi, J. (2013). Are companies ready for the revolution in design – modelling maturity for virtual prototyping. In International Conference on Engineering Design, ICED13.

Aurich, J., & Rößing, M. (2007). Engineering change impact analysis in production using VR. Digital Enterprise Technology. Retrieved from http://link.springer.com/chapter/10.1007/978-0-387-49864-5_8

Backhouse, C., & Brookes, N. (1996). Concurrent Engineering: What Works Where (272 p.). Gower Pub Co.

Badke-Schaub, P., Neumann, A., Lauche, K., & Mohammed, S. (2007). Mental models in design teams: a valid approach to performance in design collaboration? CoDesign, 3(1), 5–20. doi:10.1080/15710880601170768

Becker, I., Toivonen, V., & Leino, S. (2011). Using virtual reality in designing the assembly process of a car. In International Conference on Engineering Design, ICED11.

Bergsjö, D. (2009). Product Lifecycle Management – Architectural and Organisational Perspectives. Chalmers University of Technology.

Blessing, L. T. M., & Chakrabarti, A. (2009). DRM, a Design Research Methodology. London: Springer London. doi:10.1007/978-1-84882-587-1

Boothroyd, G. (1987). Design for assembly – the key to design for manufacture. The International Journal of Advanced Manufacturing Technology, 2(3).

Bordegoni, M., Cugini, U., Caruso, G., & Polistina, S. (2009). Mixed prototyping for product assessment: a reference framework. International Journal on Interactive Design and Manufacturing (IJIDeM), 3(3), 177–187. doi:10.1007/s12008-009-0073-9

Boujut, J., & Laureillard, P. (2002). A co-operation framework for product–process integration in engineering design. Design Studies, 23, 497–513. Retrieved from http://www.sciencedirect.com/science/article/pii/S0142694X01000448

Bowman, C., & Ambrosini, V. (2000). Value Creation Versus Value Capture: Towards a Coherent Definition of Value in Strategy. British Journal of Management, 11(1), 1–15. doi:10.1111/1467-8551.00147

Bowman, D. A., Mcmahan, R. P., & Tech, V. (2007). Virtual Reality : How Much Immersion Is Enough? Computer, 40(7), 36–43.

Brooks, F. P. (1999). What's Real About Virtual Reality? Computer Graphics and Applications, IEEE, 19(6), 16–27.

Cagan, J., & Vogel, C. M. (2002). Creating breakthrough products: Innovation from product planning to program approval. Ft Press

Castells, M., & Himanen, P. (Eds.). (2013). Kestävän kasvun malli – Globaali näkökulma. Helsinki: Valtioneuvoston kanslia.

Cecil, J., & Kanchanapiboon, A. (2007). Virtual engineering approaches in product and process design. The International Journal of Advanced Manufacturing Technology, 31(9-10), 846–856. doi:10.1007/s00170-005-0267-7

Chakrabarti, A., & Blessing, L. (Eds.). (2014). An Anthology of Theories and Models of Design Philosophy, Approaches and Empirical Explorations. Springer.

Checkland, P. (2000). Soft Systems Methodology: A Thirty Year Retrospective. Systems Research and Behavioral Science, (17), 11–58.

Cheng, C. (2014). Intent understanding for virtual environments. In I. Horváth & Z. Rusak (Eds.), Proceedings of TMCE 2014, May 19–23, 2014, Budapest, Hungary (pp. 981–992).

Choi, A. C. K., & Guda, P. (2000). Product design enhancement by integration of virtual design and assembly analysis tools. Assembly Automation, 20(4), 283–290.

Chryssolouris, G., Mavrikios, D., Fragos, D., & Karabatsou, V. (2000). A virtual reality-based experimentation environment for the verification of human-related factors in assembly processes. Robotics and Computer Integrated Manufacturing, 16, 267–276.

Cobb, S. V. G., D'Cruz, M. D., & Wilson, J. R. (1995). Integrated manufacture: A role for virtual reality? International Journal of Industrial Ergonomics, 16(4-6), 411–425. doi:10.1016/0169-8141(95)00022-9

Cooper, R., & Edgett, S. (2008). Maximizing productivity in product innovation. Research-Technology Management, 51(2), 47–58. Retrieved from http://www.ingentaconnect.com/content/iri/rtm/2008/00000051/00000002/art00009

Crnkovic, G. D. (2010). Constructive Research and Info-computational Knowledge Generation. In L. Magnani, W. Carnielli, & C. Pizzi (Eds.), Model-Based Reasoning in Science and Technology (pp. 359–380).

Darses, F., & Wolff, M. (2006). How do designers represent to themselves the users' needs? Applied Ergonomics, 37(6), 757–64. doi:10.1016/j.apergo.2005.11.004

Davis, M. C., Challenger, R., Jayewardene, D. N. W., & Clegg, C. W. (2014). Advancing socio-technical systems thinking: a call for bravery. Applied Ergonomics, 45(2), 171–80. doi:10.1016/j.apergo.2013.02.009

De Jong, A. M., & Vink, P. (2002). Participatory ergonomics applied in installation work. Applied Ergonomics, 33(5), 439–48. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12236653

Di Gironimo, G., Lanzotti, A., & Tarallo, A. (2014). A virtual reality framework for the design review of complex industrial assemblies: case study on the interiors of superjet 100 aircraft. In I. Horváth & Z. Rusak (Eds.), Proceedings of TMCE 2014, May 19-23, 2014, Budapest, Hungary (pp. 1553–1560).

Doherty, N. F. (2014). The role of socio-technical principles in leveraging meaningful benefits from IT investments. Applied Ergonomics, 45(2), 181–7. doi:10.1016/j.apergo.2012.11.012

Dul, J., Bruder, R., Buckle, P., Carayon, P., Falzon, P., Marras, W. S., & van der Doelen, B. (2012). A strategy for human factors/ergonomics: developing the discipline and profession. Ergonomics, 55(4), 377–95. doi:10.1080/00140139.2012.661087

Durmusoglu, S. S. (2009). The role of top management team's information technology (IT) infrastructure view on new product development: Conceptualizing IT infrastructure capability as a mediator. European Journal of Innovation Management, 12(3), 364–385. doi:10.1108/14601060910974237

Earthy, J., Jones, B. S., & Bevan, N. (2001). The improvement of human-centred processes – facing the challenge and reaping the benefit of ISO 13407. International Journal of Human-Computer Studies, 55(4), 553–585. doi:10.1006/ijhc.2001.0493

Eason, K. (2013). Afterword: The past, present and future of sociotechnical systems theory. Applied Ergonomics, 1–8. doi:10.1016/j.apergo.2013.09.017

Eder, W. E. (2008). Theory of Technical Systems and Engineering Design Science – legacy of Vladimir Hubka. International Design Conference – DESIGN 2008. Dubrovnik – Croatia, May 19–22, 2008.

Edwards, K., & Jensen, P. L. (2014). Design of systems for productivity and well being. Applied Ergonomics, 45(1), 26–32. doi:10.1016/j.apergo. 2013. 03.022

Ellis, S. R. (1994). What are virtual environments? IEEE Computer Graphics and Applications, 14(1), 17–22.

Engelbrektsson, P., & Söderman, M. (2004). The use and perception of methods and product representations in product development: A survey of Swedish industry. Journal of Engineering Design, 15(2), 141–154. doi:10.1080/09544820310001641245

Engeström, Y. (1987). Learning by expanding – An activity-theoretical approach to developmental research (p. 269). Helsinki: Orienta-Konsultit. Retrieved from http://lchc.ucsd.edu/mca/Paper/Engestrom/Learning-by-Expanding.pdf

Engeström, Y. (2001). Expansive Learning at Work: Toward an activity theoretical reconceptualization. Journal of Education and Work, 14(1), 133–156. doi:10.1080/13639080020028747

Engeström, Y. (2004). New forms of learning in co-configuration work. Journal of Workplace Learning, 16(1/2), 11–21. doi:10.1108/13665620410521477

Eppinger, S. D., & Chitkara, A. R. (2009). The Practice of Global Product Development. MIT Sloan Management Review, 47(4), 22–30.

Ferrise, F., Bordegoni, M., & Cugini, U. (2013). Interactive Virtual Prototypes for Testing the Interaction with new Products. Computer-Aided Design and Applications, 10(3), 515–525. doi:10.3722/cadaps.2013.515-525

Fleche, D., Bluntzer, J.-B., Mahdjoub, M., & Sagot, J.-C. (2014). Proposition of new and complementary evaluation approach of collaborative tools in a product design process. In I. Horváth & Z. Rusak (Eds.), Proceedings of TMCE 2014, May 19–23, 2014, Budapest, Hungary (pp. 1283–1294).

Fox, S. (2008). Evaluating potential investments in new technologies: Balancing assessments of potential benefits with assessments of potential disbenefits, reliability and utilization. Critical Perspectives on Accounting, 19(8), 1197–1218. doi:10.1016/j.cpa.2007.11.002

Fox, S. (2013a). Getting real about ICT: Applying critical realism to the framing of information and communication technologies. Management Research Review, 36(3), 296–319. doi:10.1108/01409171311306427

Fox, S. (2013b). The innovation big picture: Including effectiveness dependencies, efficiency dependencies, and potential negative effects within the framing of new technologies. Technology in Society, 35(4), 306–314. doi:10.1016/j.techsoc.2013.08.001

Future Virtual Design Environment – Cofex Project Workshop. (2013). VTT Technical Research Centre of Finland, Tampere

Gero, J. (1990). Design prototypes: a knowledge representation schema for design. AI Magazine, 11(4), 26–36. Retrieved from http://www.aaai.org/ojs/index.php/aimagazine/article/viewArticle/854

Gero, J. S., & Kannengiesser, U. (2004). The Situated Function–Behaviour–Structure Framework. Design Studies, 25(4), 373–391. doi:10.1016/j.destud.2003.10.010

Gerritsen, B., Gielingh, W., Dankwort, W., & Anderl, R. (2011). Frameworks and technologies for exchanging and sharing product life cycle knowledge. Computer-Aided Design, 43(5), 459–463. doi:10.1016/j.cad.2010.12.009

Gomes de Sa, A., & Zachmann, G. (1998). Integrating virtual reality for virtual prototyping. In Proceedings of DETC'98 1998 ASME Design Engineering Technical Conferences September 13–16, 1998, Atlanta, Georgia, USA.

Gomes de Sá, A., & Zachmann, G. (1999). Virtual reality as a tool for verification of assembly and maintenance processes. Computers and Graphics, 23, 389–403.

Gregor, S., Martin, M., Fernandez, W., Stern, S., & Vitale, M. (2006). The transformational dimension in the realization of business value from information technology. The Journal of Strategic Information Systems, 15(3), 249–270. doi:10.1016/j.jsis.2006.04.001

Grieves, M. (2005). Product Lifecycle Management: Driving the Next Generation of Lean Thinking (1st ed., 288 p.). McGraw-Hill.

Grote, G. (2014). Adding a strategic edge to human factors/ergonomics: principles for the management of uncertainty as cornerstones for system design. Applied Ergonomics, 45(1), 33–9. doi:10.1016/j.apergo.2013.03.020

Gruchalla, K. (2004). Immersive well-path editing: investigating the added value of immersion. In IEEE Virtual Reality 2004 (pp. 157–164). IEEE. doi:10.1109/VR.2004.1310069

Grönroos, C. (2008). Service logic revisited: who creates value? And who co-creates? European Business Review, 20(4), 298–314. doi:10.1108/09555340810886585

Gupta, S., Hanssens, D., Hardie, B., Kahn, W., Kumar, V., Lin, N., & Sriram, N. (2006). Modeling customer lifetime value. Journal of Service Research, 9(2), 139–155. Retrieved from http://jsr.sagepub.com/content/9/2/139.short

Haque, B., & James-moore, M. (2004). Applying lean thinking to new product introduction. Journal of Engineering Design, 15(1), 1–31. doi:10.1080/0954482031000150125

Harnesk, D., & Thapa, T. (2013). A Framework for Classifying Design Research Methods. In J. vom Brocke & E. Al (Eds.), Design Science at the Intersection of Physical and Virtual Design – 8th International Conference, DESRIST 2013 Helsinki, Finland, June 2013 Proceedings (469 p.). Berlin: Springer-Verlag.

Harrison, G., Haruvy, E., & Ruström, E. (2011). Remarks on Virtual World and Virtual Reality Experiments. Southern Economic Journal, 78(1), 87–94.

Retrieved from http://journal.southerneconomic.org/doi/abs/10.4284/0038-4038-78.1.87

Heikkilä, J. (2006). Engineering Quality for Service Performance – Reliability Management in Product Design Process – Preliminary Project plan.

Heikkilä, J. (2009). VIRVO project results 2006–2009. Seminar presentation.

Heikkilä, J., Helin, K., & Leino, S.-P. (2011). Customer Requirements Validation with VR Technologie – Case Metso Minerals. In K. Helin & M. D. D'Cruz (Eds.), Joint VR Conference of euroVR and EGVE, 2011 Current and Future Perspectives of Virtual Reality, Augmented Reality and Mixed Reality: Industrial and Poster Track (pp. 9–15). VTT Symposium 269. Espoo: VTT.

Hines, P., Francis, M., & Found, P. (2006). Towards lean product lifecycle management: A framework for new product development. Journal of Manufacturing Technology Management, 17(7), 866–887. doi:10.1108/17410380610688214

Hollnagel, E. (2014). Human factors/ergonomics as a systems discipline? "The human use of human beings" revisited. Applied Ergonomics, 45(1), 40–4. doi:10.1016/j.apergo.2013.03.024

Hollnagel, E. (ed). (2003). Handbook of Cognitive Task Design. Erlbaum.

Horvath, L., & Rudas, I. (2007a). Information Content Orientated Product Model Assisted Change Management. In 5th International Symposium on Intelligent Systems and Informatics, 2007. SISY 2007. (pp. 225–230). Retrieved from http://ieeexplore.ieee.org/xpls/ abs_all.jsp?arnumber= 4342656

Horvath, L., & Rudas, I. (2007b). Towards intelligent change management in product modeling. In 3rd International Symposium on Computational Intelligence and Intelligent Informatics ISCIII, (pp. 269–274). Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4218433

Horváth, L., & Rudas, I. (2009). Indirect communication between engineers through product model. In 7th International Symposium on Intelligent Systems and Informatics, 2009. SISY'09. (pp. 383–388). Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5291127

Horváth, L., Rudas, I. J., & Hancke, G. (2010). New Content behind the Concept Intelligent Engineering. In INES 2010 14th International Conference on Intelligent Engineering Systems (pp. 73–78).

Hu, Y., Wu, D., Fan, X., & Zhen, X. (2010). Grid-enabled collaborative virtual assembly environment. Assembly Automation, 30(4), 352–364. doi:10.1108/01445151011075816

Hubka, V., & Eder, E. (1988). Theory of Technical Systems: a Total Concept Theory for Engineering Design. Springer-Verlag.

Hubka, V., & Eder, E. (1996). Design Science: Introduction to the Needs, Scope and Organization of Engineering Design Knowledge (251 p.). Springer.

Huet, G., Culley, S., McMahon, C., & Fortin, C. (2007). Making sense of engineering design review activities. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 21, 243–265.

Ibusuki, U., & Kaminski, P. C. (2007). Product development process with focus on value engineering and target-costing: A case study in an automotive company. International Journal of Production Economics, 105(2), 459–474. doi:10.1016/j.ijpe.2005.08.009

Internal company report on virtual environments pilots in ManuVAR project (2012).

Jokioinen, T. (2006). Liikkuvien työkoneiden hydrauliikka- ja sähköreititityssuunnittelun kehittäminen. Tampere University of Technology.

Jørgensen, K. (1992). Videnskaplige arbejsparadigmer. Aalborg.

Kalawsky, R. S. (1993). The Science of Virtual Reality and Virtual Environments: A Technical, Scientific and Engineering Reference on Virtual Environments. Addison-Wesley Pub.

Kaptelin, V. (1996). Computer-aided activity: functional organs in social and developmental contexts. In B. Nardi (Ed.), Context and consciousness: Activity Theory and human-computer interaction (pp. 45–68). Cambridge, MA: The MIT Press.

Kaptelinin, V., & Nardi, B. (1997). Activity Theory: Basic concepts and applications. CHI'97 Extended Abstracts on Human Factors in Computing Systems, 158–159. Retrieved from http://dl.acm.org/citation.cfm?id=1120321

Kariniemi, O.-P. (2014). Utilizing multiple product structures in technology industry (in Finnish). Tampere University of Technology.

Keenaghan, G., & Horváth, I. (2014). State of the art of using virtual reality technologies in built environment education. In I. Horváth & Z. Rusak (Eds.), Proceedings of TMCE 2014, May 19–23, 2014, Budapest, Hungary (pp. 935–948).

Keizer, J. a., & Halman, J. I. M. (2009). Risks in major innovation projects, a multiple case study within a world's leading company in the fast moving consumer goods. International Journal of Technology Management, 48(4), 499. doi:10.1504/IJTM.2009.026691

Kimpimäki, H. (2014). Enterprise Architecture in Practice : From IT Concept towards Enterprise Architecture Leadership. Tampere University of Technology.

Kiritsis, D. (2011). Closed-loop PLM for intelligent products in the era of the Internet of things. Computer-Aided Design, 43(5), 479–501. doi:10.1016/j.cad.2010.03.002

Kissel, M., Bradford, N., Kreimeyer, M., & Lindemann, U. (2012). Product structure management as the backbone of engineering design: exploration of a reference model. International Design Conference – DESIGN 2012, 1709–1718.

Kor, Y. Y., & Mahoney, J. T. (2004). Edith Penrose's (1959) Contributions to the Resource-based View of Strategic Management. Journal of Management Studies, 41(1), 183–191.

Kossiakoff, A., & Sweet, W. (2003). Systems Engineering Principles and Practice. Hoboken, New Jersey: John Wiley and Sons.

Koudal, P., & Coleman, G. C. (2005). Coordinating operations to enhance innovation in the global corporation. Strategy & Leadership, 33(4), 20–32. doi:10.1108/10878570510608013

Kremer, K. (1998). A Concept For Virtual Reality Tools For Design Reviews. In Visualization '98 (pp. 205–211).

Krishnan, V., & Ulrich, K. (2001). Product Development Decisions: A Review of the Literature. Management Science, 47(1), 1–21.

Kropsu-Vehkapera, H., Haapasalo, H., Harkonen, J., & Silvola, R. (2009). Product data management practices in high-tech companies. Industrial Management & Data Systems, 109(6), 758–774. doi:10.1108/02635570910968027

Kujala, S. (2003). User involvement: A review of the benefits and challenges. Behaviour & Information Technology, 22(1), 1–16. doi:10.1080/01449290301782

Le Masson, P., & Weil, B. (2012). Design theories as languages of the unknown: insights from the German roots of systematic design (1840–1960). Re-

search in Engineering Design, 24(2), 105–126. doi:10.1007/s00163-012-0140-2

Lee, C. (2001). Modeling the business value of information technology. Information & Management, 39 (September 2000). Retrieved from http://www.sciencedirect.com/science/article/pii/S0378720601000908

Lee, C., Leem, C. S., & Hwang, I. (2011). PDM and ERP integration methodology using digital manufacturing to support global manufacturing, 53, 399–409. doi:10.1007/s00170-010-2833-x

Lee, H. J., Ahn, H. J., Kim, J. W., & Park, S. J. (2006). Capturing and reusing knowledge in engineering change management: A case of automobile development. Information Systems Frontiers, 8(5), 375–394. doi:10.1007/s10796-006-9009-0

Leikko, K. (2012). Inbound productization and developing it (in Finnish). Tampere University of Technology.

Leino, S.-P., Koivisto, T., & Riitahuhta, A. (2013). Value of virtual prototyping – a strategic resource based view. In Proceedings of the 19th International Conference on Engineering Design (ICED 13) (pp. 249–261).

Leino, S.-P., Lind, S., Heikkilä, J., & Uuttu, O. (2010). Integration of manual work related information to PLM. In International Design Conference – DESIGN2010 (pp. 1–10).

Leino, S.-P., & Pulkkinen, A. (2012). Design for human – virtual engineering is a media for knowledge transfer. In Proceedings of DESIGN 2012, the 12th International Design Conference (pp. 1507–1514).

Leino, S.-P., & Riitahuhta, A. (2012). State of the art of virtual engineering based human-machine system lifecycle knowledge transfer and management. In Proceedings of TMCE 2012, May 7–11, 2012, Karlsruhe, Germany (pp. 573–586).

Leino, S.-P., & Riitahuhta, A. (2014). Reality – virtuality phenomena model in virtual prototyping. In I. Horváth & Z. Rusak (Eds.), Proceedings of TMCE 2014.

Leino, S.-P., Vehviläinen, M., Kiviranta, S., Mäkiranta, A., Nuutinen, P., Hokkanen, I., Multanen, P., Rantanen, P., Heikkilä, J. & Martikainen, T. (2010). Collaboration between design and production by exploiting VR/AR and PLM-case Metso Minerals. In 3rd International Conference on Applied Human Factors and Ergonomics(AHFE2010). Miami, USA.

Leont'ev, A. (1978). Activity, consciousness, and personality. Englewood Cliffs: Prentice- Hall.

Leont'ev, A. (1981). Problems of the development of the mind. Moscow.

Lind, S., Leino, S.-P., Viitaniemi, J., Helin, K., Multanen, P., Mäkiranta, A., & Heik-kilä, J. (2008). Development of a virtual environment for promoting safety in machine maintenance. In Proceedings of the 6th International Conference on Occupational Risk Prevention ORP2008, A Coruna, Spain.

Liu, J., Ning, R., Yao, J., & Wan, B. (2006). Product lifecycle-oriented virtual assembly technology. Frontiers of Mechanical Engineering in China, 1(4), 388–395. doi:10.1007/s11465-006-0045-8

Liu, S., & Boyle, I. M. (2009). Engineering design: perspectives, challenges, and recent advances. Journal of Engineering Design, 20(1), 7–19. doi:10.1080/09544820802670914

Lukka, K. (2006). Konstruktiivinen tutkimusote: luonne, prosessi ja arviointi. In Rolin, Kakkuri-Knuutila, & Henttonen (Eds.), Soveltava yhteiskuntatiede ja filosofia (pp. 111–133). Helsinki: Gaudeamus.

Lukka, K., & Kasanen, E. (1995). The problem of generalizability : anecdotes and evidence in accounting research. Accounting, Auditing & Accountability Journal, 8(5), 71–90.

Ma, D., Zhen, X., Hu, Y., Wu, D., Fan, X., & Zhu, H. (2011). Collaborative Virtual Assembly Operation Simulation and Its Application. In D. Ma, Gausemei-erJurgen, X. Fan, & M. Grafe (Eds.), Virtual Reality and Augmented Reality in Industry (pp. 55–81). Springer.

Maguire, M. (2001). Methods to support human-centred design. International Journal of Human-Computer Studies, 55(4), 587–634. doi:10.1006/ijhc.2001.0503

Mahdjoub, M., Khatib, A. A. L., & Bluntzer, J. (2013). Multidisciplinary convergence about "product – use " couple: intermediary object' s structure. International Conference on Engineering Design – ICED13, Seoul, Korea

Malmqvist, J. (2002). A classification of matrix-based methods for product modeling. In 7th International Design Conference, Dubrovnik, Vol. 14, p. 17.

Mao, B. J., Vredenburg, K., Smith, P. W., & Carey, T. (2005). User-centered design practice. Communications of the ACM, 48(3), 105–109.

Martikainen, T. (2010). Using virtual techniques and risk analysis in product development of rock crushing machinery. (In Finnish.) Lappeenranta University of Technology.

McMahon, C. (2012). Reflections on diversity in design. Journal of Engineering Design, 23(8), 563–576.

Melville, N., Kraemer, K., Gurbaxani, V., & Ew, M. (2004). Review: Technology Information An Performance: Organizational Integrative Model of IT Business. MIS Quarterly, 28(2), 283–322.

Mørup, M. (1993). Design for Quality. Technical University of Denmark.

Morgan, J., & Liker, J. (2006). The Toyota Product Development System: Integrating People, Process And Technology (400 p.). Productivity Press.

Moser, H. (2014). Systems Engineering, Systems Thinking, and Learning – A Case Study in Space Industry. Springer.

Mujber, T. S., Szecsi, T., & Hashmi, M. S. J. (2004). Virtual reality applications in manufacturing process simulation. Journal of Materials Processing Technology, 155–156, 1834–1838. doi:10.1016/j.jmatprotec.2004.04.401

Mylopoulos, J. (2008). Conceptual modelling and Telos 1. Retrieved from http://www.cs.toronto.edu/~jm/2507S/Readings/CM+Telos.pdf

Määttä, T. (2003). Virtual environments in machinery safety analysis. Tampere University of Technology.

Nardi, B. (1996). Activity Theory and human-computer interaction. In Context and consciousness: Activity Theory and human–computer interaction, 436 (pp. 4–8).

Nardi, B. A. (1996). Studying Context: A Comparison of Activity Theory, Situated Action Models, and Distributed Cognition. In Activity Theory and human-computer interaction (pp. 69–102).

Neap, H., & Celik, T. (1999). Value of a product: A definition. International Journal of Value-Based Management, 12(2), 181–191. Retrieved from http://link.springer.com/article/10.1023/A:1007718715162

Neville, C. (2007). Introduction to Research and Research Methods (46 p.). University of Bradford School of Management. Retrieved from http://www.brad.ac.uk/management/media/management/els/Introduction-to-Research-and-Research-Methods.pdf

Nevo, S., Nevo, D., & Kim, H. (2012). From recreational applications to workplace technologies: An empirical study of cross-context IS continuance in the case of virtual worlds. Journal of Information Technology, 27(1), 74-86.

Nicolai, A., & Seidl, D. (2010). That's Relevant! Different Forms of Practical Relevance in Management Science. Organization Studies, 31(9-10), 1257–1285. doi:10.1177/0170840610374401

Niiniluoto, I. (1980). Johdatus tieteenfilosofiaan: Käsitteen- ja teorianmuodostus (Finnish Edition). Helsinki: Otava.

Nonaka, I. (1994). Dynamic Theory of of Organizational Knowledge Creation. Organization Science, 5(1), 14–37.

Nonaka, I., Konno, N., Tokuoka, K., & Kawamura, T. (1992). Hypertext Organization for Accelerating Organizational Knowledge Creation (in Japanese). Diamond Harvard Business.

Nonaka, I., & von Krogh, G. (2009). Perspective–Tacit Knowledge and Knowledge Conversion: Controversy and Advancement in Organizational Knowledge Creation Theory. Organization Science, 20(3), 635–652. doi:10.1287/orsc.1080.0412

Norros, L. (2013). Developing human factors/ergonomics as a design discipline. Applied Ergonomics 45, 61–71.

Oja, H. (2010). Incremental Innovation Method for Technical Concept Development with Multi-disciplinary Products. Tampere University of Technology.

Olesen, J. (1992). Concurrent Development in Manufacturing – based on dispositional mechanisms. The Technical University of Denmark

Oliveira, M., & Ferreira, J. (2011). Facilitating qualitative research in business studies-Using the business narrative to model value creation. African Journal of Business Management, 5(1), 68–75. Retrieved from http://ria.ua.pt/handle/10773/7110

Ottosson, S. (2002). Virtual reality in the product development process. Journal of Engineering Design, 13 (January), 159–172. Retrieved from http://www.tandfonline.com/doi/abs/10.1080/09544820210129823

Ovtcharova, J. G. (2010). Virtual engineering: principles, methods and applications. In International design conference – DESIGN 2010 (pp. 1267–1274).

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. H. (2007). Engineering Design – A Systematic Approach. (K. Wallace & L. Blessing, Eds.) (3rd ed.). Springer.

Pang, Y., Nee, A. Y. C., Ong, S. K., Yuan, M., & Youcef-Toumi, K. (2006). Assembly feature design in an augmented reality environment. Assembly Automation, 26(1), 34–43. doi:10.1108/01445150610645648

Peng, G., Wang, G., Liu, W., & Yu, H. (2010). A desktop virtual reality-based interactive modular fixture configuration design system. Computer-Aided Design, 42(5), 432–444. doi:10.1016/j.cad.2009.02.003

Penrose, E. (1959). The Theory of the Growth of the Firm. New York: John Wiley.

Piirainen, K. A., & Gonzalez, R. A. (2013). Seeking Constructive Synergy: Design Science and the Constructive Research Approach. In J. vom Brocke & E. Al (Eds.), Design Science at the Intersection of Physical and Virtual Design – 8th International Conference, DESRIST 2013 Helsinki, Finland, June 2013 Proceedings (pp. 59–72). Berlin: Springer-Verlag.

Porter, M. (1985). Competitive Advantage: Creating and Sustaining Superior Performance. New York: Free Press.

Porter, M. E., & Kramer, M. R. (2011). The Big Idea : Creating Shared Value. Harvard Business Review, 89(1).

Prahalad, C., & Hamel, G. (1990). The Core Competence of the Corporation. Boston (Ma), 1990, 235–256.

Pulkkinen, A. (2007). Product Configuration in Projecting Company: The Meeting of Configurable Product Families and Sales-Delivery Process. Tampere University of Technology.

Putkonen, A. (2010). Macroergonomic approach applied to work system modelling in product development contexts. University of Oulu

Raposo, A., Wagner, G. N., Santos, I. H. F., & Gattass, M. (2006). Towards the Use of CAD Models in VR Applications. In VRCAI 2006 ACM Virtual Reality Continuum and its Applications, Hong Kong, China (Vol. 1, pp. 14–17).

Rehfeld, I. (2010). Virtual Reality as an Integral Part of Product Lifecycle Management (PLM). In Joint Virtual Reality Conference of EGVE-ICAT – EuroVR.

Roper, S., Du, J., & Love, J. H. (2008). Modelling the innovation value chain. Research Policy, 37(6–7), 961–977. doi:10.1016/j.respol.2008.04.005

Roundtable discussion on the thesis research (2013). Participants from Metso MAC (Ylä-Outinen, K., Heikkilä, J., Leikko, K., Jokinen, L.), Tampere University of Technology (Riitahuhta, A., Pulkkinen, A., Huhtala, P.) and VTT (Koivisto T., Viitaniemi, J., Leino, S-P.). VTT, Tampere

Saariluoma, P. (2005). Explanatory frameworks for interaction design. In Future interaction design (pp. 67–83). London: Springer.

Salvatierra-Garrido, J., & Pasquire, C. (2011). Value theory in lean construction. Journal of Financial Management of Property and Construction, 16(1), 8–18. doi:10.1108/13664381111116043

Savioja, P., & Norros, L. (2012). Systems usability framework for evaluating tools in safety–critical work. Cognition, Technology & Work, 15(3), 255–275. doi:10.1007/s10111-012-0224-9

Seth, A., Vance, J. M., & Oliver, J. H. (2011). Virtual reality for assembly methods prototyping: a review. Virtual Reality, 15(1), 5–20. doi:10.1007/s10055-009-0153-y

Sheridan, T. B. (2014). Evaluating models in systems ergonomics with a taxonomy of model attributes. Applied Ergonomics, 45(1), 78–84. doi:10.1016/j.apergo.2013.03.018

Simon, H. (1996). The Sciences of the Artificial (3rd ed., 231 p.). Cambridge, MA: The MIT Press.

Simon, H. A. (1964). On the Concept of Organizational Goal. Administrative Science Quarterly, 9(1), 1–22.

Simon, H. A. (1979). Rational Decision Making in Business Organizations. The American Economic Review, 69(4), 493–513.

Simon, H. A. (1991). Bounded Rationality and Organizational Learning. Organization Science, 2(1), 125–134.

Simon, H. A. (1995). Problem Forming, Problem Finding, and Problem Solving in Design. In Collen & Gasparski (Eds.), Design and systems; General applications of methodology (Vol. 3, pp. 245–257). New Brunswick: Transaction Publishers.

Simon, H., Dantzig, G., & Hogarth, R. (1987). Decision making and problem solving. Interfaces, 17 (October), 11–31. Retrieved from http://pubsonline.informs.org/doi/abs/10.1287/inte.17.5.11

Simula, H., Lehtimäki, T., & Salo, J. (2008). Re-thinking the product – from innovative technology to productized offering. In Proceedings of the 19th Inter-

national Society for Professional Innovation Management Conference, Tours, France.

Soh, C., & Markus, M. L. (1995). How IT creates business value: A process theory synthesis. In ICIS 1995 (pp. 29–41).

Sousa Santos, B., Dias, P., Pimentel, A., Baggerman, J.-W., Ferreira, C., Silva, S., & Madeira, J. (2008). Head-mounted display versus desktop for 3D navigation in virtual reality: a user study. Multimed Tools Appl., 41(1), 161–181. doi:10.1007/s11042-008-0223-2

Srinivasan, V. (2011). An integration framework for product lifecycle management. Computer-Aided Design, 43(5), 464–478. doi:10.1016/j.cad.2008.12.001

Sriram, R. (Ed.). (2002). Distributed and Integrated Collaborative Engineering Design. Sarven Publishers.

Stabell, C., & Fjeldstad, Ø. (1998). Configuring value for competitive advantage: on chains, shops, and networks. Strategic Management Journal, 19(November 1996), 413–437. Retrieved from http://www.peopleandprocess.com/resources/Stabell_chain_shop_net.pdf

Stark, J. (2006). Product Lifecycle Management – 21st Century Paradigm for Product Realisation (441 p.). London: Springer-Verlag.

Sutherland, I. E. (1965). The Ultimate Display. In Proceedings of IFIP Congress (pp. 506–508).

Sveiby, K. (2001). A Knowledge-Based Theory of the Firm to guide in strategy formulation. Journal of Intellectual Capital, 2(4), 344–358.

Söderman, M. (2005). Virtual reality in product evaluations with potential customers: An exploratory study comparing virtual reality with conventional product representations. Journal of Engineering Design, 16(3), 311–328. doi:10.1080/09544820500128967

Takeuchi, H., & Nonaka, I. (1986). The new new product development game. Harvard Business Review, 64(1), 137–146.

Taylor, F. (1911). The Principles of Scientific Management. Harper & Brothers.

Thatcher, M. E., & Pingry, D. E. (2007). Modeling the IT value paradox. Communications of the ACM, 50(8), 41–46.

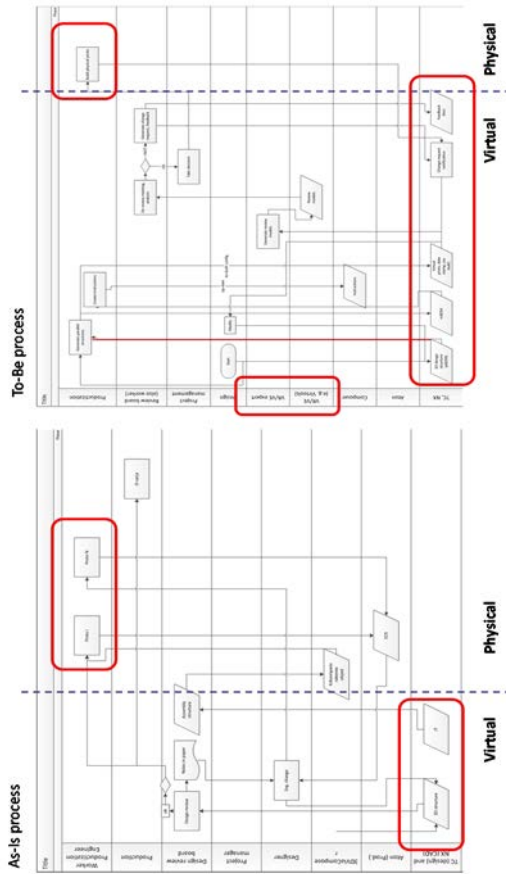Thompson, J. (1967). Organizations in action. New York: McCraw Hill.

Tjalve, E. (1979). A short course in industrial design. London: Newnes-Butterworths.

Toma, M. I., Gîrbacia, F., & Antonya, C. (2012). A comparative evaluation of human interaction for design and assembly of 3D CAD models in desktop and immersive environments. International Journal on Interactive Design and Manufacturing (IJIDeM), 6(3), 179–193. doi:10.1007/s12008-012-0144-1

Tseng, M. M., Jiao, J., & Su, C.-J. (1998). Virtual prototyping for customized product development. Integrated Manufacturing Systems, (9), 334–343.

Tushman, M. L., & Reilly, C. A. O. (1996). Ambidextrous Organizations: Managing Evolutionary and Revolutionary Change. California Management Review, 38(4), 8–30.

Ulrich, K., & Eppinger, S. (2004). Product Design and Development (3rd ed., 366 p.). New York: McCraw Hill.

Unger, D., & Eppinger, S. (2011). Improving product development process design: a method for managing information flows, risks, and iterations. Journal of Engineering Design, 22(10), 689–699. doi:10.1080/09544828.2010.524886

Wang, G. G. (2002). Definition and Review of Virtual Prototyping. Journal of Computing and Information Science in Engineering, 2(3), 232. doi:10.1115/1.1526508

Watts, F. (2011). Engineering Documentation Control Handbook – Configuration Management and Product Lifecycle Management (4 edition). William Andrew.

Weber, C. (2014). Modelling Products and Product Development Based on Characteristics and Properties. In A. Chakrabarti & L. Blessing (Eds.), An Anthology of Theories and Models of Design – Philosophy, Approaches and Empirical Explorations (pp. 327–352). Springer.

Weber, C., & Husung, S. (2011). Virtualisation of product development / design – seen from design theory and methodology. In International Conference on Engineering Design, ICED11, Copenhagen, Denmark.

Weber, C., Werner, H., & Deubel, T. (2003). A different view on Product Data Management/Product Life-Cycle Management and its future potentials. Journal of Engineering Design, 14(4), 447–464. doi:10.1080/09544820310001606876

Vehviläinen, M. (2014). Exploiting data created in engineering systems in supporting manual work throughout the product lifecycle (In Finnish). Tampere University Technology.

Weidlich, D., Cser, L., Polzin, T., Cristiano, D., & Zickner, H. (2009). Virtual reality approaches for immersive design. International Journal on Interactive Design and Manufacturing (IJIDeM), 3(2), 103–108. doi:10.1007/s12008-009-0063-y

Wernerfelt, B. (1984). A Resource-based View of the Firm. Strategic Management Journal, 5(2), 171–180.

Westkämper, E. (2007). Digital Manufacturing in the global Era. In Digital Enterprise Technology (pp. 3–14). Springer US.

Wiener, N. (1954). The Human Use of Human Beings. Boston: Houghton Mifflin Co.

Willaert, S. S. ., de Graaf, R., & Minderhoud, S. (1998). Collaborative engineering: A case study of Concurrent Engineering in a wider context. Journal of Engineering and Technology Management, 15(1), 87–109. doi:10.1016/S0923-4748(97)00026-X

Wilson, J. R. (1997). Virtual environments and ergonomics: needs and opportunities. Ergonomics, 40(10), 1057–1077. doi:10.1080/001401397187603

Wilson, J. R. (2014). Fundamentals of systems ergonomics/human factors. Applied Ergonomics, 45(1), 5–13. doi:10.1016/j.apergo.2013.03.021

Wilson, J. R., & D'Cruz, M. (2006). Virtual and interactive environments for work of the future. International Journal of Human-Computer Studies, 64(3), 158–169. doi:10.1016/j.ijhcs.2005.08.007

Vink, P., Imada, a S., & Zink, K. J. (2008). Defining stakeholder involvement in participatory design processes. Applied Ergonomics, 39(4), 519–26. doi:10.1016/j.apergo.2008.02.009

Womack, J., Jones, D., & Roos, D. (1991). The Machine That Changed the World: The Story of Lean Production. Harper Paperbacks.

Vredenburg, K., Mao, J.-Y., Smith, P. W., & Carey, T. (2002). A survey of user-centered design practice. In Proceedings of the SIGCHI conference on Human factors in computing systems Changing our world, changing ourselves – CHI '02 (p. 471). New York, New York, USA: ACM Press. doi:10.1145/503457.503460

Vygotsky, L. (1978). Mind in Society: the development of higher psychological processes. Cambridge, Mass: Harvard University Press.

Yin, R. K. (2009). Case Study Research. Design and Methods (4th ed., 219 p.). SAGE Inc.

Zeltzer, D. (1992). Autonomy, interaction, and presence. Presence: Teleoperators and Virtual Environments, 1(1), 127–132.

Zhang, T., & Dong, H. (2009). Human-Centred Design : An Emergent Conceptual Model. In Include2009, Royal College of Art, London.

Zhang, Y., Gregory, M., & Shi, Y. (2008). Global engineering networks (GEN): Drivers, evolution, configuration, performance and key patterns. Journal of Manufacturing Technology Management, 19(3), 299–314. doi:10.1108/17410380810853740

Zimmermann, P. (2008). Virtual Reality Aided Design: A Survey of the Use of VR in Automotive Industry. In D. Talaba & A. Amditis (Eds.), Product Engineering – Tools and Methods based on Virtual Reality (pp. 277–296). Springer.

Zorriassatine, F., Wykes, C., Parkin, R., & Gindy, N. (2003). A survey of virtual prototyping techniques for mechanical product development. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 217(4).
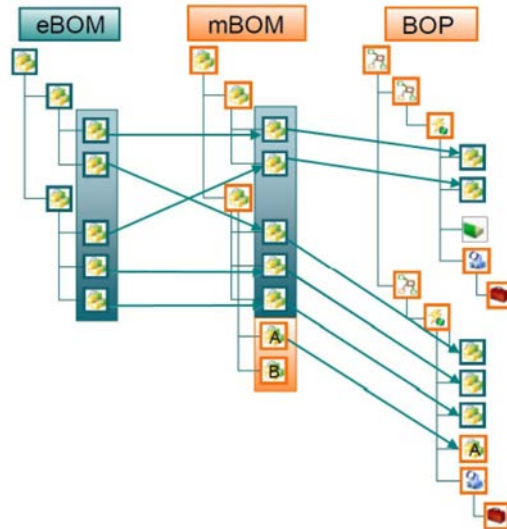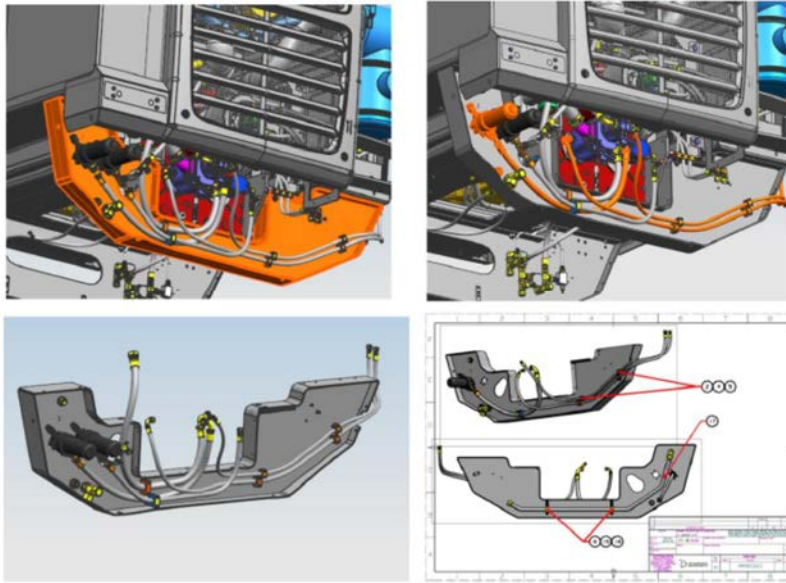
Appendix A: As-is and to-be process models

Source: ManuVAR project. Simulation game at the case company.

Appendix B: Bill of Material and Bill of Process

Source: Kariniemi, 2014

Appendix C: Terminology

Abductive approach	In the context of constructive research, information systems, and management science, the abductive method is an iterative cycle of deduction and induction, which, as an inferential procedure, creates conjectures that would contribute to the understanding of an ill-structured problem of the world when they were correct. (Harnesk & Thapa, 2013)
Activity system	The collective, object-oriented and artefact-mediated human conduct as unit of analysis. (Engeström, 1987)
Artefact	Objects and phenomena that result from human intervention in the natural world, e.g. design. (Herbert Simon, 1996)
Business value dimension	One of the virtual prototyping value dimensions of this thesis. The business value dimension discusses the value of virtual prototyping from the perspective of business management. Business means taking into account largely the activity that is carried out in order to provide goods or services in exchange for money. Business value is created in respect to business management which is largely dealing with decision making, including all activity that supports decision making, e.g. communications and negotiations (Nicolai & Seidl, 2010).
Case study	An empirical research method that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and its context are not clearly evident. (Yin, 2009)
Complexity	In business management, it is helpful to understand the difference (Amaral, L.A. & Uzzi, 2007) between the notions of complicated (have many interacting components through predefined rules) and complex systems (have many components that can autonomously interact through emergent rules), because often business systems, organisations and processes are treated by engineers like complicated linear and causal systems.
Concept design	Concept design produces a product concept that is a concise description of how the product will satisfy customer needs, including an approximate description of the technology, working principles, and form of the product (Ulrich & Eppinger, 2004).
Conceptual modeling	Conceptual modeling is the activity of formally describing some aspects of the physical and social world around us for the purposes of understanding and communication. (Mylopoulos, 2008)
Concurrent engineering	The systematic approach to the integrated development of products and their related processes (Backhouse & Brookes, 1996).

Configurable product	Configuration as an object means a structurally varied object that is a composition of related sub-elements when varied means that the configuration is different from another configuration (of the same kind). The differences appear both in the structure and in the function of the configuration. However, there are generic similarities between configurations (of the same kind), which can be classified as generic attributes, i.e. structural characteristics and functional properties, of the configuration. (Pulkkinen, 2007)
Constructive approach	The constructive approach implies building an artefact (practical, theoretical or both) that solves a domain-specific problem in order to create knowledge of how the problem can be solved (or understood, explained or modelled) in principle. Scientific knowledge is constructed by scientists with the help of cognitive tools. Therefore, it is the opposite of the positivist epistemology which sees scientific knowledge as discovered in the world. Knowledge is created through interaction between the observer and the observed, and in networks of interacting agents. (Crnkovic, 2010)
Contradiction	Contradictions have a central role as a source of change and development within activity systems, i.e. organisations. The concept of contradiction refers to anything that opposes the overall motive of the activity system (Allen et al., 2013). However, they are not the same as problems or conflicts (Engeström, 2001), but rather historically accumulating structural tensions within and between activity systems.
Conventional prototyping	The prototyping activity based on physical prototypes
Core competence	A concept of management theory that emphasizes the harmonized combination of multiple resources and skills that distinguish a firm in the marketplace (Prahalad & Hamel, 1990)
Data	The lowest level of abstraction, from which information and then knowledge are derived.
Data pipeline	The data processes between design and engineering tools, such as CAD, to virtual prototypes and virtual environment
Design	Design is thinking, deciding and solving problems (Simon, 1969). Design is about understanding the demands of people and society, and the process of transforming the demands into product descriptions.
Design description	A design description (or specification) is generally represented graphically, numerically or textually with the purpose of transferring sufficient information about the designed artefact to stakeholders, like manufacture (Gero, 1990).
Design maturity	Design maturity refers to the progress of value of a technical system during the design process (Hubka & Eder, 1988).

Design description maturity	Refers to the capability of a design description to represent sufficient and eligible information about the designed artefact to stakeholders.
Design review	Evaluation and control of engineering design activities, and opportunities for all the parties to share information about the product and related processes (Huet, Culley, McMahon, & Fortin, 2007).
Design review board	The members participating the design review activities, typically representing the product stakeholders
Detail design	The detail design phase includes the complete specification of the geometry, materials, and tolerances of all of the unique parts in the product and the identification of all of the standard parts to be purchased from suppliers (Ulrich & Eppinger, 2004).
Disposition	The disposition means that part of a decision made in one activity which affects the type, content, efficiency, and progress of activities within other functional areas (Andreasen & Mcaloone, 2008).
Domain	Domain Theory (Andreasen, 1980) approaches the product synthesis from the viewpoint of four domains: transformation, function, organ, part. In each domain, design synthesis progresses through detailing and concretization. Each domain is a system in which the structural characteristics which define or specify the system, and its behavioural properties must be distinguished.
Embodiment design	The phase of design process, where the product architecture, i.e. principles and basic structures, are determined. Embodiment design refers to the design layout phase between conceptual design, and detail design (Hubka & Eder, 1988).
Engineering	Engineering sciences model known objects, contrary to design theories that are frameworks to guide the elaboration of still unknown objects (Le Masson & Weil, 2012)
Engineering change	A modification that affects only the documentation or a modification to a product(s) that is necessary to make that product: Meet the product specification including reliability and maintenance requirements; Meet the product safety specifications; Manufactured at a minimum/reduced cost; Maintained at a minimum/reduced cost; Exceed its product specification (usually called "product improvements"). (Watts, 2011)
Engineering change management (ECM)	The formal process of an engineering change usually consists of four stages: initiating an engineering change request (ECR), evaluating the ECR, issuing engineering change orders (ECOs) to relevant participants, and storing and analyzing the ECOs for management purposes. (Lee et al., 2006)
Engineering	In the case company, during the case studies, EDM was the IT

data management (EDM)	database-solution that managed CAD and other design objects before they were released to PDM (product data management) system
Engineering design	Engineering design is a process performed by humans aided by technical means through which information in the form of requirements is converted into information in the form of descriptions of technical systems, such that this technical system meets the requirements of mankind (Hubka & Eder, 1988).
Epistemological	Epistemological knowledge dimensions vary between tacit and explicit knowledge. (Nonaka, 1994)
Explicit knowledge	The word explicit refers to codified knowledge that can be transmitted by formal and systematic language. (Nonaka, 1994)
Externalization	In the Dynamic Theory of Knowledge Creation (Nonaka, 1994), externalization refers to the conversion of tacit knowledge into explicit knowledge
Feedback	In the context of this thesis, feedback refers to the information from the downstream product stakeholders, e.g. from production and service, to engineering designers, and product managers
Frontloading	In the context of product design and development, frontloading means investing more effort into the early design process stages aiming to save overall time and cost is the new product development project. Thus, frontloading aims to reduce time-to-market, and time-to-profit
Haptics	One of the sensory modalities of virtual environments related to human sense of touch and force. (Kalawsky, 1993)
Historicity of activity	The principle of Theory of Expansive Learning, that highlights the fact that activity systems take shape and become transformed over lengthy periods of time, and therefore their problems and potentials can only be understood against their history. (Engeström, 2001)
Human centred design (HCD)	Design approach based on the active involvement of users in improving the understanding of user and task requirements, and the iteration of design and evaluation(Mao et al., 2005), (Vredenburg et al., 2002), (Maguire, 2001). Most literature considers UCD and HCD as synonyms, but some sources distinguish that HCD emphasizes more the needs of different stakeholders in broader contexts (Zhang & Dong, 2009).
Human Factors / Ergonomics (HF / E)	Ergonomics (or human factors) is the scientific discipline concerned with the understanding of the interactions among humans and other elements of a system, and the profession that applies theoretical principles, data and methods to design in order to optimize well-being and overall performance(Dul et al., 2012). The term 'ergonomics' is originated in Europe, and 'human

	factors' in the Americas. In Theory of Technical Systems (Hubka & Eder, 1988), the concept of ergonomics is defined as the study of relationships between humans and technical systems, especially direct interactions between them. The term ergonomic also refers to a property of a technical system.
Hypertext organisation	In the Dynamic Theory of Knowledge Creation (Nonaka, 1994), knowledge-creating organisations have three interacting layers: business system (formal), project team (cross-functional), and the knowledge-base which stores and shares the explicit knowledge in the form of documents, files, databases
Immersion	In the context of virtual environments, to be immersed in the experience means that the person feels part of the actual environment (Kalawsky, 1993). Immersion refers to the objective level of sensory fidelity (Bowman et al., 2007).
Information	Information is a flow of messages, while knowledge is created and organized by the very flow of information, anchored on the commitment and beliefs of its holder. Information is pieces which may change, restructure or contribute to knowledge. Compared to knowledge, data and information are much easier to store, describe and manipulate. (Nonaka, 1994)
Information model	The framework that links the pieces of data and information together so that it can be shared, retrieved and interpreted correctly.
Intermediary object	A sociology rooted concept that covers a general category of physical (plans, mock-ups, sketches, etc.) or digital (CAD models, calculation results, etc.) artefacts produced by the participants during their work covering all kinds of externalisation. (Boujut & Laureillard, 2002)
Intermediary virtual prototyping (IVP)	The new concept resulting from this research. It underscores the many layers from technical advantages of virtual reality to the expanded mediating object of product development activity system.
Knowledge	In the context of this thesis the definition of (Ameri & Dutta, 2005) is valid: "Knowledge is evaluated and organized information that can be used purposefully in a problem-solving process". Knowledge is created and organized by the very flow of information, anchored on the commitment and beliefs of its holder (Nonaka, 1994)
Knowledge management	In the context of product lifecycle management, knowledge management typically refers to the management of explicit knowledge by means of IT-solutions. However, knowledge management should be seen rather as a process (Sveiby, 2001) than a pure IT technology and explicit information issue. Both approaches are discussed in this thesis.
Manual work	In the context of this thesis, manual work refers to the physical

	product related work tasks, e.g. manual assembly and mainte-nance work. Not automated or robotized work
Mental model	By aid of mental models, people construct their internal working models of the world, and structure their knowledge (Badke-Schaub & al., 2007).
Metadata	Metadata is data about data. It can be structural or descriptive. In the context of this thesis, metadata refers to product data management. Metadata includes for instance item codes, at-tributes, and product structure.
Model	In the context of design, models are defined as restricted rep-resentations of reality on different abstraction levels (Hubka & Eder, 1988)
Multi-voicedness of activity	The notion of Theory of Expansive Learning (Engeström, 1987) meaning the multiple viewpoints, traditions and interests within an activity system
New product development (NPD)	New product development (NPD) can be defined as the crea-tion of a new product from the generation of an initial concept or idea through to the decision to commercialize the product (Hines et al., 2006), or more specifically as a sequence of steps or activities that an enterprise employs to conceive, design, and commercialise a product (Ulrich & Eppinger, 2004).
Ontological	The ontological knowledge creation dimension includes social interaction between individuals, departments, and organisa-tional boundaries. (Nonaka, 1994)
Partially configurable product	A such product where a separate set of engineering design tasks is involved in sales-delivery process. There, an open, mixed module system is the basis for the configuration, and the members of the product family include non-modules in their product individuals (i.e. configurations). (Pulkkinen, 2007)
Participatory design	Participatory design is an user involvement philosophy intro-ducing the idea of bringing end users and other stakeholders into direct contact with designers(Kujala, 2003). Participatory design has been promoted as an approach to secure optimiza-tion of both the economic and ergonomic aspects of work (Vink et al., 2008).
Phenomena model	The theoretical starting point for valuing virtual prototyping in the empirical case study. The model is synthesized and based on Theory of Technical Systems (Hubka & Eder, 1988) and Theory of Virtual Reality and Virtual Environments (Kalawsky, 1993). The model constructs links between the theories
Presence	Degree of presence depends on the subjective psychological feel of being part of a synthetic experience, while immersion refers to the objective level of sensory fidelity (Bowman et al., 2007). On the other hand, Sheridan (1992) has noted that

	presence is a subjective sensation which is not a totally objective physiological definition and measurement.
Product	The word 'product' is ambiguous. In the context of this thesis it means both the virtual descriptions of product types, and the physical product individuals, such as rock crushers
Product characteristics	Refers to product design synthesis, where designers are determining product characteristics in order to meet the demanded product properties. Product characteristics mean the same as design properties in the terminology of (Hubka & Eder, 1988)
Product data management	Refers to a database, and processes for formal management of product related data and information. The core of product lifecycle management technology architecture.
Product development	Product development is a process consisting of cycles that include the steps of synthesis, analysis, determining individual deviations, overall evaluation (Weber & Husung, 2011). Product development is the wider process that transforms market opportunities, i.e. customer needs, into a product available for sale, while product design refers to the specification of design parameters (Krishnan & Ulrich, 2001).
Product lifecycle management (PLM)	The strategic approach to creating and managing a company's product-related intellectual capital from cradle to grave, integrating organizations, processes, methods, models, IT tools and product related information (Ameri & Dutta, 2005), (Grieves, 2005), (Stark, 2006).
Product process	In the context of this thesis, product process is a general term meaning diverse set of product related processes from product design and development to manufacture and service of physical and abstract products.
Product property	In the terminology of (Hubka & Eder, 1988), product properties are categorized as: 1) External properties interest the users, operators, and customers. The external properties are the relationships of the technical system to its environment, 2) Internal properties deal with relationships between the elements of the system and the properties of those elements, 3) Design properties serve as a means for the designer to create the desired external properties. These properties are usually hidden from the system users.
Product structure model	In PDM, which is the backbone of PLM, the product structure is normally the main framework that constitutes the information model.
Productisation	Productisation at Metso MAC means the activity of preparing new products for market. It should be distinguished as internal and external productization (Leikko, 2012). The internal productisation means the preparation and development of new prod-

	ucts or modules for standard/serial production with a target cost level, while external productisation is related to customer interface, sales and marketing.
Prototype	Ulrich and Eppinger (Ulrich & Eppinger, 2004) define the term 'prototype' as "an approximation of the product along one or more dimensions of interest". This definition includes such diverse forms of prototypes as concept sketches, mathematical models, and fully functional preproduction versions of the product
Prototyping	Prototyping is the process of developing an approximation of the product (Ulrich & Eppinger, 2004) including the dimensions: a) Physical vs. analytical, b) comprehensive vs. focused.
Ramp-up	The process of preparation and launching new products to standard production
Resource Based View to the Firm	The theory which looks at firms in terms of their portfolio of resources rather than in terms of their portfolio of products, and gives a different perspective on strategic options. (Wernerfelt, 1984)
Serial production	In the context of this thesis, and the case company, serial production refers to the production mode where configurable product types are manufactured in series
Simulation	The word simulation refers to imitation of appearance or character of something (Oxford Dictionaries). In this thesis refers to use of computer simulation models of the product in order to evaluate certain product properties. This research is focused on real-time interactive models that are manipulated in virtual environments.
Social value dimension	One of the virtual prototyping value dimensions of this thesis. The social value dimension discusses the value of virtual prototyping from the perspective of individual people and organisations
Stakeholder	In this thesis context, stakeholders refer to everyone interested or concerned in the product during its lifecycle. "A person with an interest or concern in something, especially a business." (http://www.oxforddictionaries.com)
Standard production	In the context of this thesis, and the case company, standard production refers to production mode, where the product descriptions are stabilized
System	System is composed of interrelated components organized so as to achieve one or more stated purposes
Tacit knowledge	Tacit knowledge has a personal quality and a cognitive mental model which makes it difficult to formalize and communicate (Nonaka, 1994)
Time-to-market	The time period needed for launching a new product to market place

Time-to-profit	The time period needed for the cash-flow of a new product to become positive
Transformation system	The fundamental model of Theory of Technical Systems (Hubka & Eder, 1988). The transformation system model incorporates elements of system theory. It explains the role of technology in society, and the elements of a socio-technical system model. All transformation systems have a certain purpose, i.e. fulfilling stated needs by transformation of an operand (materials, energy, and information).
User centred design	A design approach based on the active involvement of users in improving the understanding of user and task requirements, and the iteration of design and evaluation (Mao et al., 2005), (Vredenburg et al., 2002), (Maguire, 2001).
Validation	Refers to the evaluation of product properties against the original user and/or customer demands
Value	Value theories aim to understand how, why and to what degree people value things. In the context of products and services generally, value can be defined as equal to the cost of the product plus a subjective part of the value (Neap & Celik, 1999). Universal virtues, i.e. costs, through-put-time, quality, efficiency, flexibility, risk, and environmental effects are general measurable quantities for assessing company's value creation and realization for all functional areas (Olesen, 1992)
Value capture	The act of turning a value proposition into real benefits that contribute to the success of the participants and their organizations
Value chain model	One of the value configuration frameworks for structuring the business and economic value creation of a manufacturing company
Value configuration	In this thesis propose three alternative value configurations (value chain, value shop, value network) by (Stabell & Fjeldstad, 1998) were discussed as a foundation for describing business value of virtual prototyping
Value conversion	The act of converting or transforming between financial and non-financial value
Value creation	The act of converting assets into negotiable value
Value shop	Besides the sequential value chain model (Porter, 1985), business organisations can be modelled as value shops where value is created by mobilizing resources for resolving a problem, and the value network models that create value by facilitating a network relationship using a mediating technology (Stabell & Fjeldstad, 1998).
Value-in-use	The notion of value-in-use proposes that value is not embedded in goods or services (value-in-exchange), but value is rather created when goods or services are used and the skills

	and knowledge of users are added in the value creation process (Grönroos, 2008).
Verification	Refers to testing or evaluation of product characteristics against the product requirements specification
Version	Refers to the management of the evolution of a computer file, document, or model
Virtual	The word 'virtual' means something that is "almost or nearly as described, but not completely or according to strict definition". (Oxford Dictionaries). In the context of this thesis the word 'virtual' should be contrasted with 'physical' and not 'real', because in product design and development 'virtual methods and tools' mainly try to challenge conventional 'physical methods' (such as physical prototyping) (Weber & Husung, 2011), (Zorriassatine et al., 2003).
Virtual Environments (VE)	Computer-generated experience of a participant, obtained by and through an interface which engages one or more of our senses but almost always includes the visual sense (Wilson & D'Cruz, 2006).
Virtual Prototype	Computer simulation of a physical product that can be presented, analysed, and tested from concerned product life-cycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physical model. The construction and testing of a virtual prototype is called virtual prototyping (Wang, 2002). This thesis is focused on real-time interactive models that are manipulated in virtual environments.
Virtual prototype baseline	The exact virtual prototype configuration to which product knowledge can be referenced, including product structure, item revisions and model versions
Virtual prototype structure	In the context of this thesis, product structure is the main framework that constitutes the product model. The virtual prototype structure should support the design process and maturity of design description
Virtual Prototyping (VP)	Methodology that refers to activity of prototyping, i.e. the phase of product design and development process where the product specification is tested and evaluated by the use of models. In virtual prototyping, virtual product models, i.e. computer simulation models of the product, i.e. virtual prototypes are utilized instead of, or together with physical prototypes. In this thesis, virtual prototyping is focused to the use of real-time interactive computer simulations, of a product by means of virtual environments in order to analyse and develop certain of product properties
Virtual Reality (VR)	Refers to two things in literature. On the one hand, it can be seen as the ultimate ideal virtual environment where the user cannot tell whether she/he perceives the real or virtual envi-

	ronment. On the other hand, the term virtual reality refers to the technology that enables the creation of virtual environments. (Kalawsky, 1993) In this research, the latter meaning is used.
Virtuality	Virtuality aims to mimic phenomena of reality that are important for a particular purpose in design. Thus, virtuality is based on models of reality.
Zone of proximal development	The distance between the present everyday actions of the individuals and the historically new form of the societal activity that can be collectively generated as a solution to the double bind (i.e. social dilemma) potentially embedded in the everyday actions". This fifth principle of Activity Theory deals with the possibility of expansive transformation in activity systems (Engeström, 1987)

Title	**Reframing the value of virtual prototyping**
	Intermediary virtual prototyping – the evolving approach of virtual environments based virtual prototyping in the context of new product development and low volume production
Author(s)	Simo-Pekka Leino

Abstract	This thesis studies how the evolving approach of virtual environments-based virtual prototyping can be evaluated in the context of product design and development in the manufacturing industry. The entry point for this research is the relatively long experience in applied research in virtual prototyping with industry. As the virtual prototyping technology has become more mature, the focus of research and development has extended from technology demonstrations towards utilization in product design and development processes. However, lack of scientific and practical knowledge of real benefits and the value of virtual prototyping has seemed to be a deterrent to its wider adoption of industry. The aim of this thesis is by means of scientific research to increase the knowledge of the value contribution of virtual prototyping as well as its impacts in a practical industrial context.
	This problem was approached from the science base by formulating an expanded theory framework for value modelling, and from the problem base by an empirical case study in one manufacturing company. The research approach was constructive and exploratory.
	The research results consist of three types of knowledge. Firstly, the scientific theoretical foundation was elaborated for initiating value modelling of virtual prototyping and virtual environments. Secondly, new knowledge on the value of virtual prototyping within new product development was created in an industrial case study. Finally, knowledge on how virtual prototyping (VP) impacts the company was reported. The impact was discussed in the dimensions of process, social and technological implications.
	This research contributed to engineering design science by conceptualizing virtual prototyping in the context of product design and development expanding to the dimensions of human factors and management theory. Thus, the contribution is also manifested by constructing the expanded theory framework for virtual prototyping value modelling in four dimensions with causal justification from virtual reality technology to business value elements which led to the new concept of Intermediary Virtual Prototyping (IVP). The discussed concept of IVP underscores the many layers from technical advantages of virtual reality to the expanded mediating object of product development activity system.
	The discussion was carried on from the perspective of a partially configurable products and manual work-intensive variant production mode. This perspective is novel compared to the majority of virtual prototyping and virtual environments literature. It is proposed that IVP is particularly beneficial in this context, where human skills and knowledge contribute to the flexibility of production system.
	IVP should be considered as a strategic investment that will produce income in the long run. IVP contributes to the co-creation and variant production paradigms by involving human creativity at an early product design and development phase, thus increasing flexibility. IVP creates value in use, but in turn it impacts the company in all the four dimensions mentioned.

Nimeke	**Virtuaaliprototypoinnin vaikuttavuuden arvioinnin laajennettu viitekehys** Lähestymistapa virtuaaliympäristöjä hyödyntävään virtuaaliprototypointiin uustuotekehityksessä matalan volyymin tuotannossa
Tekijä(t)	Simo-Pekka Leino
Tiivistelmä	Tässä väitöstyössä tutkittiin virtuaaliympäristöihin perustuvan virtuaaliprototypoinnin arvoa valmistavan teollisuuden tuotekehityksessä. Työn lähtökohtana oli suhteellisen pitkä virtuaaliprototypoinnin soveltava tutkimus teollisuudessa. Soveltavan tutkimuksen painopiste on laajentunut alkuaikojen teknologiademonstraatiosta virtuaaliprototypoinnin hyödyntämiseen tuotesuunnittelussa ja -kehityksessä. Sekä tieteellisen että käytännöllisen tietämyksen puute virtuaaliprototypoinnin todellisesta hyödystä ja arvosta näyttää kuitenkin olevan hidaste sen laajempaan käyttöönottoon teollisuudessa. Tämän väitöstyön tavoitteena on lisätä tietämystä virtuaaliprototypoinnin arvosta ja vaikutuksista teollisuudessa tieteellisen tutkimuksen keinoin. Virtuaaliprototypoinnin arvon ja vaikutuksen arviointiin liittyvää ongelmaa lähestyttiin työssä toisaalta luomalla teoriakehys arvon mallintamiseen ja toisaalta teollisen case-tutkimuksen suunnasta. Tutkimusote oli konstruktiivinen ja eksploratiivinen. Väitöstutkimus tuotti kolmentyyppisiä tuloksia. Kehitetty teoriakehys toimii virtuaaliprototypoinnin arvon mallintamisen kehyksenä. Tutkimus tuotti uutta tietämystä virtuaaliprototypoinnin arvosta tuotekehityksessä teollisessa ympäristössä. Kolmanneksi tutkimus tuotti tietoa siitä, miten virtuaaliprototypoinnin käyttöönotto vaikuttaa teolliseen yritykseen prosessien, organisaation ja teknologian dimensioissa. Väitöstyön kontribuutio on teknisen suunnittelun alueella käsitteellistämällä virtuaaliprototypointia tuotesuunnittelun ja tuotekehityksen kontekstissa sekä rakentamalla siltaa teknisen suunnittelun, virtuaaliprototypoinnin, inhimillisten tekijöiden sekä johtamisen käsitteistön välille. Siten kontribuutio ilmenee myös laajennetun virtuaaliprototypoinnin arvon teoriakehyksessä tunnistaen neljä dimensiota sekä johdonmukaisen perustelun sille, miten virtuaalitodellisuusteknologiasta voidaan johtaa arvon elementtejä liiketoiminnan näkökulmasta. Empiirisen case-aineiston ja teoriakehyksen laajenemisen vuoropuhelu johti uuteen välitteisen virtuaaliprototypoinnin (Intermediary Virtual Prototyping, IVP) käsitteeseen, joka korostaa sekä virtuaaliprototypoinnin monia teknologisia kerroksia että sen asemaa tuotekehityksen toimintajärjestelmän välitteisenä objektina. Työn uutuusarvo tulee erityisesti case-tutkimuksesta, jossa tarkastellaan osittain konfiguroituvia matalan volyymin tuotteita ja manuaalista, työintensiivistä varianttituotantoa. Työn johtopäätöksenä väitetään, että IVP on erityisen hyödyllinen, kun ihmisten tietämys ja taidot mahdollistavat tuotantojärjestelmän joustavuuden. IVP:tä tulisi tarkastella strategisena investointina, joka maksaa itsensä takaisin pitkällä aikavälillä. IVP luo arvoa, kun sitä käytetään integroituna yrityksen liiketoimintaan, mutta kääntöpuolena sillä on systeemisiä vaikutuksia teknologiaan, prosesseihin, tiedonhallintaan, organisaatioon ja johtamiseen.
ISBN, ISSN	ISBN 978-951-38-8252-5 (nid.) ISBN 978-951-38-8291-4 (URL: http://www.vtt.fi/publications/index.jsp) ISSN-L 2242-119X ISSN 2242-119X (Painettu) ISSN 2242-1203 (Verkkojulkaisu)
Julkaisuaika	Toukokuu 2015
Kieli	Englanti, suomenkielinen tiivistelmä
Sivumäärä	312 s. + liitt. 13 s.
Projektin nimi	
Rahoittajat	
Avainsanat	Arvo, virtuaaliprototypointi, tuotekehitys
Julkaisija	Teknologian tutkimuskeskus VTT Oy PL 1000, 02044 VTT, puh. 020 722 111

Simo-Pekka Leino:
Reframing the value of virtual prototyping
Intermediary virtual prototyping – the evolving approach of virtual environments based virtual prototyping in the context of new product development and low volume production

The entry point for this research is the relatively long experience in applied research in virtual environments based virtual prototyping with industry. Lack of scientific and practical knowledge of real benefits and the value of virtual prototyping has seemed to be a deterrent to its wider adoption of industry. The aim of this thesis is by means of scientific research to increase the knowledge of the value contribution of virtual prototyping as well as its impacts in a practical industrial context.

The research results consist of three types of knowledge. Firstly, the scientific theoretical foundation was elaborated for initiating value modelling of virtual prototyping and virtual environments. Secondly, new knowledge on the value of virtual prototyping within new product development was created in an industrial case study. Finally, knowledge on how virtual prototyping (VP) impacts the company was reported. The impact was discussed in the dimensions of process, social and technological implications.

This research contributes to engineering design science by conceptualizing virtual prototyping in the context of product design and development expanding to the dimensions of human factors and management theory.