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Dissertation
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Virtual prototyping in evaluation of human factors and ergonomics of human-machine systems

Susanna Aromaa

VTT SCIENCE 172

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Teknologian tutkimuskeskus VTT Oy
PL 1000 (Tekniikantie 4 A, Espoo)
02044 VTT
Puh. 020 722 111, faksi 020 722 7001

Teknologiska forskningscentralen VTT Ab
PB 1000 (Teknikvägen 4 A, Esbo)
FI-02044 VTT
Tfn +358 20 722 111, telefax +358 20 722 7001

VTT Technical Research Centre of Finland Ltd
P.O. Box 1000 (Tekniikantie 4 A, Espoo)
FI-02044 VTT, Finland
Tel. +358 20 722 111, fax +358 20 722 7001

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Abstract

Industrial work is evolving due to the digitalisation and complexity of the systems. This creates challenges for workers in performing their work tasks well, and with their well-being considered. These challenges can be addressed by investing in improving issues in human factors/ergonomics (HFE) during the design of human-machine systems. In recent years, the use of virtual prototyping (VP) has increased in the product development process due to the matured and low-cost technologies. In addition, VP has proven to be useful in the design of work systems targeted at users. However, the design and use of virtual prototypes to support HFE evaluation is not a simple task. It is important to enhance the understanding of this topic, and to adopt systematic approaches in the use of VP in HFE evaluation.

The goal of the thesis is to understand how to use VP in HFE evaluations when designing human-machine systems. The research of this thesis belongs to the field of HFE but it also contributes to the human-computer interaction (HCI) discipline by enhancing the understanding of digitalization and emerging new technologies in a work context. A case study approach was adopted for the research: six case studies were investigated and all of them were related to VP use in the evaluation of HFE. Case studies included topics such as suitability of virtual prototypes to support HFE evaluation, benefits and challenges of the use of VP in HFE evaluation, a systematic preparation of VP design reviews, and systematic deployment of VP in companies. Mainly qualitative data analyses were used, but quantitative measures were also applied.

The thesis identifies critical issues related to VP use in HFE evaluation, and proposes an HFE/VP model. The model guides design engineers and research scientists through the critical steps when using VP in HFE evaluation. It supports the deployment of VP for company use, and provides instructions for designing VP systems to be used in HFE evaluation. The model proposes an HFE approach that can be adopted during VP. In addition, the understanding of key benefits and challenges of the use of VP in HFE evaluation are identified.

This thesis contributes to both the research community and industry: the HFE/VP model includes practical and theoretical contributions that can be used when researchers are studying the use of virtual prototypes, and in industrial companies during product development. In research, the contribution of this thesis is in the intersection of the research fields of HFE/HCI and virtual reality.

Tiivistelmä

Teollinen työympäristö muuttuu digitalisoitumisen myötä monimutkaisemmaksi ja haastavammaksi. Työntekijöille voi tuottaa vaikeuksia käyttää monimutkaisia järjestelmiä tehokkaasti ja siten, että heille ei aiheudu siitä ylimääräistä kuormitusta. Ratkaisevaa on ihmisen ja koneen välisen vuorovaikutuksen hyvä suunnittelu. Virtuaaliprototypoinnin (VP) hyödyntäminen tuotekehityksessä on lisääntynyt teollisuudessa viime vuosina. VP-teknologioiden laskeneet hinnat ja kehittyminen ovat osasyy tähän. VP on erityisen hyödyllinen suunniteltaessa monimutkaisia ihmisen ja koneen vuorovaikutuksia. Vaikka VP:n käyttö onkin lisääntynyt viime aikoina, on vielä tarve kehittää sen systemaattista käyttöä erityisesti ergonomian (human factors / ergonomics, HFE) arvioimisessa.

Tämän väitöskirjan tavoitteena on tutkia VP:n käyttöä erityisesti ihmisen ja koneen vuorovaikutuksen arvioinnissa, jolloin otetaan huomioon käyttäjien tarpeet liittyen mm. ergonomiaan ja käyttökokemukseen. Tavoitteena on ymmärtää keskeiset tekijät käytettäessä VP:a ergonomian arvioinnissa.

Tämä väitöskirja kuuluu ergonomian (HFE) tieteenalaan. Se on keskittynyt ennakoivaan ergonomian kehittämiseen suunnittelun aikana ja arvioi erityisesti käyttäjän ja koneen vuorovaikutusta. Väitöskirjan kontribuutio ulottuu myös ihmisen ja tietokoneen vuorovaikutuksen tutkimuksen tieteenalaan (human-computer interaction, HCI) auttamalla ymmärtämään digitalisoitumisen ja uusien tietoteknisten työkalujen käyttöä suunnittelijan työssä. Väitöskirja perustuu tapaustutkimukseen. Siinä kuvataan kuusi erilaista tapaustutkimusta, ja ne liittyvät VP:n hyödyntämiseen ergonomian arvioinnissa suunnittelun aikana. Tapaustutkimusaiheet liittyivät mm. virtuaaliprototyyppien soveltuvuuteen tukemaan ergonomian arviointia, mahdollisiin hyötyihin ja haasteisiin VP:a käytettäessä ergonomian arvioinnissa, systemaattiseen VP:n suunnitteluun ja systemaattiseen VP:n käyttöönottoon yrityksissä. Väitöskirjassa on käytetty sekä laadullisia että määrällisiä aineiston arviointimenetelmiä.

Tämä väitöskirja tunnistaa kriittisiä aiheita liittyen VP:n käyttöön ergonomian arvioinnissa ja kuvaa HFE/VP-mallin sovellettavaksi siinä. Mallin avulla suunnittelijoiden ja tutkijoiden on helpompi hyödyntää VP:a ergonomian arvioinnissa. Malli tukee VP:n käyttöönottoa yrityksissä ja VP:n suunnittelua. Mallissa on otettu käyttöön ergonominen lähestymistapa, joka perustuu kokeelliseen ja evaluointipohjaiseen tutkimukseen. Myös merkitykselliset hyödyt ja haasteet VP:n hyödyntämisessä ergonomian arvioinnissa on tunnistettu.

Tämän väitöskirjan kontribuutio hyödyntää sekä tiedeyhteisöä että teollisuutta. Molemmat voivat käyttää väitöskirjassa esitettyjä systemaattisia lähestymistapoja virtuaaliprototyyppien rakentamiseen ja käyttöön ergonomian arvioinnissa. Erityisesti tutkimustyö ergonomian ja VP:n rajapinnassa hyötyy tästä väitöskirjasta.

Preface

I started my research career at VTT Technical Research Centre of Finland Ltd right after getting a master's degree from the Technical University of Tampere. After working at VTT for a while, I began to feel that doctoral studies are a natural step towards being better at work. It is a way to improve research skills, apply a systematic approach to research work and become a "real scientist". Therefore, I took the chance, made a decision and started this journey.

First, I would like to thank my supervisor Professor Kaisa Väänänen, who guided me through this process. I appreciate the time she regularly spent meeting and guiding me. She gave valuable advice when pursuing towards a scientific mindset and practices.

I am grateful to Dr. Eija Kaasinen, who also gave valuable advice and support during this journey. Even though I know as her co-worker that she was busy with work, she somehow always found time to provide insightful comments about my publications and doctoral thesis. In addition, I appreciate the encouraging words that she shared when I needed them.

I would like to thank my co-authors and the work community at VTT for supporting this undertaking. I am grateful to Dr. Simo-Pekka Leino and Juhani Viitaniemi with whom I had many discussions in the beginning of my research career and this journey. I am thankful to Jaakko Karjalainen, Sauli Kiviranta, Nicolas Philippon and Kaj Helin for the valuable technical support during the research. Additional thanks to Jaakko Karjalainen for the cover picture and Antti Väätänen for his modeling work. I would like to mention Iina Aaltonen and Päivi Heikkilä for sharing the ups and downs of this journey. You really made this endeavour easier by sitting next to me at lectures and sharing the challenges when writing and publishing papers – peer support is valuable. In addition, many thanks to the other co-authors who were not already mentioned: Lauri Jokinen, Nikos Frangakis and Domenico Tedone. Furthermore, thanks to Dr. Paula Savioja for the support and inspiration to do the work and team leader Raimo Launonen for providing the practical support. I would like to thank the whole "Human factors, virtual and augmented reality" team for being supportive and I am assuming that there will be many other doctoral theses completed in coming years.

I have been honoured to have Professor Monica Bordegoni from the Politecnico di Milano and Associate Professor W. Patrick Neumann from Ryerson University as the official preliminary examiners of my thesis. I am thankful for their insightful comments on the thesis. In addition, I would like to thank Professor Seppo Väyrynen from the University of Oulu for agreeing to be the opponent of my doctoral defence.

Without research projects, this work could not have been done. Therefore, I am grateful to all parties that funded and supported the research: the Finnish funding agency for technology and innovation (Tekes, currently Business Finland), the European Union (EU), the Finnish Metals and Engineering Competence Cluster Ltd. (FIMECC, currently DIMECC), VTT and companies such as Metso Minerals Oy, Sandvik Mining and Construction Oy and Kalmar. I am grateful for the easy co-operation with the project partners during the research. In addition, thanks to all test participants who took part in the studies.

At last, I would like to thank my family and friends. From Janne, I am grateful for the support, encouragement and understanding during this journey. Aleksanteri and Aino-Sofia for being there to take my mind of the thesis work. I hope, this thesis will be an inspiration to you in life as proof that if you want something and work for it, it is possible to achieve it. In addition, I would like to thank my parents Sirkka and Heikki for the support they have provided (throughout my life) as well as Marja, Kari and Jorma. Warm thanks to my brother Kari and his family, and all my other family members and friends.

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Susanna Aromaa

Academic dissertation

Supervisor Prof. Kaisa Väänänen
Department of Pervasive Computing
Tampere University of Technology
Finland

Thesis advisor Dr. Eija Kaasinen
Digital Engineering
VTT Technical Research Centre of Finland Ltd
Finland

Pre-examiners Prof. Monica Bordegoni
Dipartimento di Meccanica
Politecnico di Milano
Italy

Assoc.Prof. W. Patrick Neumann
Department of Mechanical and Industrial Engineering
Ryerson University
Canada

Opponent Prof. Seppo Väyrynen
Wellbeing and Productivity
University of Oulu
Finland

List of publications

This thesis is based on the following original publications, which are referred to in the text as P1–P6. The publications are reproduced with the kind permission of the publishers.

P1	Aromaa, S., Leino, S. P., Viitaniemi, J., Jokinen, L., & Kiviranta, S. (2012). Benefits of the use of Virtual Environments in product design review meeting. In DS 70: Proceedings of DESIGN 2012, the 12th International Design Conference. University of Zagreb and the Design Society, Dubrovnik, Croatia.
P2	Aromaa, S., Viitaniemi, J., Philippon, N. (2012). New task-related dynamic field of view analysis in virtual environment. In proceedings of NES2012, the Nordic Ergonomics and Human Factors Society Conference, KTH Royal Institute of Technology, Stockholm, Sweden.
P3	Aromaa, S., Leino, S. P., & Viitaniemi, J. (2013). Are companies ready for the revolution in design - Modelling maturity for virtual prototyping. In DS 75-9: Proceedings of the 19th International Conference on Engineering Design (ICED13), Design for Harmonies, Vol. 9: Design Methods and Tools. Design Society, Seoul, Korea.
P4	Aromaa, S., & Väänänen, K. (2016). Suitability of virtual prototypes to support human factors/ergonomics evaluation during the design. Applied ergonomics, 56, 11-18.
P5	Aromaa, S. (2017). Virtual prototyping in design reviews of industrial systems. In Proceedings of the 21st International Academic Mindtrek Conference. ACM, Tampere, Finland.
P6	Aromaa, S., Frangakis, N., Tedone, D., Viitaniemi, J., & Aaltonen, I. 2018. Digital Human Models in Human Factors and Ergonomics Evaluation of Gesture Interfaces. **Submitted to** the 10th ACM SIGCHI Symposium on Engineering Interactive Computing Systems (EICS 2018). ACM, Paris, France.

Author’s contributions

Publication 1 “Benefits of the use of virtual environments in product design review meeting” presents benefits that come from the use of virtual prototyping (VP) in design reviews. Aromaa was designing case studies and gathering data from them with other authors. Aromaa made a qualitative analysis of the data and others supplemented. The feature-benefit model was a joint effort between Aromaa and Leino. Aromaa is the main author of the paper and responsible for its structure.

Publication 2 “New task-related dynamic field of view analysis in virtual environment” presents a validation study of a developed dynamic field of view (FOV) analysis. The development of the concept idea of FOV analysis was a collective effort of all authors. Aromaa was the main person responsible for test planning, execution, and data analysis. Aromaa is responsible for the structure of the publication and is the main author of it.

Publication 3 “Are companies ready for the revolution in design - modelling maturity for virtual prototyping” presents a VP maturity model that supports companies in improving their implementation and use of VP. Conducting the studies and developing the maturity model were collective efforts by the list of authors. Aromaa was responsible for adapting the maturity model in company cases. Aromaa is responsible for the structure of the paper and is the main author of the paper.

Publication 4 “Suitability of virtual prototypes to support human factors/ergonomics evaluation during the design” presents the suitability of two different virtual prototypes to support human factors/ergonomics (HFE) evaluations. Aromaa is the main person responsible for test design, test execution, data gathering, and analysis. Aromaa is responsible for the structure of the paper. Aromaa is the main author of the paper.

Publication 5 “Virtual prototyping in design reviews of industrial systems” presents whether the use of VP supports design reviews, and identifies critical issues related to it. Aromaa was responsible for the test design, data gathering, and data analysis. The applied VP design review template was based on earlier research that was done together with Simo-Pekka Leino and Juhani Viitaniemi. Aromaa is responsible for the structure of the paper and is its sole author.

Publication 6 “Digital Human Models in Human Factors and Ergonomics Evaluation of Gesture Interfaces” presents an HFE evaluation of two gesture-based systems for robot control. Digital human models (DHMs) were applied during the HFE evaluation. Aromaa had the leading role in designing tests, executing tests, and data analysis. Aromaa was the one of the two researchers who did posture analysis with the DHM. Aromaa is responsible for the structure of the paper and is the main author of the paper.

Contents

Appendices

List of symbols

3D	Three-dimensional
AMA	Average muscle activation
AR	Augmented reality
CAD	Computer-aided design
DHM	Digital human model
FOV	Field of view
HCD	Human-centred design
HCI	Human-computer interaction
HFE	Human factors/ergonomics
HMD	Head-mounted display
HMS	Human-machine system
IEA	International Ergonomic Association
IO	Intermediary objects
IoT	Internet of things
ISO	International Organization for Standardization
iVP	Interactive virtual prototype
MAUVE	Multi-criteria assessment of usability for virtual environments
MR	Mixed reality
NASA-TLX	Task load index
NIOSH	National institute for occupational safety and health
P1-P6	Publication 1 - Publication 6
P50	The percentage of observations (or population) falls below the value of a variable
PC	Personal computer
PDM	Product data management
PDP	Product development process
PLM	Product life-cycle management
RPE	Perceived exertion

RQ	Research question
RULA	Rapid upper limb assessment
SPSS	Software for statistical analysis
SSP	Static strength prediction
SSQ	Simulator sickness questionnaire
TENK	Finnish Advisory Board on Research Integrity
VE	Virtual environment
VEDS	Virtual environment development structure
VIRMA	Virtual prototyping implementation maturity model
VP	Virtual prototyping
VR	Virtual reality
VRUSE	A computerised diagnostic tool for usability evaluation of virtual environment systems

1. Introduction

Based on a European Commission survey, at least one quarter (27%) of the working population (employees, manual workers, self-employed) have experienced health problems that were either caused by or made worse by work (European Commission, 2014a). The respondents mentioned bone, joint, or muscle problems, and stress, among other things. The European Union's strategic framework on health and safety at work 2014-2020 aims to ensure high standards for working conditions both within the European Union and internationally (European Commission, 2014b). They see that investment in occupational safety and health contributes to the well-being of workers and is cost-effective.

The discipline that studies this topic is called human factors/ergonomics (HFE). Ergonomics originates from the Greek words ergon (work) and nomos (laws), and means the study of work. It has evolved into a human factors/ergonomics (HFE) discipline that studies interactions among humans and other elements of a system to optimise human well-being and overall system performance (IEA, 2000). Dul et al. (2012) define three fundamental characteristics of HFE: it takes a systems approach, it is design driven, and it focuses on two related outcomes: performance and well-being. This system approach means that technologies are designed and developed by focusing on the interaction among all of the components of a system relative to system goals (Czaja and Nair, 2006). Usually, these components are a human operator (e.g., capacities and limitations), a technology (e.g., products, machines, devices, processes, computer-based systems), and the broadly defined environment (e.g., business processes, organisational structure, the nature of work systems) (Karwowski, 2006). HFE is closely related to and, in some parts, overlaps a human-computer interaction (HCI) discipline that focuses on the interaction between humans and computers, and evaluates usability and user experience issues.

By applying human-centred design (HCD) (ISO 9241-210, 2010) principles, it is possible to consider HFE issues early in a product development process (PDP). The HCD approach tries to make systems usable and useful by focusing on the users, their needs and requirements (ISO 9241-210, 2010). During HCD, one way to obtain feedback from users is to use prototypes, which can be seen as representations of real interactive products (ISO 9241-210, 2010).

This thesis focuses on the improving human-machine systems in order to optimise well-being and overall performance by evaluating HFE issues during the prototyping phase. It is of particular note in this thesis that the used prototypes are virtual and they do not exist in real-life form.

1.1 Background and motivation

In recent years, the digitalisation of industries has increased and smart factories with new levels of human-system interaction have emerged. For example, INDUSTRIE 4.0 is a current trend of computerisation of manufacturing (Kagermann et al., 2013). The term INDUSTRIE 4.0 originates from a project in the high-tech strategy of the German government, and it involves the technical integration of physical and virtual world systems into manufacturing and logistics. In addition, the use of the Internet of Things (IoT) in industrial processes is a part of it. Digital twin is another rising trend. This means that there is a digital replica of a real product, system, or process. The digital representation provides both the elements and the dynamics of how a device operates throughout its life-cycle (IBM Watson Internet of Things, 2017). Virtual prototypes are part of this digitalisation and can be considered as digital twins of real products.

Virtual prototyping (VP) has been considered as an effective prototyping solution that can overcome the shortcomings of conventional prototyping methods such as costly and time-consuming production of a physical prototype (Karkee et al., 2011; Kulkarni et al., 2011; Seth et al., 2011). In addition, virtual prototypes are powerful when providing users with an illustration of a design object and a context in which it is used. For this reason, virtual prototypes are beneficial in making it possible to evaluate HFE issues in an early design phase. The use of VP has grown in PDP lately, and especially in the assessment of complex systems targeted at users (Berg and Vance, 2016). It has increased due to the improved availability and lowered prices of VP technologies (Choi et al., 2015).

VP can be complex, and the benefits of its use may be lost in the wrong decisions during the development and use of virtual prototypes. This same analogy of selecting the right tools and methods applies in HFE evaluation: Leonard et al. (2006) said that it is difficult to give an absolute right or wrong answer when selecting the right HFE method because “it depends”. It can depend, for example, on the evaluation target, the experience of the evaluator, and the allocated time for the evaluation. When the use of virtual prototypes is added to this, the evaluation of HFE during VP can be a real challenge: virtual prototypes can be completely or partly virtual and their fidelity level (which means their realism compared to a real product) may vary.

Practically, the research in this thesis is motivated by the possibilities that digitalisation and, more specifically, VP can provide when designing good-quality user-task-product systems for industrial use. There is a need to understand more profoundly the suitability of VP to support HFE evaluation, to be able to develop efficient human-machine systems that support well-being at work. Theoretically, this thesis contributes to sociotechnical systems theory (Read et al., 2015; Trist and Bamforth, 1951). One important characteristic of sociotechnical systems is that it comprise both social and technical aspects. In addition, a central assumption of sociotechnical systems theory is that joint optimisation of social and technical aspects is needed for successful system performance. This thesis investigates if the use of VP in HFE evaluation can improve the joint optimisation process during the design of human-machine systems.

1.2 Research objective and questions

The focus of this thesis is in the field of human factors/ergonomics (HFE) and human-centred design (HCD). The overall objective of this research is to increase the understanding of the ways in which virtual prototyping (VP) can be used in HFE evaluation. This issue is addressed by investigating the following four research questions.

RQ1: What kind of approaches should be used in evaluation of human factors/ergonomics in virtual prototyping?

The first research question focuses on HFE evaluation during VP. It means that the system of the user, task, product, and environment is evaluated to optimise well-being and performance. This HFE evaluation is proactive and occurs during the product development process (PDP) when a virtual prototype of the product exists. **RQ1** addresses the challenge that it is not clear what kinds of HFE evaluations should be adopted during VP.

RQ2: How should virtual prototyping systems be designed when using them for human factors/ergonomics evaluation?

The second research question focuses on the topic of how to design VP systems for HFE evaluation purposes. The design of virtual environments (VEs) is a complex task and, when VEs are used for prototyping purposes, the design process needs even more consideration. VE design processes need to be expanded to VP system design processes. **RQ2** addresses this gap.

RO3: What are the benefits and challenges of the use of virtual prototyping in human factors/ergonomics evaluation?

The third research question focuses on the benefits and challenges that may arise when using VP in HFE evaluation. It enhances the understanding of particular advantages that VP can provide when HFE is evaluated. **RQ3** addresses the topic of why virtual prototypes should be used when evaluating HFE.

RQ4: How should industrial companies deploy virtual prototyping?

The fourth research question focuses on the company-level issues related to the use of VP. It is important to understand what is required from companies to be able to use VP. This company-level foundation needs to be solid to be able to use VP systematically and evaluate HFE issues. **RQ4** addresses the challenge of deploying VP in companies.

By answering these research questions, new scientific and practical understanding is created on the use of VP in HFE evaluation. As a result, an HFE/VP model is proposed that contributes to all the research questions. It contributes by enhancing understanding of VP use in HFE, by presenting an HFE approach to be adopted.

The HFE approach supports selection of suitable evaluation methods during VP. The HFE/VP model also includes a systematic design process for VP systems. Its purpose is to make VP system design more systematic and to provide practical guidance to be adopted for everyday use during PDP. In addition, key benefits and challenges in VP use in HFE evaluation are identified. A comprehensive way to deploy VP in companies is also presented as a result. The contributions of this thesis can be used when adopting VP in the HFE evaluation, to be able to produce ergonomic human-machine systems. In addition, the HFE/VP model contributes to knowledge in the HFE discipline and VR research community.

1.3 Overview of the research approach and process

The research in this thesis belongs to the field of HFE, which focuses on studying human-machine systems in order to optimise well-being and performance. The research is based on a case study approach (Yin, 2013): six case studies were conducted during the research and published in six publications (**P1-P6**) which can be found from the thesis's appendices. They were mainly qualitative and empirical in nature. Observations and questionnaires were mostly used as data collection methods, and both qualitative and quantitative data analyses were applied. All the case studies were made in an industrial product development context in collaboration with companies. The findings from the case studies were analysed using a cross-case analysis approach, in order to come up with the answers to **RQ1**, **RQ2**, **RQ3**, and **RQ4**. Thematic analysis (Braun and Clarke, 2006) was used to support data analysing phase. **Table 1**, below, describes the publications' contributions to the research questions. All publications (**P1-P6**) contribute to **RQ2** and **RQ3**. The publications **P1**, **P2** and **P4-P6** contribute to **RQ1** and **P3** contributes **to RQ4.**

Table 1. The publications' contributions to the research questions.

Research questions		**Publications**					
		P1	**P2**	**P3**	**P4**	**P5**	**P6**
RQ1	What kind of approaches should be used in evaluation of human factors/ergonomics in virtual prototyping?	x	x		x	x	x
RQ2	How should virtual prototyping systems be designed when using them for human factors/ergonomics evaluation?	x	x	x	x	x	x
RQ3	What are the benefits and challenges of the use of virtual prototyping in human factors/ergonomics evaluation?	x	x	x	x	x	x
RQ4	How should industrial companies deploy virtual prototyping?			x			

1.4 Structure of the thesis

The introduction of the thesis consists of the background and motivation of the research. In addition, it describes the research objective and research questions. It includes an overview of the research approach and process, and the structure of the thesis. Chapter 2 describes the conceptual background for the thesis. It describes topics related to PDP, HFE, and VP. Chapter 3 describes the related work regarding VP in HFE evaluation, and states the research gap. In Chapter 4, the research approach and methodologies are discussed. Chapter 5 summarises the six case studies. Chapter 6 describes the results of the four research questions and contributes an HFE/VP model as a result. The final chapter, “Discussions and conclusions”, summarises the contributions and implications of the research, evaluates the validity of the research, proposes suggestions for future research, and finally, concludes the research.

2. Conceptual background

This chapter presents the conceptual background for the thesis. It describes essential theories and definitions related to the topic of the thesis. In addition, it describes how the thesis positions itself within this theoretical background. The chapter includes topics related to the product development process (PDP), the design of human factors/ergonomics (HFE), and virtual prototyping (VP). The main research focus of the thesis is evaluating HFE proactively by using VP to provide good-quality products for users. This means that the research focus is in the intersection of HFE and VP, as illustrated in **Figure 1**.

Figure 1. The research focus of the thesis is in the intersection of human factors/ergonomics and virtual prototyping.

2.1 Product development process

Ulrich and Eppinger (2003) define a product development process (PDP) as "*the sequence of steps or activities which an enterprise employs to conceive, design, and commercialize a product*". They divide the product development process into five phases: planning, concept development, system-level design, detail design, testing and refinement, and production ramp-up (**Figure 2**). In practice, the process does not proceed in a sequential fashion but is more iterative in nature. The planning phase concentrates on business goals and target markets for the product. The concept development phase includes definition of needs, evaluation of alternative product concepts, and the selection of one concept for further development and testing. A definition of a product concept is that it is an approximate description of the technology, working principles, and form of the product, and how the product will satisfy the customer needs. The system-level design defines the product architecture, and the detail design includes the complete specifications of the product. The testing and refinement phase includes the construction and evaluation of multiple preproduction versions of the product. During the production ramp-up, products are made and any remaining problems are solved (Ulrich and Eppinger, 2003).

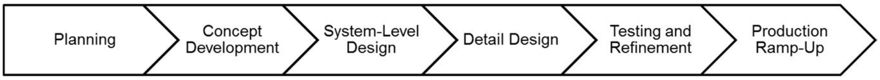


Figure 2. The product development process (Ulrich and Eppinger, 2003).

The stepwise product development process (**Figure 2**) can be considered to be a waterfall approach because it is seen as sequential, flowing through the steps. Another approach to product development is called agile design, which responds to changing markets by using iterative and flexible methodologies (Naylor et al., 1999; Yusuf et al., 1999). By using agile design, organisations can quickly satisfy customer orders and introduce new products in a timely manner (Yusuf et al., 1999).

The topic of this thesis, VP, can be used to support waterfall or agile approaches. However, the PDP process (**Figure 2**) is most illustrative when emphasising that the thesis concentrates on the concept development phase in the PDP, and especially on testing product concepts by using prototyping. However, its nature can be iterative. In addition, most companies involved in the thesis case studies were traditional manufacturing companies whose origins are especially in the waterfall approach.

Product development projects can be divided into four types: new product platforms (new family of products), derivatives of existing product platforms (add new products to existing product platform), incremental improvements to existing products (adding or modifying some features of existing products), and fundamentally new products (Ulrich and Eppinger, 2003). The research in this thesis focuses mainly on incremental improvement. Four of the publications in this thesis (**P1, P2, P4, P5**) consider incremental improvements to existing products. One publication (**P6**) studies a new concept, and one (**P3**) considers adapting VP for company use in general.

2.1.1 Prototypes in product development

Prototyping efforts can occur throughout the PDP, from concept development to production ramp-up. A prototype can be defined as "*a representation of all or part of an interactive system, that, although limited in some way, can be used for analysis, design and evaluation*" (ISO 9241-210, 2010). In addition, prototyping is the process of developing and testing such a presentation of the product (Ulrich and Eppinger, 2003). According to Beaudouin-lafon and Mackay (2003), "*Prototypes increase creativity, allow early evaluation of design ideas, help designers think through and solve design problems, and support communication within multi-disciplinary design teams*". Lim et al. (2008) expand the understanding of the characteristics of prototypes by defining two key dimensions: prototypes as filters and as manifestations. Filtering means that the designer cuts out aspects of the design that a prototype does not need to explore. In addition, a prototype manifests a certain aspect of a design idea, and therefore, designers need to make choices about the prototype's material, fidelity, and scope. Ullman (1992) classifies prototypes into four categories, based on their purpose: proof-of-concept or proof-of function, proof-of-product, proof-of-process, and proof-of-production. The proof-of-concept concentrates on comparing the prototype to user requirements and engineering specifications. The proof-of-product prototype helps refine the components and assemblies. The proof-of-process prototype verifies the geometry and manufacturing process, and the proof-of-production is used to verify the entire production process.

Prototypes can be low-fidelity and high-fidelity, based on their realism (Yang, 2005). This means how well a prototype replicates the final product. The building of a prototype is often a trade-off between fidelity and the time, effort, and cost needed to create the prototype (Yang, 2005). The prototype fidelity plays an important role in usability and human factors testing: how to build enough fidelity into a prototype to gain valid evaluation results (Sauer et al., 2010). According to Virzi et al. (1996), prototype fidelity is a continuum, and a prototype and a final product can vary in breadth of features, degree of function, similarity of interaction, and aesthetic refinement. Breadth of features refers to the number of features the prototype supports. The degree of functionality means in how much detail functions are modelled. Interaction similarity refers to the interface (e.g., buttons, displays). Aesthetics means the visual appearance of the prototype (e.g., colour, shape, size). Prototypes may be as simple as a sketch or a static mock-up, or as complicated as a fully functioning interactive system (ISO 9241-210, 2010). Ulrich and Eppinger (2003) classify prototypes along two dimensions: physical-analytical and focused-comprehensive. Physical prototypes are tangible artefacts, and analytical prototypes are non-tangible (e.g., mathematical). Comprehensive prototypes implement most of the product's attributes, and focused prototypes implement only one or a few attributes.

2.1.2 Design reviews in product development

Design reviews are important milestones within a PDP. According to Verlinden et al. (2009), the design reviews are one of the most influential parts of the design process, in which prototypes and other design representations are essential. The goal of the design review is to assess the design against the requirements, identify improvement needs, and guide towards appropriate actions. The design review process includes planning, organisation, actual meetings, and reporting (IEC-61160, 2005). Design review participants can include a design manager, design team members, relevant specialists, and/or customers/users. The design reviews are efficient tools for sharing knowledge about the product and for managing knowledge exchange (Huet et al., 2007). By using appropriate tools and methods, it is easy to support cooperation between different stakeholders during design reviews (Verlinden et al., 2009).

Knowledge sharing and communication are key aspects of design reviews. Knowledge sharing refers to the utilisation of task information and know-how to help collaborate with others to solve problems and develop new ideas (Cummings, 2004; Wang and Noe, 2010). There are two different knowledge types: explicit and tacit. Explicit or codified knowledge refers to knowledge that is transmittable in formal, systematic language (Polanyi, 1966). Tacit knowledge has a personal quality, which makes it hard to formalise and communicate. Tacit knowledge is deeply rooted in action, commitment, and involvement in a specific context (Nonaka, 1994). Design reviews especially support the use and disclosure of tacit knowledge.

2.2 Human factors and ergonomics

This section introduces the disciplines and definitions of human factors/ergonomics (HFE) and human-computer interaction (HCI). The section describes the human-centred design (HCD) approach and defines human-machine systems (HMS). In addition, it illustrates typical HFE evaluation methodologies, and describes a sociotechnical systems theory as a theoretical background.

2.2.1 The discipline of human factors/ergonomics

The International Ergonomic Association (IEA) defines HFE as: "*the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance*" (IEA, 2000). Czaja and Nair (2006) say that "*the focus in HFE is on studying performance within the context of tasks and environments*". Dul et al. (2012) define three fundamental characteristics of HFE: it takes a systems approach, it is design driven, and it focuses on two related outcomes: performance and well-being. Dul et al. (2012) define "*performance (e.g. productivity, efficiency, effectiveness, quality, innovativeness, flexibility, (systems) safety and security, reliability, sustainability) and well-being (e.g. health and safety, satisfaction, pleasure, learning, personal development)".* The domains of specialisation within the discipline of HFE can be broadly stated to be the following: physical ergonomics, cognitive ergonomics, and organisational ergonomics (IEA, 2000). Wilson (2014) has listed six defining features for HFE: systems focus, context, interactions, holism, mergence, and embedding. Within the wide scope of issues addressed by the HFE discipline are: human characteristics, information presentation and communication, display and control design, workplace and equipment design, environment, system characteristics, work design and organisation, health and safety, social and economic impact of the system, and methods and techniques (Karwowski, 2006).

Human-computer interaction (HCI) is a discipline closely related to HFE. However, HCI focuses particularly on the interaction of humans and computers, and evaluates usability and user experience issues. In other words, it studies the cognitive aspects of interactions, such as how logical, fluent, and usable they are. The discipline is a mixture of other fields, such as computer science, sociology, psychology, communication, human factors engineering, industrial engineering, rehabilitation engineering, and many others (Lazar et al., 2010). Hewett et al. (1992) define

HCI as follows: "*Human-computer interaction is a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them*."

HFE and HCI are similar disciplines and overlap in many cases. For example, when evaluating human-computer interaction, this could belong to both disciplines. However, HCI more often studies human-computer interaction in variety of contexts, such as leisure use of products in a home and public environments. The case studies in this thesis are related to human-machine systems design and product use in a work context. Therefore, it can be said that this thesis belongs primarily to the field of HFE because it takes a systems approach: it studies the human-machine interaction in a work context. The thesis is design driven, which means that the thesis concentrates on the proactive design of HFE and evaluates designs during the prototyping phase. The focus of the publications is on the industrial work context, which includes both the efficiency of the system and health and safety issues among workers. However, the findings of this thesis also contribute to the HCI discipline because it studies the digitalisation of work (e.g., design engineers are starting to use virtual reality technologies in their work).

The HFE definitions presented in this chapter are agreed to be a basis for the thesis. However, due to the focus of the thesis, which is on the concept design phase and prototyping, a simplified definition is proposed. The focus is more on physical HFE and performance evaluations than on the consideration of organisational aspects**. In this thesis, HFE means the study of human-machine systems in order to optimise human well-being and overall system performance.**

2.2.2 Human-centred design approach

Human-centred design (HCD) is an approach "*to make systems usable and useful by focusing on the users, their needs and requirements, and by applying human factors/ergonomics, and usability knowledge and techniques*" (ISO 9241-210, 2010). The approach is iterative and includes the following activities: (1) understand and specify the context of use; (2) specify the user requirements; (3) produce design solutions to meet these requirements, and (4) evaluate the designs against the requirements. The HCD approach is an important basis for the thesis, especially due to its iterative nature. The studies in the thesis are part of the iterative development process, but in this thesis they were investigated only in one phase of the iterative cycle. This means that none of the studies were researched through several iterative steps. Because this thesis concentrates on applying virtual prototypes in the design of HFE issues and obtaining feedback from the users, it is mainly related to the "evaluating the design" phase from the iterative HCD process.

The participatory design approach involves users (and other stakeholders) in the design process, to contribute to a design and develop high-quality products (Ehn, 1993; Muller and Kuhn, 1993). In addition, the participatory design can support democracy at the workplace. In participatory design, benefits come from sharing knowledge and learning from each other. This is conterminous with Nonaka's (1994)

Model of Knowledge Creation, in which knowledge is created through the conversion between tacit and explicit knowledge (e.g., by interaction between individuals). The participatory design approach is used in the publications of this thesis by involving different stakeholder during design reviews.

2.2.3 Human-machine systems approach

Traditionally, the product design has focused on the technical components of the system. HFE tries to optimise the performance of both the human and physical components of the system. By definition, *"a human-machine system (HMS) is a system in which an interaction occurs between people and other system components, such as hardware, software, tasks, environments, and work structures"* (Czaja and Nair, 2006). The elements of this combination are used together to perform a given task or achieve a specific goal. Human–machine interactions and processes occur in realistic contexts.

When designing HFE, it is important to understand the whole system and its functions. Pheasant (1996) says that "*the object is to achieve the best possible match between the product and its users, in the context of the (working) task that is to be performed"* (**Figure 3**). The system approach is applied throughout this thesis when considering the evaluation of HFE. This thesis focuses on the whole user-task-product-environment system, and not only on the evaluation of a user.

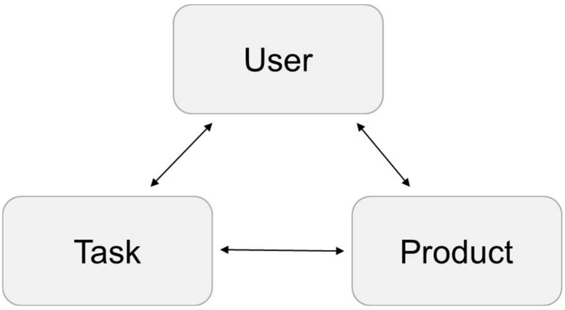


Figure 3. The goal of the design of HFE is to optimise user, task, and product interaction (Pheasant, 1996).

2.2.4 Theoretical background

HFE is a mixture of many fields such as anatomy, physiology, psychology, medicine, and engineering. For that reason, it is possible to adopt many different kind of theories in the field of HFE. Chung and Williamson (2018) have find out, however, that there is a theory-research gap in HFE. They identified that the HFE discipline may have neglected theory development and therefore, little attention has been given to theory in HFE journal articles over the years.

A sociotechnical systems theory (Read et al., 2015; Trist and Bamforth, 1951) is one of theories used in the field of HFE. Sociotechnical systems undertake processes that convert inputs to outputs and contain paradigm that the whole is more than the sum of its parts (Read et al., 2015). A central assumption of sociotechnical systems theory is that joint optimisation of system parts is needed for successful system performance. This means that technical systems do not exist in isolation, and the social and the technical system have to be designed together. Eason (2014) sees "*the sociotechnical systems theory the most powerful way of explaining systems behaviour and the most useful in designing new systems*". The use of the sociotechnical systems theory in design has led to many design methods and principles that aim to create systems that are jointly optimised in relation to the shared task of the work system (Eason, 2014).

This thesis is based on the sociotechnical systems theory.The thesis provides methods and approaches for practical application of the sociotechnical systems theory in design of human-machine systems.

2.2.5 Human factors/ergonomics evaluation methods

HFE evaluation plays an important role in system design and evaluation. However, the selection of suitable methods can be challenging because the taxonomy of HFE methodologies is not straightforward, as there are areas that overlap. In addition, several different classifications of methods can be found in the literature. HFE methods are used, among other things, to collect information about user needs, provide feedback on the design solution from the user's perspective, assess whether user requirements have been achieved, and establish baselines or make comparisons between designs (ISO 9241-210, 2010).

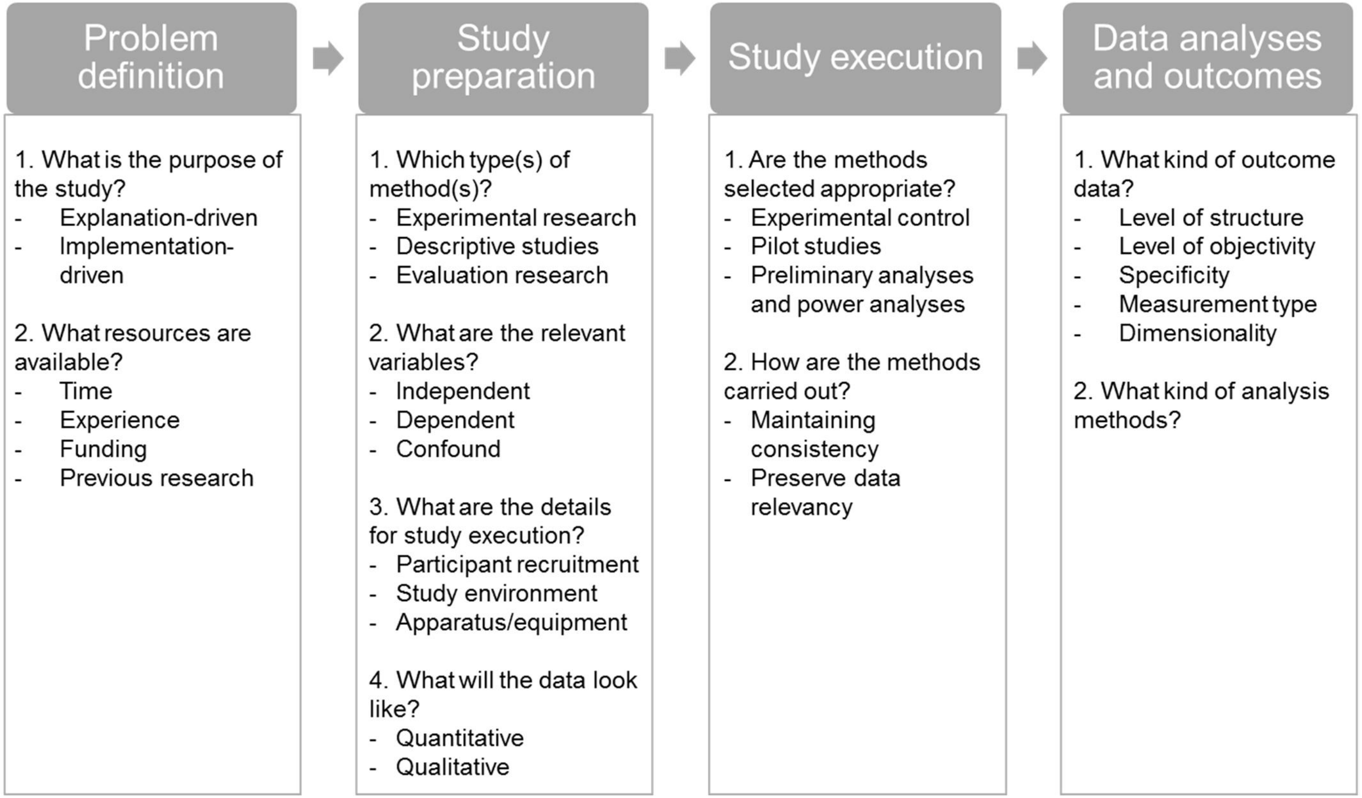
A frequently used classification for HFE research is: descriptive studies, experimental research, and evaluation research (Sanders and McCormick, 1993). Descriptive studies attempt to characterise a specific population in terms of certain attributes. In experimental research, variables are manipulated and their effect on humans, performance, or the system is evaluated. Usually in experimental research, the concern is whether a variable has an effect on behaviour and the direction of that effect. Evaluation-based research is often used to evaluate a design or a product. In addition, evaluation-based research embodies features of both of descriptive studies and empirical research. ISO 9241-210 (2010) defines two approaches for HFE evaluation: user-based testing and inspection-based evaluation. User-based testing gathers feedback direct from the users, and inspection-based methods can be performed by usability experts. This is similar to the experimental and evaluation-based approaches. The Sanders and McCormick (1993) classification is used in this thesis, and especially the experimental and evaluation-based research approaches.

Annett (2002) classifies HFE methods into two categories: analytic and evaluative methods. By analytic methods, he means methods that aim to understand processes affecting HMS (e.g., task analysis). Evaluative methods focus on measuring specific variables (e.g., workload measurement). Nielsen (1994) identifies four ways of evaluating user interfaces: automatically, empirically, formally, and informally. Automatic evaluation is done by computers, and empirical tests are done with the user. Formal tests use exact models and formulas to calculate measures, and informal evaluation uses the experience of the evaluators.

The feasibility of an HFE method depends on a number of factors: the stage of design the project is at, the time and resources available, the skills of the evaluation expert, access to the end-user population, and what kinds of data are required (Stanton et al., 2014). When choosing methods, it is important to consider the accuracy of the methods, the criteria to be evaluated, the acceptability and appropriateness of the methods, and the cost-benefit of the methods and the products (Stanton et al., 2005). Stanton et al. (2005) made a literature review of HFE methods. They identified eleven categories of HFE methods and techniques:

- data collection
- task analysis
- cognitive task analysis
- charting
- human error identification
- mental workload assessment
- situation awareness measurement
- interface analysis
- design
- performance time prediction/assessment
- team performance analysis techniques

Within these eleven categories, numerous HFE methods are described. It can be seen that the challenge is not a lack of HFE methods but the selection of one of them. Therefore, it is important to have a clear idea of the evaluation goal. Making a decision on a suitable method is difficult because there is no right or wrong answer when selecting HFE methods. Leonard et al. (2006) say that the selection of HFE methods depends on many factors. Therefore, they propose a framework that guides the selection and application of HFE methods (**Figure 4**). It has four basic steps: problem definition, study preparation, study execution, and data analysis and outcomes. In addition, it includes key questions to consider during the process.



Problem definition

1. What is the purpose of the study?
- Explanation-driven
- Implementation-driven

2. What resources are available?
- Time
- Experience
- Funding
- Previous research

Study preparation

1. Which type(s) of method(s)?
- Experimental research
- Descriptive studies
- Evaluation research

2. What are the relevant variables?
- Independent
- Dependent
- Confound

3. What are the details for study execution?
- Participant recruitment
- Study environment
- Apparatus/equipment

4. What will the data look like?
- Quantitative
- Qualitative

Study execution

1. Are the methods selected appropriate?
- Experimental control
- Pilot studies
- Preliminary analyses and power analyses

2. How are the methods carried out?
- Maintaining consistency
- Preserve data relevancy

Data analyses and outcomes

1. What kind of outcome data?
- Level of structure
- Level of objectivity
- Specificity
- Measurement type
- Dimensionality

2. What kind of analysis methods?

Figure 4. General framework for human factors/ergonomics investigations (Leonard et al., 2006)

2.3 Virtual prototyping

2.3.1 Concepts of virtual prototyping

The definition of a virtual prototype and virtual prototyping (VP) by Wang (2002) is used in this thesis. He defines that: "*A 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*". Virtual prototyping emphasises more the human-product interaction if compared to conventional engineering simulations (e.g., the simulation of system dynamics) (Wang, 2002). In this thesis, a virtual prototype means a virtual model of the design object, and VP means a construction and evaluation of a virtual model. **Figure 5** represents a typical example of VP in this thesis: a user is in VE and evaluates the design of a product.

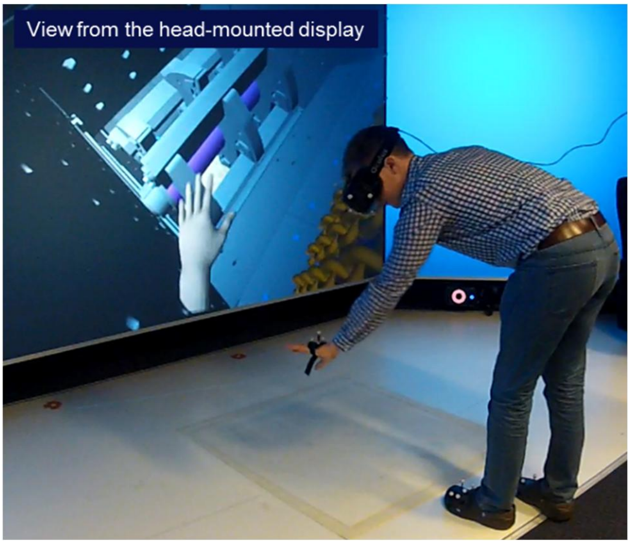


Figure 5. A user is interacting with the virtual model of a machine. The user is able to see his hands and shoes in the virtual environment because they are tracked. The view from the user's head-mounted display is projected in front of the user.

Virtual prototypes can be different in their level of virtuality and fidelity. Milgram et al. (1995) have proposed a reality-virtuality continuum, which is a continuous scale ranging from the completely real to the completely virtual (**Figure 6**). Bordegoni et al. (2009b) have made a framework for mixed prototyping, which discusses the dimensions of prototypes. The framework represents two dimensions for prototype and user, in which both can be either real or virtual. The framework also includes indirect and direct interaction modalities.

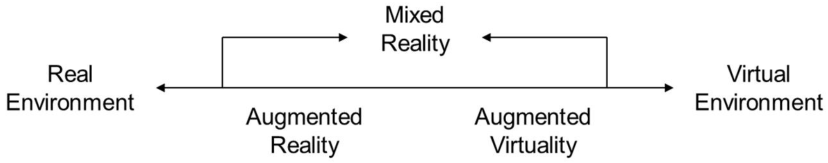


Figure 6. Reality-virtuality continuum (Milgram et al., 1995).

Virtual reality (VR) technologies and virtual environments (VEs) are used to create virtual prototypes. Using the definition by Kalawsky (1993), a VE uses VR technologies in order to provide human beings with the means of manipulation and sensory modalities. Practically, it means that humans are able to navigate in the VE (e.g. move from one place to another), manipulate objects (e.g. pick up a virtual object), and get sensory feedback (e.g. see and hear things). The term mixed reality (MR) describes environments that combine elements of the virtual and the real. An example of MR is augmented reality (AR), which means that the real world is supplemented with virtual objects (Azuma et al., 2001). With AR technology, the user is able to see both the real world and the virtual object in the same space. Nee et al. (2012) has made a review of the use of AR applications in design and manufacturing. Siltanen (2015) has studied AR in interior design in her thesis, and pursues the use of AR towards being commonplace in consumer applications. Key definitions of virtual prototyping for this thesis are summarised in **Table 2**.

Table 2. Key definitions of virtual prototyping.

Terminology	**Definition**
Virtual reality (VR) technology	A technology (software and hardware) that generates realistic sensory stimulations for the user in a virtual environment.
Virtual environment (VE)	A computer-generated, three-dimensional representation of real-world or abstract objects. It is an artificial environment that the user is in and interacts with.
Mixed reality (MR)	Environment that combines elements of the virtual and the real.
Augmented reality (AR)	The real world is supplemented with virtual objects.
Virtual prototype	A computer simulation of a physical product that can be presented, analysed, and tested.
Virtual prototyping (VP)	The construction and testing of a virtual prototype.

When applying VEs, it is important to acknowledge that VR technologies may cause users direct (e.g., skin irritation) and indirect effects (e.g., eyestrain) (Viirre et al., 2014). The response to VE exposure varies with the dose, the capacity of the individual exposed, and exposure duration (Stanney et al., 2014). Motion sickness is one of the common indirect effects, and its symptoms can be addressed using a simulator sickness questionnaire (SSQ) (Kennedy et al., 1993; Lawson, 2014).

In this thesis, mainly the terms VE and AR from the reality-virtuality continuum (Milgram et al., 1995) are used when defining the technology used in the case studies. Nevertheless, some of the VE studies could also be considered as MR studies (e.g., in **P2**, real machine joysticks were used in the interface). The focus of this thesis is on the use of VP in design and development, but not on other VP use areas, such as learning and training.

The use of digital human models (DHMs) can be considered as VP. Chaffin et al. (2001) state that DHMs represent the technology of using a computer to build a virtual representation of a real person, to simulate human motion and exertion. Demirel and Duffy (2007) say that DHM can be considered a digital representation of a human inserted into a simulation or virtual environment, to facilitate prediction of safety and/or performance. According to Badler (1997), virtual humans are computer models of people that can be used as substitutes for 'the real thing' in ergonomic evaluations of computer-based designs. Examples of DHMs include Jack (Badler et al., 1993) (**Figure 7**), Ergoman (Schaub et al., 1997), and Delmia V6 Human. DHMs can be used for the evaluation of HFE issues during the early design phase. It is possible to use DHM software for the analysis of a wide variety of HFE, including injury risk, timing, user comfort, reachability, lines of sight, energy expenditure, fatigue limits, and other HFE-related parameters.

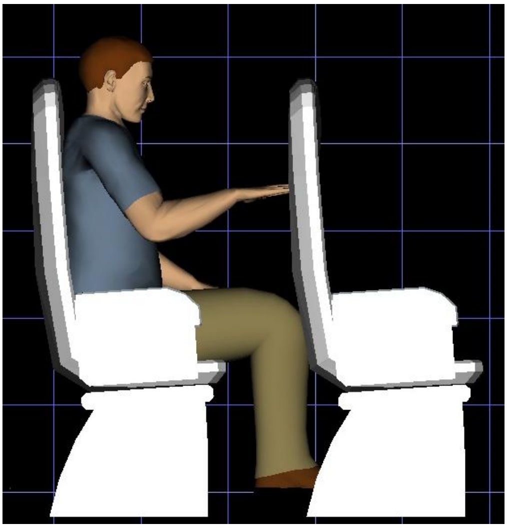


Figure 7. An example of a digital human model, Jack.

When using VP, immersion and presence are important characteristics of VE. Immersion is "*a description of a technology, and describes the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding and vivid illusion of reality to the senses of a human participant*" (Slater and Sylvia, 1997). It is good to remember that the VE and VP definitions differ from each other: VP systems do not necessarily incorporate VEs, which means that immersion is not absolutely required (Wang, 2002). Presence means that participants experience the VE as a more engaging reality than the surrounding physical world (they have a sense of being in a place) (Slater and Sylvia, 1997).

2.3.2 Evaluation of virtual environments and virtual prototypes

When discussing HFE evaluation and VR technologies, it is important to understand and elaborate clearly what is the target of the evaluation. For example, there are lots of studies related to the HFE evaluation of VE systems: Wilson (1999) discusses the usability and ergonomics of the VE; Kalawsky et al. (1999) introduce HFE assessment of the VE system; and Wang and Dunston (2006) define HFE features to consider in AR (and other mixed reality) systems. Another approach is to use VR technologies in product assessment, for example in the evaluation of usability of a washing machine (Bordegoni et al., 2009). Other examples of this type of study are Lawson et al.'s (2015) study of ease of entry and exit of vehicles, and Lämkull et al.'s (2009) evaluation of the manual assembly of automobiles. This division seems quite straightforward, but sometimes there is confusion between them, because it is possible to evaluate both point of views within the same VE system. **Figure 8** illustrates this issue.

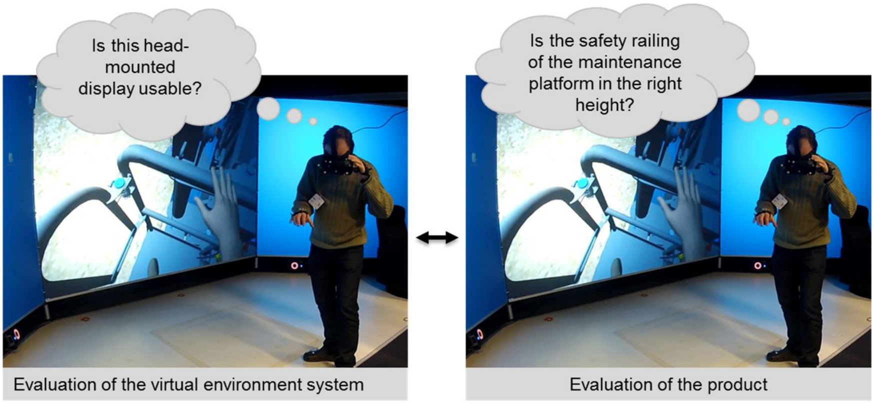


Figure 8. On the left-hand side, the HFE evaluation target is a virtual environment system; and on the right-hand side, the HFE evaluation target is a virtual prototype of a product.

In the left-hand side of the figure, the user is evaluating the usability of the VE system; and in the right-hand side of the figure, the user is evaluating a product (a maintenance platform). When evaluating the VE system, the purpose is to improve the user interface, presence, and immersion (e.g., are the interaction tools usable or is the resolution of the image good enough). The goal of the second approach is to improve products' HFE by evaluating the product in a VE. In this case, VEs are used as tools to support the HFE evaluation of a design object (e.g., is the safety railing of the maintenance platform at the right height).

This thesis focuses on the second approach, which uses VEs in the HFE evaluation of the design object. In other words, it concentrates on VE use in the design of products, and not in the development of better VEs. However, the VEs need to be designed accordingly to be able to evaluate a design object.

3. Related work

This chapter reviews the work related to the use of virtual prototyping (VP) in human factors/ergonomics (HFE). It addresses issues such as VP in the product development process (PDP), design and construction of virtual prototypes, application domains for VP, virtuality levels of virtual prototypes, reliability and validity of virtual prototypes, and HFE evaluation in VP. In addition, it describes the research gap.

3.1 Virtual prototyping in product development

In recent years, the use of virtual prototyping (VP) has increased in product development processes due to the improved availability and lowered prices of VP technologies (Berg and Vance, 2016; Choi et al., 2015). It can be used in different phases of the PDP process to support HFE design. Virtual prototyping is especially useful in the concept design phase, and it enables better integration of the HFE approach into product design and development (Leino, 2015). Several studies (Bordegoni et al., 2009; Bullinger and Dangelmaier, 2003; Cecil and Kanchanapiboon, 2007; Karkee et al., 2011; Kim et al., 2011; Kremer, 1998; Kulkarni et al., 2011; Lawson et al., 2016; L. Ma et al., 2011; Mujber et al., 2004; Park et al., 2009; Seth et al., 2011) state that VP has been considered as a new and powerful prototyping solution to overcome the shortcomings of conventional prototyping methods such as physical prototyping. They say that production of the physical prototype is costly and time-consuming, and therefore a reduction in the number of physical prototypes would shorten the time-to-market. In addition, the use of virtual prototypes may provoke more development ideas compared to physical prototypes (Tiainen et al., 2014) and can be used to support communication and interaction between different stakeholders (Bordegoni et al., 2009; Bordegoni and Caruso, 2012; Davies, 2004; Kremer, 1998; Leino, 2015; Shen et al., 2010). Several studies have studied the use of DHMs in design processes (and workplace design) (such as Chaffin, 2005; Jayaram et al., 2006; Perez and Neumann, 2015; Sundin and Örtengren, 2006; and Zhou et al., 2016) and product life-cycle management (Joung et al., 2015). Ong et al. (2008) made a survey of the use of AR applications in the manufacturing industry. Based on these research studies, it can be seen that virtual prototypes have been adopted for industry use, and they are seen to be beneficial.

Berg and Vance (2016) made a review of how VP is used in product design and manufacturing today. They listed current research challenges in the use of VP: "*better graphics and brighter displays, environmental simulation, easier model conversion process, automated model preparation, wider field-of-view in head-mounted display (HMD), better collision detection and haptics and transportable VR labs*". Choi et al. (2010a) have addressed the model conversion process by proposing an approach that supports the process from product data management (PDM) to virtual reality application.

Berg and Vance (2016) made a generalised VR technology use process that was based on surveyed company processes. It illustrates the typical VR technology use process. Its steps include: VR request, model acquisition, model preparation, build virtual environment, proof-of-concept demo, VR session, and outcome summary (**Figure 9**).

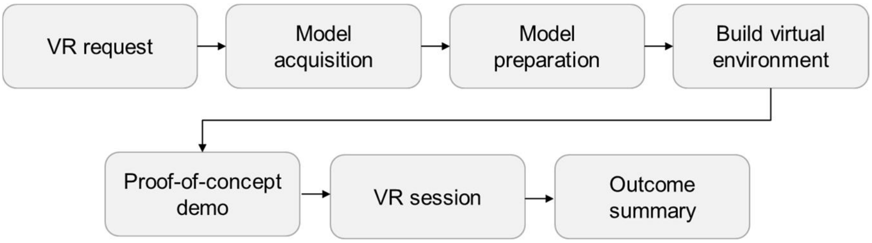


Figure 9. Virtual reality use process (Berg and Vance, 2016).

3.2 Design and construction of virtual prototypes

Many approaches have been proposed for the design of VEs and VP systems. The approaches try to model, systemise, and structure the design work of VEs. The following approaches were selected to give an understanding of the topics and research related to the design of VEs. Therefore, this is not a thorough review of current VE design methods.

One well-known and comprehensive approach is a virtual environment development structure (VEDS) (Eastgate et al., 2014). This has been used to support the development of VEs for industrial use, industrial training, and education. It is a thorough framework with goal-setting and constraints, requirement analysis, task and user analyses, appropriate interface guidelines, predictions of task performance, an iterative design/test cycle, and an evaluation process. The top-level outline of the main stages is illustrated in **Figure 10**. It includes the following stages: project definition, requirements analysis, specification, overall design, resource acquisition, detail design, VE programming, verification, deployment, and validation. Evaluations in this approach are related to the evaluation of the VE and not the evaluation of design objects (see section 3.6).

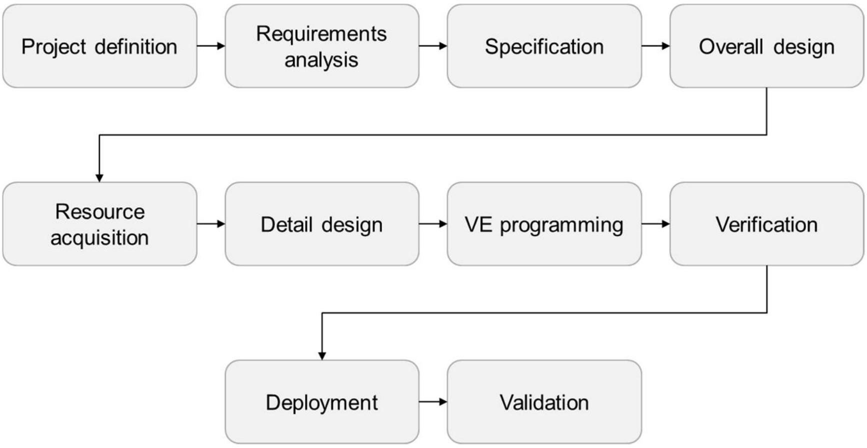


Figure 10. Outline of virtual environment development structure (VEDS) (Eastgate et al., 2014).

Aromaa et al. (2014a) propose a framework for VP in human-machine interaction design to develop and test virtual prototypes systematically (**Figure 11**). Their framework includes human, interface, and system model elements. The human interacts with the system model through the interface. In addition, it contains a test model element that can contain different data collection and analysis methods (e.g., HFE, comfort, user experience). This approach focuses more on the evaluation of the product, and therefore the use of the VE in VP.

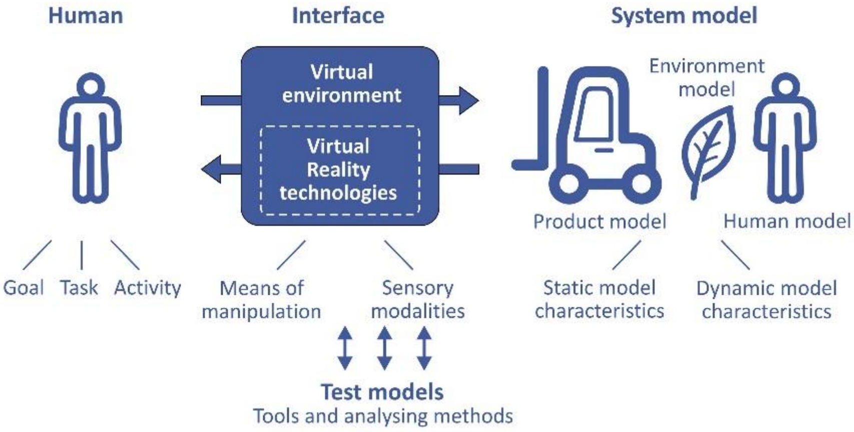


Figure 11. A framework for virtual prototyping in human-machine interaction design (Aromaa et al., 2014a)

Mahdjoub et al. (2013) have introduced an approach that is based on the concept of intermediary objects (IOs). They consider a virtual prototype to be one type of IO.

The approach includes seven inter-related models: the product model, product use model, interaction model, support tools model, rules and interaction model, evaluation model, and convergence situation model. The structure can be used to understand and choose IOs, but its use in real cases and integration with product development processes was not described in this publication.

Wang (2002) describes how a virtual prototype includes three types of models: a CAD model, a human-product interaction model, and perspective test models. In his approach, the user interface serves as the integration component that coordinates the behaviour of models and provides useful information to the system user.

An interactive virtual prototype (iVP) is introduced by Ferrise et al. (2013). The iVP is a combination of functional sensorial models accessed by means of a multimodal and multisensory input/output interaction environment. Ferrise et al. emphasise that the interaction and interface modules are required when the user uses the virtual prototype.

Bordegoni and Ferrise (2013) propose a multisensory interaction model for the development of VP applications. The model describes the flow of information that is extracted from the virtual prototype and that is conveyed to the user through various senses. Bordegoni and Ferrise say that when multiple senses are involved in the perception of virtual objects, this improves the quality and the fidelity of interaction.

There are also different aspects to consider when designing virtual prototypes, such as a reference framework for mixed prototyping, which locates mixed prototyping in respect to physical prototyping (Bordegoni et al., 2009). This represents a two-dimensional prototype and a user that can be either real or virtual. The framework also includes interaction that can be direct or mediated.

Chung et al. (2002) want to support the selection of appropriate VR technologies and the design of a cost-effective VE application. They propose an analysis framework for applying VE technology in manufacturing tasks. The framework consists of three steps: evaluate overall feasibility, assess potential benefits, and conduct a cost/benefit analysis.

When designing VEs and VP systems, it is also important to consider their usability. Stanney et al. (2003) introduced a systematic approach to design and evaluate VE usability: multi-criteria assessment of usability for virtual environments (MAUVE). Usability characteristics are divided into two main categories: a VE system interface and a VE user interface. Kalawsky (1999) has also introduced a tool (VRUSE) to evaluate the usability of virtual interfaces.

In summary, these proposed VE/VP design approaches have good qualities but have not been adopted in industry or in the research community at large. There should be more research into their applicability to industry, to be able to develop them further. This would support their systemisation and standardisation for use in everyday practices during a PDP.

3.3 Virtual prototyping application domains

The use of VP in HFE design has been studied in several research projects (such as those by Wilson and D'Cruz, 2006; Bullinger and Dangelmaier, 2003; Park et al., 2009; Bordegoni et al., 2009; Karkee et al., 2011). The research has addressed different industry domains, such as aerospace (Sanjog et al., 2015), automotive (Hanson et al., 2006; Lawson et al., 2015; Vogt et al., 2005), and industrial workplaces (Balaji and Alphin, 2015; Chang and Wang, 2007; Colombo et al., 2016; Lämkull et al., 2009, 2007; Tripathi et al., 2014).

Different tasks and human-machine systems have been addressed by the current research. VP has been studied in assembly and disassembly tasks (De Magistris et al., 2013; Gonen et al., 2016; Lämkull et al., 2009; Pontonnier et al., 2014, 2013; Vance et al., 2011) and maintenance tasks (Regazzoni and Rizzi, 2013; Tripathi et al., 2014). VP has been used in cabin and workplace layout design (Bordegoni and Caruso, 2012; Colombo and Cugini, 2005; Godwin et al., 2008; Godwin and Eger, 2009; Kim et al., 2011). Pentenrieder et al. (2007) developed a VP system for factory design and planning. VP use has been studied in the design of human interaction with tools and machines (Bordegoni et al., 2014; Colombo, 2013; Colombo et al., 2010; Colombo and Cugini, 2005; Hu et al., 2012, 2011; L. Ma et al., 2011). Manual handling tasks such as lifting and push-pull tasks have also been studied (Demirel and Duffy, 2017; Ma et al., 2010; Wu et al., 2012). User interface design has been investigated by Barbieri et al. (2013) and Bruno and Muzzupappa (2010). Lawson et al. (2015) studied the ease of entry and exit to/from a car. Berg and Vance (2016) reviewed the current use of VP in product design and manufacturing. They detected the following use contexts: visibility/viewability, ergonomics/reachability, packaging, aesthetic quality/craftsmanship, storytelling, abstract data visualisation, communication across disciplines.

Current research has addressed design engineers' point of view towards VP. Design engineers and other stakeholders' point of view towards the use of VP was studied by Lawson et al. (2016) and Perez and Neumann (2015). Perez and Neumann (2015) made a study to better understand the experiences, perceptions, needs, and expectations of the users of VP systems. Based on the studies, they identified characteristics that may hinder the use of VP: time, cost, training, difficulty of use, trustworthiness, graphics, flexibility, usefulness, and report presentation. Lawson et al. (2016) interviewed engineers and other stakeholders about their physical and virtual processes in automotive manufacturing. They suggested future developments for VR technologies and applications: develop a greater range of virtual contexts; use multi-sensory simulation; address perceived differences between virtual and real cars; improve motion capture capabilities; implement networked 3D technology; and use VR for market research

According to Ma et al. (2011), the collaborative VE is a useful tool for supporting complex product design. Therefore, VP can be used to support communication and interaction between different stakeholders during design reviews (Bordegoni et al., 2009; Bordegoni and Caruso, 2012; Kremer, 1998; Leino, 2015; Shen et al., 2010).

According to Huet et al. (2007), design reviews are efficient tools for sharing information about the product and for managing knowledge exchange. A participatory approach has also been used in safety analysis in VP (Määttä, 2003). Regenbrecht et al. (2002) developed an AR system that enables collaborative design reviews.

3.4 Virtuality and fidelity in virtual prototypes

Many different kinds of virtual prototypes can exist because they are dispersed on a reality-virtuality continuum (Milgram et al., 1995): they can be partly physical and virtual, or completely virtual. Virtual prototypes can also vary in their fidelity level, from low-fidelity to high-fidelity based on their realism. Bordegoni et al. (2009b) proposed a mixed prototyping framework that says that prototypes and users can vary from real to virtual. They discuss different combinations of these two dimensions within this framework; for example, the user can be real and the prototype virtual, or both the user and prototype can be virtual.

Pontonnier et al. (2013) have one example of a study that used different fidelity and virtuality levels of prototypes. They compared the assembly task in a real environment, a virtual environment, and a virtual environment with force feedback. Mixed reality examples can be found from the studies of AR systems used for the design of an assembly, a factory, an airplane cab, and a car control panel (Ong et al., 2007; Pentenrieder et al., 2007; Porter et al., 2010; Regenbrecht et al., 2005). Ferrise et al. (2015) also proposed strategies for using real, mixed, and virtual prototypes for multisensory experience. Users have been virtual in studies that use DHMs; for example, Lämkull et al. (2009) evaluated the ergonomics of manual assembly tasks in the automotive industry. They used DHMs to evaluate working height, working distance, clearance, and hidden assembly. Aromaa et al. (2014b) discussed the suitability of virtual and physical prototypes in the design of HFE.

These changing virtuality and fidelity levels can be difficult to manage during VP. In addition, during the prototyping, there are always trade-offs between fidelity and the time, effort, and cost needed to create the prototype (Yang, 2005).

3.5 The reliability and validity of the human factors/ergonomics evaluation

It is always important to know whether the results obtained from HFE evaluation during VP are valid to support design decisions. To solve these issues, there has been research done in which the use of virtual prototypes is compared with other prototypes or real situations. Studies discovered inconsistencies between virtual and real-life evaluations but also consistencies between them.

Inconsistencies were detected, among other things, when comparing HFE measurements between VEs and the real environment: in VEs, users may become fatigued more quickly, require more time and greater effort, and experience more discomfort and more task difficulty than in a real environment (Hu et al., 2012, 2011). Wu et al. (2012) discovered that the results from the 1991 revised NIOSH lifting equation tool were significantly larger in a virtual prototype than in a physical prototype. This may be because of the HMD's narrow field of view, which affected the posture of the user (did not see enough and needed to bend the body more). Lawson et al. (2015) compared virtual and physical prototypes and discovered that virtual prototypes had lower validity and reliability than physical ones for identifying entry and exit issues in passenger vehicles. Pontonnier et al. (2013) compared assembly tasks in real environments, VEs, and also in VEs with haptics. They discovered that the mechanical limitations of the haptic device in the VE lowered the sensation of presence and reported an increase in the difficulty compared to real environments and VEs without haptics. Another study by Pontonnier et al. (2014), which compared real and virtual environments in ergonomic analysis, showed a gap between situations for objective measures, as well as contradictory results with subjective measures.

Consistencies in reliability and validity research have also been discovered. Lämkull et al. (2009) say that DHM tools have been proven to correctly predict ergonomics issues for standing and unconstrained working posture, and therefore, DHMs can be used to optimise working heights. The static strength prediction (SSP) and NIOSH lifting equation results were not significantly different between manually setup DHM postures and DHM postures tracked from real people (Wu et al., 2012). From a usability point of view, Bruno and Muzzupappa (2010) discovered that VR techniques are a valid alternative to traditional methods for product interface usability evaluation, and that the interaction with the virtual interface does not invalidate the usability evaluation itself. Pontonnier et al., 2014 say that fairly good correlations were found for posture and averaged muscle activation analysis between real and virtual environments.

In summary, it can be seen that there is research that supports VP use in HFE evaluation. However, there are also research results that are against this. It seems that there are still too few research studies related to this topic to draw any further conclusions. Therefore, the reliability and validity of the HFE evaluation results in VP should be studied more.

3.6 Human factors/ergonomics evaluation using virtual prototypes

Related research described in Section 3 (especially in 3.3 and 3.5) has evaluated different HFE factors related to VP. These factors are summarised in **Table 3**. The table includes categories for user, product, task, and prototype that are based on Pheasant's (1996) approach. In addition, prototype characteristics are added as one category. User measurements were related to user preferences, experiences, and impressions of a product. In addition, the experience of stress, fatigue, perceived exertion, and discomfort were evaluated. Users were also measured by considering force, average muscle activation, and compression forces in the two lowest vertebrae in the lumbar spine (L4/L5). Body joint angles, postures, and risks associated with lifting tasks were also considered. The studied product characteristics were related to visibility, accessibility, reachability, manoeuvrability, and passageways. In addition, ergonomics and safety were measured on a general level. Measurements related to task characteristics included task difficulty, performance, and time. Virtual prototype characteristics were studied with regard to fidelity, validity, and feasibility issues. Most of the HFE evaluations could be considered to be experimental or evaluation-based (Sanders and McCormick, 1993).

Table 3. A summary of human factors/ergonomics evaluation targets from the related work.

Evaluation target	
User	- user preferences - user experiences - user impressions - stress - fatigue - perceived exertion (RPE) - body-part discomfort - force - average muscle activation (AMA) - compression forces in two lowest vertebrae in the lumbar spine (L4/L5) - body joint angles - postures (RULA) - risk associated with lifting and lowering tasks (NIOSH lifting equation) - static strength prediction (SSP)
Product	- visibility - accessibility - reachability - manoeuvrability - passageways (entry/exit of a car) - ergonomics - safety
Task	- task difficulty - task performance - time
Prototype	- fidelity - validity - feasibility

Based on the summary, it can be seen that versatile HFE factors have been evaluated using VP. It is also good that all three key system parts (user-task-product) have been evaluated using VP systems. Some of the evaluation targets were quite detailed, and some of them were more general (e.g., compression forces in lumbar spine vs. ergonomics in general). It should be taken into account that this research area is still quite fragmentary. This means that some of the HFE evaluation factors have been studied only once. There should be more research for each HFE evaluation factor, to make any final conclusions regarding suitable methods and their validity.

3.7 Research gap

Based on the literature review, it can be seen that VP is used increasingly for evaluating HFE during the PDP. However, often the HFE evaluations in the VR research community tackle the issues related to improving the HFE of VEs, and the application of VP in HFE evaluation is not discussed at large. The difference between VE evaluation and product evaluation in a VE is not discussed in the scientific community at a theoretical level. However, while publishing VR research, it would be important to clarify for the reader in which category the research belongs.

The design of VP systems is a complex task and there are no standardised approaches that would be in everyday use. Müller et al. (2016) say that the main challenge of VP is the interaction with virtual models and interfaces. Despite the Section 3.2 design approaches, there is no easy and simple guidance for design engineers on how to design VEs (Wilson & Cruz 2006) and use them during the design. Sometimes the construction of virtual prototypes is based on hopeful expectations rather than systematic goal-oriented design (Chung et al., 2002), and too much depends on the design engineers’ ability and experience (Choi et al., 2010b). The lack of proper guidance makes decision-making harder for design engineers: choices affect sensory feedback, cognition, and motor control (Pontonnier et al., 2014). In addition, there might be barriers that make it difficult to pick up and use VP systems, or they are used too late in the PDP (Perez and Neumann, 2015). In addition, many research studies related to prototyping concentrate mainly on prototype fidelity studies rather than supporting design (Lim et al., 2008). Berg and Vance's (2016) review of VP use in industrial product design and manufacturing shows that VP is currently actively used and it works. However, when participants proposed future developments, streamlining the VR use process was still one of them. In addition, when Berg and Vance (2016) discussed this with companies, they found that it is challenging to start up and maintain the VR effort in a company.

The selection of HFE evaluation methodologies and suitable VP systems requires the consideration of many variables. Leonard et al. (2006) say that there is no right or wrong answer when selecting HFE methodologies because “it depends”. This “it depends” also applies when designing suitable VP systems (e.g., the most appropriate fidelity level depends on the case). Therefore, ways of evaluating HFE in VP is a research topic that deserves more attention. Regardless of the fact that it might be challenging, there should be a pursuit of more clarity, systematisation, and guidance related to this topic.

4. Research approach and methods

This chapter presents the overall research approach, research process and methods, and research ethics of the thesis.

4.1 Research approach

This thesis belongs to the field of HFE, which focuses on studying human-machine systems in order to optimise well-being and overall performance. The main goal of the thesis is to understand the elements that contribute to VP use in HFE evaluation during PDP. An inductive research approach was selected for use in this thesis to be able to understand VP use in HFE evaluation. The inductive research approach observes phenomena and identifies patterns to create generalisations and theories from them. In addition, the research is exploratory and qualitative by nature, which means that it aims to understand the investigated phenomenon in depth.

The research in this thesis is based on a case study approach (Yin, 2013). A case study means an in-depth study of a phenomenon within its real-life context (Lazar et al., 2010; Yin, 2013). The case study approach was selected because it enables observation of a certain phenomenon in a real-life context in which actual use of the system happens. Six different case studies were conducted in order to investigate the use of VP to support HFE evaluation. All the case studies were done in an industrial product development context in collaboration with companies. Data was collected using multiple methods (e.g., observation, questionnaires, and interviews) in a data triangulation fashion, to increase confidence in the results. Both qualitative and quantitative methods were used. Inductive reasoning was used to make generalisations from specific observations in the case studies.

4.2 Research process and methods

The case study approach (Yin, 2013) was selected as a method to increase the understanding of VP use in HFE evaluation by answering **RQ1**, **RQ2**, **RQ3**, and **RQ4**. In total, six case studies were conducted to gather empirical data to contribute to understanding the topic. **Figure 12** illustrates the research process and correlations between the research questions and the case studies. The case studies **P1-P2** and **P4-P6** answer the **RQ1**, all case studies (**P1-P6)** answer both **RQ2** and **RQ3**, and the case study **P3** answers **RQ4**. After performing the case studies, the findings were analysed using a cross-case analysis approach (Yin, 2013), in order to come up with the answers to **RQ1**, **RQ2**, **RQ3**, and **RQ4**. Cross-case analysis is an analysis which examines themes, similarities, and differences across multiple cases. The cross-case analysis results are presented in Chapter 6, Results. In addition, thematic analysis (Braun and Clarke, 2006) was used to support the data analysis phase.

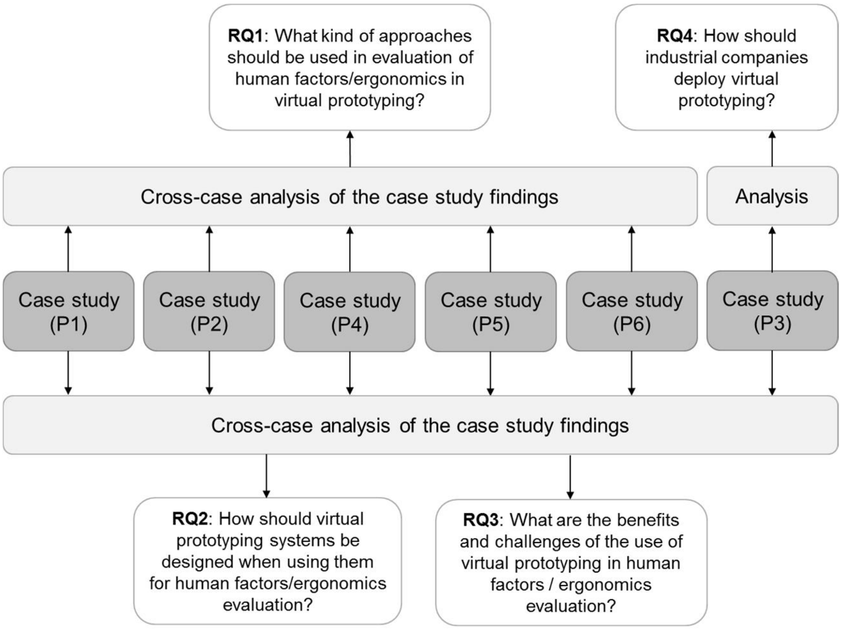


Figure 12. Connections of case studies, publications, data analysis, and research questions.

4.2.1 Summary of data gathering and analysis methods of the six case studies

The thesis includes six case studies, the data gathering and analysis methods of which are summarised in this section. In addition, the following chapter describes the case studies in more detail, and thorough descriptions can be found in the publications in the appendices to the thesis.

All the publications **P1-P6** adopted the **observation** of users and actions as a data-gathering method during the case studies. Observations are a critical approach in this type of research and supplement other data-gathering methods. By directly observing users, it is possible to acquire information on users' task performance **(P1-P6)**, communication between users (**P1,P3, P5**), HFE issues such as postures (**P2,P4,P6**) and the possible effects that VR technology use can have on users (e.g., simulation sickness symptoms) (**P1, P2, P4, P5**). In addition, with observation, it is possible to detect factors that may decrease the validity of the results, for example, maturity issues of VR technology.

Questionnaires were adopted in **P1, P4, P5,** and **P6**. Questionnaires are particularly valuable when gathering experimental data on users' opinions, experiences, and preferences. Both previously established HFE questionnaires and specifically designed questionnaires were applied to be able to address the current case study's research questions and to support the data triangulation approach. In **P1,** the questionnaire was designed for collecting data regarding the benefits of VP use. In **P4,** there were specific questionnaires to collect data on design object and suitability of the VP system for HFE evaluation. In addition, subjective workload was evaluated with NASA-TLX (Hart and Staveland, 1988) and SSQ symptoms were evaluated with the adopted SSQ questionnaire (Kennedy et al., 1993). NASA-TLX was used as it revealed mental workload differences between two virtual prototype uses. In **P5**, a specific questionnaire was used to gather information regarding the use of VP systems during a design review. In addition, an adopted SSQ questionnaire was used. In **P6**, mental load was evaluated with NASA-TLX and physical load with a specific question or body-map discomfort questionnaire. With these questionnaires, it was possible to acquire a comprehensive view on users' experience of the workload. In all case studies (**P1-P6**), a consent form was signed and demographics of the participants were collected by a questionnaire.

In **P2**, the data related to the development of a field of view analysis method was collected **automatically** by computer. By doing this, it was possible to evaluate differences in visibility between two conditions. Computer calculations were also used in **P6,** when posture analysis data was automatically calculated by DHM software.

P3 adopted **surveys, interviews, and workshops**, in addition to observations. These approaches supported the participation of several participants from the companies and supported free discussion during the workshops. In addition, action research (Coghlan and Brannick, 2014) principles were adapted in **P3**.

For the **data analyses** in case studies, both **qualitative and quantitative approaches** were adopted. A qualitative thematic analysis (Braun and Clarke, 2006) was used in **P1, P3, P5,** and **P6** to identify, analyse and report patterns within the data. A qualitative approach was also used in **P2**, in which trend lines were provided and analysed qualitatively. Content analysis (Elo and Kyngäs, 2008) was adopted in **P4**. In **P3**, functional process diagrams were applied to model processes. A quantitative data analysis was used in **P4** and **P6** when data was analysed with a paired T-test. An overview of the case studies can be found in **Table 4**.

Table 4. Overview of the case studies.

Publication	Case study topic	Participants	Data gathering methods	Data analysis
P1	Benefits of the use of virtual environments in a product design review meeting	Group 1: seven participants from six customer companies and one from a union Group 2: seven participants from the company	Observation Questionnaire	Thematic analysis

P2	Developing a task-related dynamic field of view analysis method to be used in a virtual environment	Five participants (research scientists)	Observation Automatically calculated field of view	Results were illustrated as trend lines and analysed qualitatively
P3	Supporting systematic virtual prototyping implementation in companies and improving the effectiveness of using virtual prototyping	Two industrial companies	Observations Surveys Interviews Workshops Action research	Thematic analysis Functional process diagrams ("swim lanes")
P4	Suitability of virtual prototypes to support human factors/ergonomics evaluation during design	Group 1: nine company stakeholders Group 2: ten design engineers from the company	Observation Questionnaires	Content analysis Paired T-test
P5	Systematic preparation of virtual prototyping systems for design reviews	Two design review settings: Group 1: ten participants (design engineers) Group 2: eleven participants (different stakeholders, e.g., design engineers)	Observation Questionnaires	Thematic analysis
P6	Human factors/ergonomics evaluation of gesture interfaces for robot control	Group 1: ten university researchers and students Group 2: nine research scientists	Observation Questionnaires DHM posture analysis	Thematic analysis Paired T-test

The case studies were executed in VTT Technical Research Centre Ltd.'s research projects in collaboration with four industrial partners. The partners were industrial companies that manufacture rock-crushing machines, underground drilling machines, cargo-handling solutions, and aerospace solutions. The case studies were related closely to industrial work, but due to the use of VR technology, most of the studies were done in laboratory settings. Three of the case studies (in **P1, P2** and, **P5**) were done solely in VTT's VR laboratory facility in Tampere. The case study in **P4** was done in two locations: in the Tampere VR laboratory and outdoors in the field of the manufacturing company. The case study in **P6** used the Tampere

VR laboratory and a similar facility in Athens. The case study in **P2** was done within two industrial companies and did not use the laboratories.

4.3 Research ethics

The research for this thesis has followed the principles of the Finnish Advisory Board on Research Integrity (TENK) (Finnish Advisory Board on Research Integrity, 2017). The research has been done by valuing integrity, meticulousness, and accuracy in data collection, analysis, and presentation of the results. Test situations were recorded by taking notes and pictures, and in some cases also by using video recording. Data from interviews and questionnaires was collected either in digital or paper format. For the data analysis, both qualitative and qualitative analyses were used. In the data analysis, especially regarding qualitative analysis, it has also been important to reveal both positive and negative outcomes. In addition, issues such as technology maturity, which might have had an effect on the collected data, have been discussed in the publications thoroughly. It was possible to publish all the studies, even though some studies had been related to the participating companies' technology development. Other researchers' work has been acknowledged during the research by making a state-of-the-art review and referring to publications accordingly.

There was no need to apply for research permits or an ethical review before the studies in this research. However, a consent form was collected from all participants before test participation. The consent form introduced the project and research goal; the project financer; the voluntary nature of the tests; the participants' possibility to withdraw from the tests at any time; the use of data only for research purposes; and retaining confidentiality and anonymity of the data when publishing the results. Confidentiality and anonymity were also applied to pictures and videos, if not agreed otherwise. The party financing the project was announced on the consent form and in the acknowledgements when publishing papers.

The research was conducted carefully to minimise health factors associated with VE exposure (Stanney et al., 2014). If the research was done in a VE, it was mentioned that the use of VR technologies can occasionally cause nausea and disorientation. Therefore, it was explained to participants that they could withdraw from the test if they so felt. Studies were also designed in such a way that the exposure time would not be too long (e.g., in a case study in **P6**, the maximum task performance time was 15 minutes). In addition, researchers were cautious in observing participants to detect any simulation sickness symptoms.

5. Summary of the case studies

This section describes the six case studies conducted in the manufacturing industry. The studies' goals, methods, and main findings are described in following sections.

5.1 Benefits of the use of virtual prototyping in product design reviews

The goal of this study (**P1**) was to recognise and classify benefits from the use of VP during design reviews. The benefits were studied in two industrial case studies. HCD (ISO 9241-210, 2010), participatory design (Ehn, 1993; Muller and Kuhn, 1993), and case study (Yin, 2013) approaches were applied. Questionnaires and observation were used as data collection methods. In addition, the design reviews were recorded by taking photographs and notes. A thematic analysis approach (Braun and Clarke, 2006) was used for data analysis.

The used VP system was as follows: (1) three projectors; (2) head-mounted display (HMD); (3) marker-based optical motion-capture system to capture the worker's point of view; (4) user interface system with gesture control, gaming controllers, and a basic keyboard/mouse, and (5) surround audio system. The review board was provided with an overview of the system with a projector setup, to understand the specific context. In addition, the HMD view for the worker was also projected on one extra screen for the review board to observe.

The first study was a review meeting of an upgrade concept for an existing product. The nature of the review was more about an introduction to a concept and how it would be assembled. Six customer company representatives were attending a design review. A VE expert, an HFE expert, and a company representative were also present. The purpose of the second design review was to show an engine module to the productization and production experts **(Figure 13)**. The goal was to evaluate the assembly, maintenance, safety, and structural problems, and also to discuss possible solutions. The review board consisted of company stakeholders, a VE expert, HF experts, and a review meeting chairman. The assembly worker used the HMD to observe the step-by-step assembly, and the review board discussed and made comments.

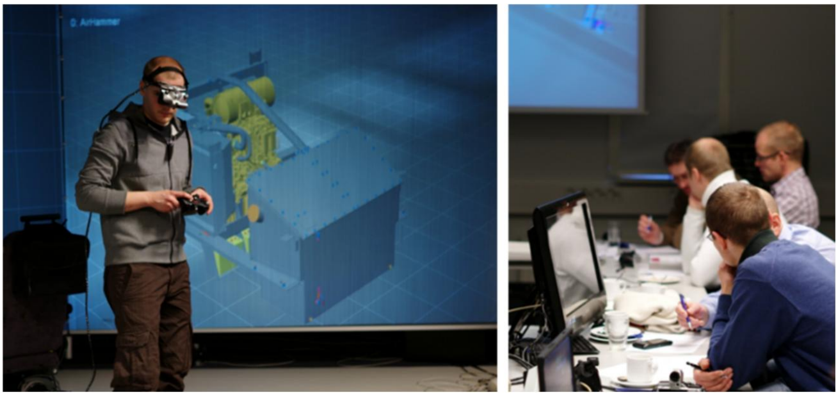


Figure 13. A design review of an engine module.

The use of VEs enabled knowledge-sharing, because it established an environment in which everyone can have the same visual understanding of the current situation. In addition, the participatory approach supported knowledge-sharing between different participants/stakeholders. User participation improves the recognition of user needs and requirements (and design engineers' collection of feedback). The participatory approach also supports decision-making and learning. In the VE, users can do the task and work in context. This can also be applied to design engineers: they can get first-hand experience of the product. Virtual prototypes can be applied iteratively in many PDP phases. However, it is most beneficial as early as possible. In addition, it is possible to achieve savings in time and money, as, for example: (1) the company can create preliminary assembly instructions based on the review meeting; (2) user acceptance will be better if based on the participatory approach; (3) assembly and maintenance will be more efficient; (4) it is possible to plan the delivery dates for subcontractor parts; (5) bottlenecks can be found and removed from production; (6) alternative assembly orders can be defined; and (7) the number of physical prototypes can be decreased.

When using VP, it is important to acknowledge users' individual characteristics, such as eye vision, stereoscopic visual capabilities, and sensitivity to simulation sickness symptoms. Participants need to be informed of the possibility of negative symptoms beforehand, and monitored during the VP sessions. In addition, virtual prototypes still have constraints that affect the user experience (e.g. force feedback or manipulating large and heavy objects). Another challenge to consider is to decide on the level of detail when working within the VP system. The more details and functions are needed, the more time it will take to make virtual prototypes. When using VP, it is important to integrate VP design reviews in the company processes in such a way that it makes the design work more efficient. This case study showed that more systematic practices in the VP design review process needs to be implemented at company level: design feedback was recorded in participants' minds or personal notes, and reported to other stakeholder verbally or by email. The design review participants might also need training to fully understand the VP system and to be able to work with it. One issue is how to link VP use and the information management (PDM, product data management) and PLM (product life-cycle management) processes. A model conversion process between CAD and VP data is one of the important issues faced by the VP community.

5.2 Developing task-related field of view analysis for a virtual environment

The purpose of the case study in **P2** was to evaluate a task-related dynamic field of view (FOV) analysis that was developed to support decision-making during VP. The FOV analysis gives design engineers quantitative information when comparing alternative design solutions (e.g., different cab structures). It also acknowledges operators' task performance and head movements. The FOV analysis method calculates the visibility of a certain target (the percentage of the visible part of the target object's pixels from all the pixels in the operator's FOV) and occlusion (the percentage of the occluded pixels from the visible target object pixels in the operator's FOV).

The VP setup included a 3D Rubber-Tyred Gantry (RTG) crane model, a four-screen visualisation system, a marker-based optical motion capture system for head tracking, shutter glasses for operator, an operator's user interface (joysticks), a motion platform, and an operator's cabin seat on the motion platform **(Figure 14)**.

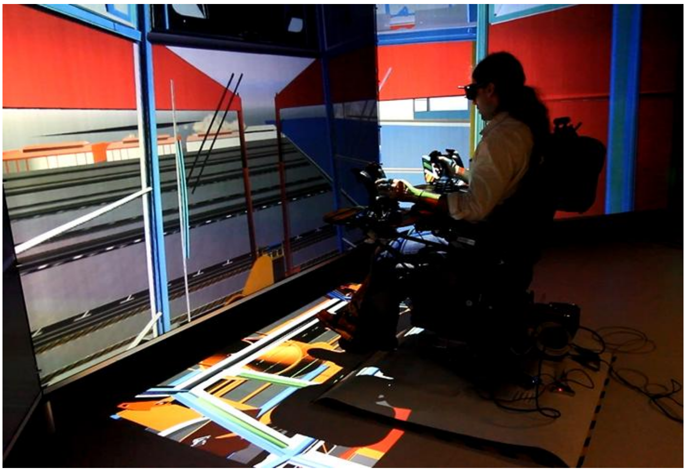


Figure 14. The user is performing a task using a virtual prototype of a crane.

The within-group setup was used to validate the FOV analysis method. Five participants (research scientists) took part in the test. They were asked to perform an operation (drive a crane, pick up a container, and place it down) using a virtual prototype of a crane. They did the task twice with different crane cabin structures (thinner and thicker structures). Participants' performances were video-recorded and their FOV was saved. The visibility of the crane's spreader is important and, therefore, occlusion and visibility values from it were recorded. Finally, the visibility and occlusion values were compared between different structure thicknesses. Mean values were illustrated as trend lines and analysed qualitatively (because the number of participants was too small for quantitative analysis).

The results of the developed FOV analysis method can be regarded as being promising in predicting visibility differences between product variants: the thinner cab structure had better visibility than the thicker cabin structure. This was a preliminary validation study of the FOV analysis method and further studies need to be made to develop and validate it further.

5.3 Deployment of virtual prototyping in industrial companies

The main goal in the case study in **P3** was to support the companies in their systematic VP implementation and to improve their effectiveness in using VP. The VP implementation maturity model (VIRMA) was developed to support these goals. Two company cases for VP implementation measurements were studied. They were both implementing VP for use during this project. In the research study, data was gathered using observations, surveys, interviews, and workshops. In addition, functional process diagrams ("swim lanes") were used for process modelling (**Figure 15**). Action research approach (Coghlan and Brannick, 2014) was adapted also. The study took several months, and several stakeholders took part in the studies. A qualitative thematic approach (Braun and Clarke, 2006) was used to categorise the findings from the case studies.

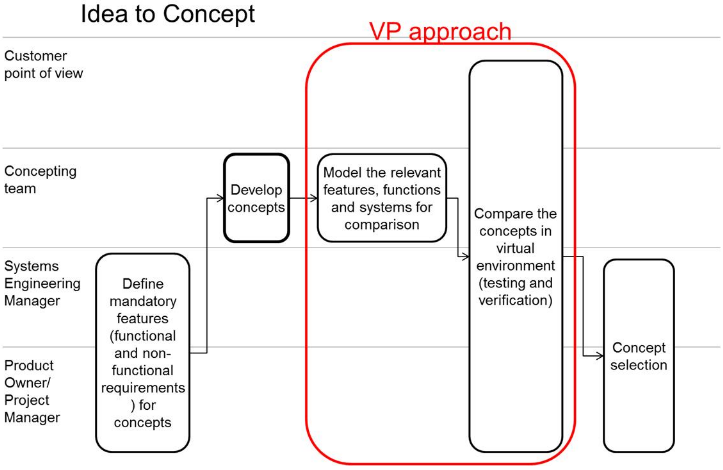


Figure 15. Example of a process diagram that was discussed during the workshop. It includes a virtual prototyping approach (red circle).

Two companies adapted a VP system for their use during these studies. The discussions with the companies revealed several challenges regarding the use of VP. Challenges were thematically grouped into human, technology, and process categories. Human-related challenges were: (1) users' attitudes towards VR technology (user acceptance, fears, interests), (2) cultural change needs time, (3) informing and involving all the people in the company is difficult, and (4) a lack of resources. Technology-related challenges were: (1) model updates; there is a need to convert models more easily and reduce costs, (2) creditability; it will be gained only 'case by case', and (3) interaction technologies (e.g. eye-tracking, haptics, HMD). Process-related challenges were: (1) the lack of a systematic approach to concept design, (2) the lack of knowledge of how to manage and measure concept design, (3) handling networks, (4) knowing how to use VP (there is a need for instructions on when to use VP and what to evaluate), and (5) no clear plan on how to implement VP.

Based on the discussions, a virtual prototyping implementation maturity model (VIRMA) was developed to support the implementation of VP. The development of VIRMA was based on company studies, our previous experience, findings from the literature, and approaches/theories such as the value chain model (Porter, 1985), design theory (Hubka and Eder, 1988), the systems engineering approach (ISO/IEC-15288, 2008), and Ameri and Dutta's (2005) definition of product life-cycle management. In addition, a "procedure model for developing maturity models" (Becker et al., 2009) was applied. This includes seven categories that are directly connected to VP implementation: (1) understanding business impacts/opportunities, (2) product process, including life-cycle, (3) virtual prototyping process, (4) virtual prototyping technology, (5) enterprise infrastructure, (6) human resources, and (7) enterprise culture and organisation. All the categories can be classified based on a general scale of one to five for maturity levels. These things need to be considered when applying VP in companies.

Using VIRMA, it is easy to measure the current maturity level in companies and to define further development steps in VP implementation. In addition, VIRMA enhances a more systematic and effective use of VP in companies. It is possible that companies will invest in new technologies, but because they do not know how to apply them, the technologies may never be used (investment does not pay back). Companies still needs guidance for implementation. VIRMA supports companies in improving their adaptations of VP and benefitting earlier from VP use in design.

5.4 Suitability of virtual prototypes to support human factors/ergonomics evaluation

The purpose of this study was to understand the suitability of VP to support HFE evaluation during design. A semi-controlled between-group experiment was used in the study. In total, 19 participants from the same company took part in the tests. Most of them were design engineers, but other stakeholders from the product life-cycle were also recruited.

The suitability of the two different virtual prototypes, an AR prototype and a VE prototype, for HFE evaluation was measured. Questionnaires were used as a data-gathering method: an overall assessment of a design object, the suitability of a prototype for HFE evaluation, an unweighted NASA-TLX (Hart and Staveland, 1988) for subjective load experience, and a simulator sickness questionnaire (SSQ) (Kennedy et al., 1993). Content analysis and a T-test in SPSS were used for the data analysis.

The participants' goal was to review the possibility of performing two maintenance tasks on the maintenance platform: a visual check of a feeder of the rock-crushing machine, and an attempt to open a bolt in the machine frame. The use case was an upgrade model of a maintenance platform for a mobile rock-crushing machine (**Figure 16**).

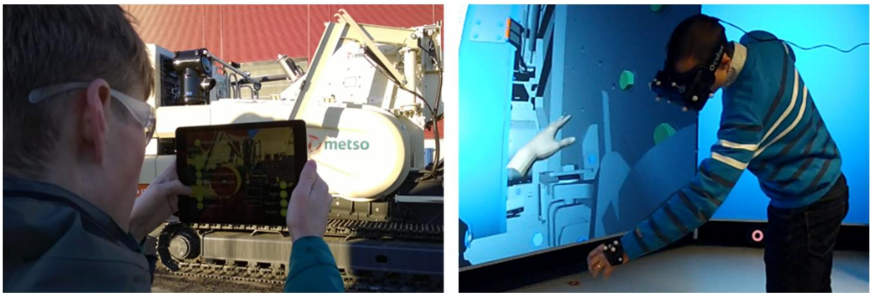


Figure 16. The participant is using an augmented reality prototype and a virtual reality prototype to evaluate a maintenance platform.

The AR system setup included a virtual model of the maintenance platform and the real rock-crushing machine, which was located in the company's back yard. The AR system was made using iPad, Unity 3D, and AR tracking with Qualcomm Vuforia. The VE system included a virtual model of the maintenance platform and also a virtual model of the rock-crushing machine. The hardware and software used were a head-mounted display (Oculus), tracking (Vicon), Unity, and Middle VR.

Two different virtual prototypes (AR and VE prototypes) were used to support the design of an additional part (maintenance platform) for an existing machine. The use of VP provided first-hand (user) experience to the design engineer. In this case study, using VP, design engineers were able to stand on the top of the maintenance platform. They were able to try out maintenance tasks (visual inspection and reaching a bolt to be changed).

The results from this study indicate that both of these prototypes were suitable for the assessment of HFE issues (except for force, environmental effects, and time). The VE prototype was assessed to be better in visibility, reach, and use of tools than the AR prototype. In addition, the use of the VE prototype provoked more comments about design issues than the AR prototype.

5.5 Virtual prototyping systems in design reviews

The purpose of this study was to investigate if the use of VP supports design reviews, and to identify critical issues related to this. In addition, it illustrates a systematic approach to VP design review preparation. The approach was based on a framework proposed by Aromaa et al. (2014a).

Two case studies were made within an industrial company. The developed VP design review template was applied to support systematic preparation and conducting the VP design reviews. During both design reviews, questionnaires and observations were used as data-collection methods. The questionnaires included an overall assessment of a design object and the suitability of the VP system to support design reviews. In addition, adapted SSQ (Kennedy et al., 1993) was used. Thematic analysis (Braun and Clarke, 2006) was used as a qualitative data analysis method.

Ten people (from the company) participated in the first study and eleven in the second (**Figure 17**). Both studies were made in the VR laboratory. Virtual models of a product were provided for the cases (a maintenance platform in the first study and noise encapsulation in the second study). In the first study, participants tried out the system alone. They used an HMD (Oculus), Tracking (Vicon), Unity, and Middle VR. In the second study, stakeholders participated in the design review together. One of them was able to use the HMD, and others were able to see the user's view displayed by a projector. The second setups consisted of an HMD (HTC Vive), an HTC Vive controller, a Leap Motion hand-tracking sensor, Unity, and a projector.

Figure 17. A virtual prototyping design review to evaluate the noise encapsulation of the rock-crushing machine.

To use virtual prototypes efficiently, it is important to define the system model and user interface characteristics carefully. This means that the things that users need to interact with should be provided in the virtual environment (e.g., the 3D model of the bolt needs to be visible if the reach distance to it will be evaluated). In this case study, the interface of the VE system was more natural and interactive than in the AR system; by using an HMD in VE system design, engineers were able to stand on the maintenance platform. With the AR system (tablet PC), this was not possible. Nevertheless, the AR system could be more beneficial when the design engineer needs a fast overview of the additional product and how it fits the machine. Existing machines could have been modified from their initial status, and therefore design engineers cannot rely solely on 3D models when designing new additions.

Two different VP design reviews were analysed in this case study. Design review participants agreed that VP supports design reviews. It was also seen that the developed VP preparation template was useful when designing design reviews. Challenges might come from the timing of the VP design review, conversion of the models, and optimisation of the processes.

The use of VP provided benefits by supporting a common understanding of the design object, and communication and knowledge-sharing between stakeholders. It enabled the first-hand experience of the product for design engineers within a context.

It is important to have a systematic approach to the preparation of a VP session, because it can have an effect on the review outcome's quality. Goals need to be defined carefully and the trade-offs with model design considered thoroughly. The design of user interfaces and system models' static and dynamic characteristics need careful consideration. Especially in design reviews, it is important to pay attention to how the visualisation is generated for the participants. In the second study, HMD visualisation was provided for one user at a time. In addition, other participants were able to see the user's field of view projected onto a screen. In this way, participants are able to discuss the same issues. In addition, the screen view was controlled by using freeze camera views from the VE. This was due to movement in the user's field of view, which may cause sickness symptoms to others.

5.6 Digital human models in human factors/ergonomics evaluation of gesture interfaces

The purpose of this study was to assess whether the use of DHMs by HFE experts can complement user evaluation of gesture interfaces. Two case studies were conducted in which gesture-based systems for remote robot control were evaluated. In total, nineteen participants (researchers and students) took part in the tests.

Data was collected using questionnaires and observation. Participants' performances were video-recorded. NASA-TLX (Hart and Staveland, 1988) and body discomfort were evaluated. Discomfort was evaluated using an open question in the first study and a body map in the second study. In addition, a Rapid Upper Limb Assessment (RULA) (McAtamney and Corlett, 1993) was made by two ergonomic experts using the DHM Jack (Badler et al., 1993). A T-test in SPSS was used for the statistical analysis. The participants' goal was to operate the robot system remotely using hand gestures. The task was to move a small object using the robot system, from location A to location B.

Two different gesture-based interfaces were evaluated: a sensor-based system and a computer-vision-based system. Both systems included the setup supporting the robot and the setup supporting the user. The setup supporting the user was different between the systems (**Figure 18**). The sensor-based system included a jacket with sensors mounted on the sleeve, and a data glove. In the computer-vision-based system, the user's arm was tracked with a depth camera, and a data glove was used. In addition, the interaction metaphor (regarding the tracked arm) was different: drifting metaphor (sensor-based system) and absolute mapping of positions (computer-vision-based system).

Figure 18. Gesture-based interfaces for robot control. The sensor-based system (on the left-hand side) and a computer-vision-based system (on the right-hand side).

Two different gesture interfaces for remote robot control were tested. This study concentrated on the HFE issues related to gestural interfaces. In addition, a VP (DHM) approach was used to support HFE evaluation. More detailed results regarding the differences between the gesture-based control systems can be found in **P6** in the appendices.

The results from the postural RULA analysis made using a DHM were consistent with the users' subjective evaluation of discomfort related to certain body parts. The RULA evaluation also showed that the sensor-based system created more load on the wrist area, and the computer-vision-based system created more load on the lower and upper arm area.

The implications for DHM use in the gesture interface design were provided based on the study. It was seen that VP can also be used for the design of gestural interaction paradigms. The use of the DHM was easy and fast because only a human manikin was required in the evaluation of gesture interfaces. There was no need for any 3D models of a product. Regardless of the easy use of DHMs and their automatic HFE analysis, some challenges were also detected. Small muscle groups (e.g., fingers) were not been able to be evaluated with this DHM software. In addition, some HFE expertise is required to achieve valid results when using DHMs.

6. Results

This chapter presents results from the cross-case analysis of the case studies. The chapter contributes to the challenges described in the introduction to this thesis and related work: the use of VP systems in HFE evaluation is a complex task because it is necessary to design correct VP systems and select suitable HFE evaluation approaches. The chapter addresses four research questions: **RQ1**: What kind of approaches should be used in evaluation of human factors/ergonomics in virtual prototyping? **RQ2**: How should virtual prototyping systems be designed when using them for human factors/ergonomics evaluation? **RQ3**: What are the benefits and challenges of the use of virtual prototyping in human factors/ergonomics evaluation? **RQ4**: How should industrial companies deploy virtual prototyping? The following sections contribute to the research questions accordingly.

6.1 Human factors/ergonomics evaluation approach in virtual prototyping

The HFE evaluation of virtual prototypes has been investigated in several studies, as shown in the work related to this thesis. However, it has not emerged how the HFE evaluation approaches should be selected systematically, especially in a VP context. This section contributes to this challenge by answering the research question:

RQ1: What kind of approaches should be used in evaluation of human factors/ergonomics in virtual prototyping?

This section presents the use of VP in HFE evaluation. First, **Table 5** summarises central issues related to HFE evaluation during VP from the case studies in publications **P1, P2,** and **P4-P6**. It includes descriptions of a user, a task, a product, an evaluation target and a VR technology, as applied in the case studies. These issues are based on the user-task-product model by Pheasant (1996), which tries to have an understanding of systems used. In addition, evaluation goals and used VR technologies are identified in the table. For this summary, only the methods that were used to evaluate the design of a product were included. Evaluations of the virtual prototypes and their use were left out of the table. For example, from **P4**, the suitability evaluation of the AR and VE systems is not included here because it is related to the evaluation of VP systems and not the evaluation of the actual design of a product. These issues are grouped into two groups based on an HFE evaluation approach. The approach is based on the HFE taxonomy of descriptive, experimental, and evaluation-based research (Sanders and McCormick, 1993). The descriptive approach is not included here because it is often interested in characterising a specific population, and is therefore beyond the scope of design engineers' normal PDP activities. **P3** is not considered here because it studied the use of VP in companies' processes and did not include any HFE evaluation sessions.

Table 5. A summary of the human-machine systems (user-task-product), evaluation targets and methods, and used virtual reality technologies from the case studies (**P1, P2, P4-P6**)

Publication	**User**	**Task**	**Product**	**Evaluation target**	**Methods**	**Virtual reality technology**
	Experimental approaches					
P2	Research scientists	Operating a crane: 1. drive the crane up to the containers 2. pick up the first container using the crane 3. lift the container 4. drive the container forward 5. place the container down	A cab of a cargo lifting crane	Visibility from the crane cab	Automated visibility calculation, observation	Mixed reality system
P4	Different stakeholders: design engineers, assembly worker, assembly designer, project leader	Maintenance tasks: 1. visually check a feeder of a rock-crushing machine 2. attempt to open a bolt in a machine frame	Maintenance platform for a rock-crushing machine	Overall assessment of the maintenance platform; is it possible to perform a maintenance task	Questionnaires, observation	Augmented reality system

P4, P5	Design engineers	Maintenance tasks: 1. visually check a feeder of a rock-crushing machine 2. attempt to open a bolt in a machine frame	Maintenance platform for a rock crushing machine	Overall assessment of the maintenance platform: is it possible to perform a task, is it safe, is there enough room, reach distances	Questionnaires, observation	Virtual environment system
P6	Digital human model (P50 male)	Drive robot forward, backward, right, and left	Two gesture-based systems for remote operation of a robot	Physical load	Posture analysis (Rapid Upper Limb Assessment, RULA)	Digital human model software
	Evaluation-based approaches					
P1	Customers	Assembly	Upgrade concept for the rock-crushing machine	Introducing a concept, how to assemble on site	Focus group: discussions and comments based on earlier experience	Virtual environment system
P1	Different stakeholders: assembly worker, design engineers, manufacturing manager, assembly supervisors, design engineers	Assembly	Engine module	Assembly, maintenance, safety, structural problems	Focus group: discussions and comments based on earlier experience	Virtual environment system
P5	Different stakeholders: design engineers, design managers, project leaders, development managers, mechanical engineers, technicians	Assembly, maintenance	Noise encapsulation of a rock-crushing machine	Overall assessment of noise encapsulation, assembly, general feasibility	Focus group: discussions and comments based on earlier experience	Virtual environment system

Table 5 shows that both experimental and evaluation-based approaches can be adopted during VP, because four experimental and three evaluation-based approaches were identified. In the **experimental HFE evaluation approaches**, the user groups varied. In one group, research scientists were test users. In two other cases, the users were from the company, such as design engineers, assembly workers, and project leaders. In addition, in one study, the DHM represented real users. It was specific to the experimental studies that the tasks were described in detail. In three cases, there were stepwise instructions to perform a task. In addition, the fourth case concentrated on the evaluation of critical postures in performing a task. In the studies, three products were a part of a large working machine, and one was a gesture interface for a remote robot operation. These represented three different human-machine interaction conditions: a user was sitting inside a cab operating a crane; a user was standing on top of a maintenance platform performing a maintenance task on a rock-crushing machine; and a user was operating a robot remotely. During these prototyping sessions, different variables were evaluated: visibility, overall assessment, task performance, safety, space, reach, and posture. The HFE evaluation methods used for the assessment of products varied: both subjective and objective approaches were used. In two cases, questionnaires and observation were used to collect users' opinions. Visibility was evaluated automatically using the software. Postural load was also evaluated using DHM software. In addition, it can be seen that a variety of virtuality levels in the prototypes were applied: AR system, MR system, VE system, and DHMs.

In all three **evaluation-based approaches**, participants were stakeholders such as customers, assembly workers, design engineers, assembly supervisors, project leaders, technicians, and different managers. All three of these studies were design reviews. It seems typical that the tasks under study were described in a broad way, such as assembly and maintenance. Products were part of a rock-crushing machine, such as an upgrade concept, an engine module, and noise encapsulation. In these cases, human-machine interaction was not evaluated on such a detailed level. Moreover, in the third case, there was a life-cycle view of human-machine interaction because both assembly and maintenance were discussed. Evaluation targets were: introducing the concept, assembly, maintenance, safety, structural issues, overall assessment, and general feasibility. The focus group was the main method used during these case studies: there was a lot of free discussion and commenting during the design reviews. All of these were evaluated in a VE setup.

Based on the summary, it can be seen that **the selection of an HFE evaluation approach has an effect on VP tests.** Task descriptions, in particular, were different between these groups. In the experimental approach, the tasks were defined on a detailed level. In the evaluation-based approach, the tasks were described on a more general level, and it was possible that there were several tasks from the product life-cycle under consideration. The selected methodologies also differed between these approaches. More specific and maybe laborious methods were used in the experimental approach, whereas the evaluation-based approach relied on expert evaluation. Because of this expert evaluation approach, the user groups also varied a little. In the experimental studies, the user groups varied more; and in the evaluation-based studies, users were stakeholders in the product life-cycle. The same thing happened with the used VP technology: in the experimental approach, it varied more on the virtuality-reality continuum. Because of these findings, two HFE approaches are proposed to be adopted in HFE evaluation during VP: experimental and evaluation-based (**Figure 19**). Both these approaches in VP are discussed more in the following sub-sections.

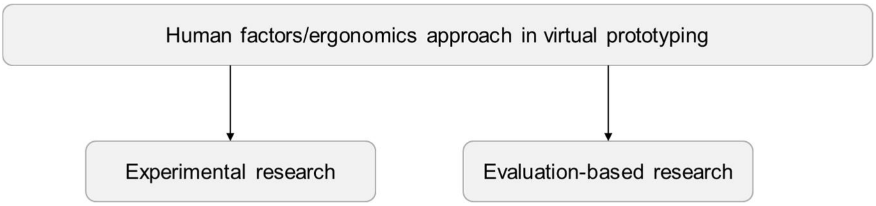


Figure 19. Two approaches to human factors/ergonomics evaluation during virtual prototyping.

6.1.1 Experimental approach in virtual prototyping

The experimental research approach is usually used to test the effects of some variable on user behaviour, workload, or something similar. It measures whether relationships between the system, performance, and human measures are due to random error or if there is a causal relationship between them. Often the system here is a user-task-product entity.

User: Usually, there can be several users participating in the experimental studies. This kind of setup is often more formal and managed by research experts. However, design reviews could also be used for gathering information on the users and stakeholders. This depends on the participants of the design review meeting. It is important to consider which kinds of users should participate. Usually, depending on the goal of the evaluations, expert users provide better results because they are more familiar with the real tasks and requirements in the use of the products. This is especially important when evaluating task performance. Based on the cross-case analysis in this thesis, four typical user groups were identified from which design engineers acquire information. Design engineers can act as users themselves, for example by using an HMD. Alternatively, if the design engineer wants to have a population view (e.g., can a small woman reach, and can a big man fit in the same space) they can use a DHM. Sometimes it is good to have all the stakeholders together to try out the system and share knowledge (e.g., different viewpoints from assembly and maintenance departments). Another possibility is to set up a user study to gather subjective experiences of the product (e.g., when comparing which feature users like the most).

Task: Tasks need to be defined to a certain level of detail during experimental evaluations. It could be useful to adopt task analysis in the preparation phase. Tasks can vary a lot in the experimental studies. They can include sitting, standing, walking, manual handling, and other operations. However, they should be realistic enough for users to be able to perform what is required. This means that the selection of VR technologies should support task performance. In addition, if there are some restrictions on things that do not perform as in the real world, users should be made aware of those (e.g., there is no haptic feedback but the colour of the product will change when there is a collision).

Product: In experimental studies, it is possible to evaluate different products. It is easy to provide virtual prototypes of machines for users to interact with (e.g., a crane cab, a rock-crushing machine). The size of the prototype is not an issue and it is easy to provide virtual prototypes of large machines. Often, it is suitable to use MR systems and provide, for example, joysticks for a user to operate a machine. However, when modelling smaller products in VE, such as hand-held and wearables, this requires more consideration. In these cases, the haptics are still a challenge, and there are also cost-efficiency questions. By using MR systems, some of the issues can be solved. These issues are always related to the target of the evaluation: if the size and shape of a hand-held product are being evaluated, some form of physical prototype is required. However, if the user interface of the hand-held product is being evaluated, VE could be enough.

Evaluation target: The evaluation target is important in every VP session. It provides the foundation for the design of the virtual prototype and the evaluation protocol. It is possible to use VP in experimental evaluations for many purposes: the evaluation of user experience, performance, load (posture), and so on. Experimental studies are especially valuable in the evaluation of interaction and of the whole user-product-task system. These evaluations should aim to gather information from the users.

Evaluation methods: Selected evaluation methods can vary in experimental studies. Questionnaires and observation seem to be the most common data-collection methods. In addition, more specific methods can be used, such as posture analysis RULA. Data can also be collected automatically. In this thesis, visibility was evaluated automatically. In addition, it could be possible to gather data from performance values such as time and errors.

Technology: In experimental studies, it is possible to use a large variety of VP technologies on the virtuality-reality continuum (Milgram et al., 1995). In experimental studies, task performance is essential, and therefore the selected VP technology needs to support the user in performing the targeted tasks. In experimental studies, tasks are defined in more detail, and often they require more interaction with virtual prototypes: more dynamic characteristics in models, means of manipulation for users, task-analysis to understand the context of use, and so on. It is possible to use all the technologies from reality-virtuality continuum to provide the possibility to perform a task. However, based on findings from the cross-case analyses, prototypes closer to the VE were found to be more suitable. Some AR technologies, such as a tablet PC, occupy both hands and may complicate task performance. In addition, users may have to be inside or on top of the virtual prototype to be able to do the task (e.g., a maintenance platform), and with AR technology, this is not possible. Therefore, completely VE or MR environments, in such a way that the controls are real, are usable choices during experimental studies. The experimental approach is often used when studying different variables and their effects on the system. These kinds of studies are easier to do in a laboratory setting. For this reason, higher virtuality-level prototypes are suitable during experimental studies. AR prototypes can also be tested in a laboratory setting, but they are most beneficial when attached to a real-life setting. DHMs can be used in the experimental approach. DHMs can be applied by using them as a desktop version in a PC or testing user groups and gathering postures by using motion-tracking systems. However, the latter is quite laborious, and therefore used more in scientific research settings than in the everyday work of design engineers. Design engineers use DHMs quite a lot during design with a PC, to see if the user can fit and reach things. However, in that case, it could be categorised as more evaluation-based research. In user studies, the maturity of the virtual/mixed prototypes should be at such a level that it is possible to provide equal test conditions for all participants.

6.1.2 Evaluation-based approach in virtual prototyping

Evaluation-based studies are another solid HFE evaluation possibility to use during VP. Evaluation-based research is generally more broad and comprehensive than experimental research. It focuses on an evaluation of a system or a product by comparison with its goals.

User: In most cases, the users are design engineers, stakeholders from the product life-cycle, or DHMs. In evaluation-based studies, design engineers can use DHMs to verify, for example, visibility requirements. In addition, they can use themselves as users and base their design decisions on their expertise in user needs. However, when using the evaluation-based approach, it is important to remember that the knowledge of design engineers and experts does not necessarily equal the users’ needs.

Task: The evaluation-based approach is not such a task-focused approach as experimental studies. It is a more fast-paced and iterative evaluation phase, which means that only some features are checked quickly, changes are made, and maybe the features are checked again. This can be done, for example, by using an HFE checklist. HFE evaluation can also be more comprehensive, because it is possible to evaluate HFE issues related to multiple users from a whole product life-cycle simultaneously.

Evaluation target: The evaluation target here is often the actual product. The target can be to introduce and evaluate new concept ideas or to discuss several issues from the product life-cycle. It is possible to check a small issue quickly (e.g., is the height of the seat correct) or it can be a more general overview of the feasibility of a product.

Evaluation methods: This approach is based largely on the expertise of design engineers and other stakeholders. This approach often includes checklists, requirements, standards, and other information that supports HFE evaluation. The purpose is to evaluate whether certain needs and requirements are achieved. With a DHM, it is also possible to use other HFE methods, such as posture and load analysis.

Technology: In the evaluation-based approach, it is also possible to use different VP technologies from the virtuality-reality continuum (Milgram et al., 1995). The nature of the evaluation-based approach is, however, often iterative and rapid, which aims to check if a design meets its goals. For this reason, the design and development of complex virtual prototypes is not often cost-effective, and therefore, more simple virtual prototypes are suggested. DHMs are a good tool for design engineers to evaluate the population view regarding, for example, fit, reach, and visibility issues. The design engineers can do this quickly and iteratively with their PCs. VEs are also usable here, especially when used for quick checking. Today's technology is mature enough that design engineers are able to switch between 3D-CAD and VE while sitting in their office workplace. Another case in which VE is usable is when conducting design reviews. During the design reviews, different stakeholders can try out the system and discuss and share knowledge. Often in this type of evaluation, the virtual prototype does not need to include all the features, as the case might be when evaluating task performance during experimental studies. However, the virtual prototype may need to include certain characteristics that different stakeholders can evaluate in the product, during the same review session. For example, maintenance and assembly personnel may have different requirements for the product. If a company designs one certain machine, it is easy to provide an MR environment in which the real machine's seat and/or controls are used during VP. AR technologies could also be used here, for example, in a case in which the design engineers are designing an upgrade for a machine. If they have real machines near their offices, it is possible to go and see how the upgrade would look on top of the real machine.

6.1.3 A summary of human factors/ergonomics approaches in virtual prototyping

This section summarises the findings from the use of the experimental and evaluation-based HFE approaches during VP. Both approaches are adoptable in the use of VP in HFE evaluation, and both support a comprehensive view of a designed human-machine system. However, they differ from each other in their nature, and when adopting a certain HFE approach, this affects the selection of model characteristics and VE interface. **Table 6** shows key issues related to the selection of HFE approaches in VP. It highlights, in particular, the differences between the approaches, but tries not to be a thorough guideline, because the selection of suitable HFE methods always depends on many variables and the context of use (Leonard et al., 2006).

Table 6. Key issues related to experimental and evaluation-based human factors/ergonomics approaches in virtual prototyping.

Human factors/ergonomics approach	**Key issues**
Experimental	Task oriented Evaluates users, tasks, products, and their systems Requires more planning (and execution) time Needs interaction in virtual prototypes Needs accurate virtual prototypes Higher fidelity to support task performance Virtual/mixed reality technologies
Evaluation-based	Evaluates the product Uses checklists, standards An overview of the product, not task focused Often only visual cues are provided in virtual prototypes Rapid and iterative in nature Lower fidelity From augmented reality to virtual reality technologies

The experimental approach is more task oriented, and evaluation targets can vary from users, tasks, and products to a whole system of these. For this reason, this approach requires more planning and preparation. In addition, virtual prototypes need to support task performance, and need to be accurate enough and include more interaction. The fidelity level needs to be such that it makes it possible to perform a task. Prototypes of all virtuality levels are suitable for use here, but MR prototypes might be most cost-effective to use (e.g., real controls and a virtual model of the product). MR prototypes provide a good basis for interaction and task performance.

The evaluation-based approach focuses more on evaluating the product by using, for example, checklists and standards. The evaluation can be more general and not so focused on the tasks. Therefore, the evaluation can be based more on using visual cues. In that sense, virtual prototypes does not necessarily need to be so interactive. It is rapid and iterative in its nature. Compared to experimental studies, lower fidelity prototypes are often enough. Virtual prototypes can vary in their virtuality level, from AR to VE use.

The use of experimental and evaluation-based research is common in the HFE discipline, but to adopt it during VP is novel. In addition, it is a novel approach when trying to enhance understanding regarding HFE evaluation in VP. These kinds of discussions are currently missing from the research community. There are studies related to the topic, but no systematic guidelines or standards exist. Therefore, the thesis addresses this topic of the HFE evaluation of a virtual prototype.

6.2 The design of virtual prototyping systems

Based on the related work, there are a few approaches to designing VEs. It can be seen that the design of VEs is a complex task, and it becomes even more complex when designing VEs to be used in VP. There is a need to understand what it means when moving from the design of VEs to the design of VP systems. This section contributes to this topic by answering to the research question:

RQ2: How should virtual prototyping systems be designed when using them for human factors/ergonomics evaluation?

This research question is addressed by presenting a VP design process and a VP design template in the following sections. These both enhance the understanding of the design of VP systems, and make VP design more systematic.

6.2.1 Virtual prototyping design process

Based on the case studies, primarily in **P5** and the literature review, it can be said that there are many approaches to designing a virtual prototype system. **Figure 20** presents a simplified illustration of the VP design process which synthesises and expands current approaches (Aromaa et al., 2014a; Bordegoni and Ferrise, 2013; Eastgate et al., 2014; Stanney et al., 2003). This synthesis does not try to be a thorough process description but rather highlights the issues that need to be considered when designing VP systems; in other words, the way the design of VP systems differs from the design of VEs. These particular features are highlighted in **Figure 20** using thicker outlines. Eastgate et al. (2014) describe a detailed process for the development of a VE, from project definitions and requirements analysis to verification and validation phases. This section complements that by considering design especially from prototyping and HFE evaluation points of view, and gives practical guidance for design engineers.

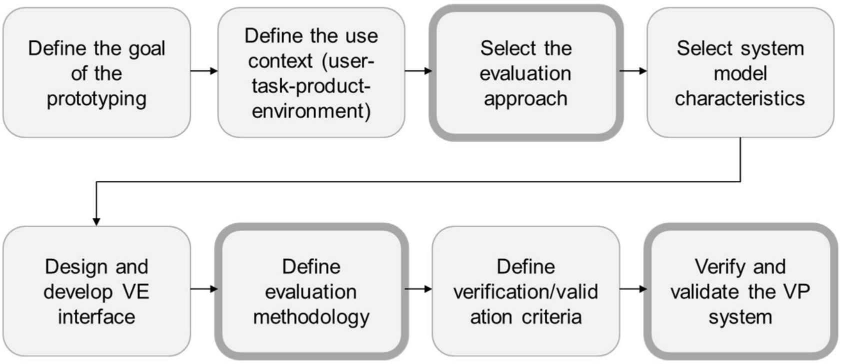


Figure 20. Design process for virtual prototyping systems.

In general, when designing VP systems for HFE evaluation, it is important to consider and design several different matters before the actual evaluations (**Figure 20**). The development of virtual prototypes always starts by defining **the goal of the prototyping**, for example that the assembly of the product needs to be evaluated. This is the most important step in the process because it defines the success of the final use of the virtual prototype in HFE evaluation. The next step is to **define the context of use**: who will be the users, what is the task, what product is used, and in which environment. The context of use could be, for example, an assembly worker who needs to assemble an engine in a factory. After this, it is necessary to consider the questions that prototyping will answer. This means that **evaluation approaches** (experimental and evaluation-based) need to be chosen. When taking a correct HFE approach, it is also important to consider whether design engineers will evaluate the product themselves as users, use DHMs, apply a design review with many stakeholders, or use user studies with several participants. Then it is time to build the VE interface and system model. **The system model** includes 3D models of the product prototyped, the environment in which it is used, and human-related models. Human-related models can be full-body DHMs, or only users' hands and shoes can be modelled from the human body (e.g., in **P4**). These models have static and dynamic characteristics. The static characteristics can mean, for example, shape and colour, whereas dynamic characteristics could be moving parts and parts that can be shown/hidden during VP. The **VE interface** includes software and hardware, which provide users with sensory feedback and means of manipulation. This stage defines the visual, auditory, and haptic cues, and navigation, manipulation, and wayfinding systems. At this stage, it is good to consider in more detail the **HFE evaluation methodology**: the methods that will be used and the evaluation procedure. When the VP system is constructed, it needs to be **verified and validated** that its fidelity level and other features are suitable for the evaluation goals of the prototyping stated in the beginning. It is also important that immersion and presence levels are correct and the usability of the system is good. In addition, it is good to test comfort issues beforehand, and possible sickness and after-effects that may occur. However, these issues also need to be monitored during the actual tests. This phase includes the evaluation of the selected HFE methods and procedure.

In the process, all the steps are important. However, the issues that are relevant to the design of VP, but which are normally not included in the design of VEs, are highlighted. It is critical to consider these steps when designing VP systems. For example, different HFE approaches require different features on a VE interface and models. The novelty of this VP design process lies in synthesising current models and expanding them, especially with VP and HFE issues. This means that many approaches, currently, focus on the design of the VE and do not consider the issues related to VE use in prototyping. When VEs are used in prototyping, test and evaluation procedures also need to be considered thoroughly.

6.2.2 Virtual prototyping design template

There are not many studies that consider the practical application of the VE/VP design approaches proposed in the literature. This means that these approaches are not adopted by the industry for everyday use. However, this kind of systematic approach could support the critical knowledge-sharing that happens during the design of VP systems. For example, in **P5**, it was seen that, due to the loose goal statement, the virtual model did not have all the features to enable proper evaluation.

For this reason, a VP design process was extracted to a virtual prototyping template to support systematisation and knowledge-sharing during the design of VP systems (**Table 7)**. The VP design template can be used, in particular, for the preparation of VP design reviews (**P5**). The most important thing in the VP design template is to define the goal of the virtual prototyping session, and then to carry on developing the VP system (by defining a design object, a task/activity, static and dynamic model characteristics, sensory modalities, means of manipulation, used VR technologies, and test models). The VP design template also serves as documentation of the VP setup.

Table 7. A virtual prototyping design template to support systematisation and knowledge-sharing during the design of virtual prototyping systems (**P5**).

Virtual prototyping template		
Date		
Goal		
Design object		
Human	Task/activity	
System model	Static model characteristics	
	Dynamic model characteristics	
Interface	Sensory modalities	
	Means of manipulation	
Technology	Virtual reality technologies	
Test models	Evaluation methods and tools	

The VP design template is a basic tool for design engineers, but its novelty is in simplifying the approaches into practical and usable form. Currently, these practical tools are missing from the industry. In addition, it forces people to work systematically when designing VP systems, and enhances knowledge-sharing between people involved in the VP system design process. It was seen in the case studies that if a goal statement for design reviews is too loosely defined, it might diminish the results of the prototype evaluation (**P5**). In addition, this kind of systematic VP design template could contribute to the VR research community by providing a systematic way to document and publish VP systems used during the studies.

6.3 Benefits and challenges of the use of virtual prototyping in human factors/ergonomics evaluation

The benefits and challenges of VP use in companies have been discussed in the literature. VP has been considered as an effective prototyping solution that can overcome the shortcomings of conventional prototyping methods (Karkee et al., 2011; Kulkarni et al., 2011; Seth et al., 2011). However, there are still some research challenges to overcome, such as the narrow field-of-view in HMDs when evaluating HFE issues (Berg and Vance, 2016). This section concentrates on understanding the particular advantages that VP can provide for HFE evaluation and challenges that need to be considered. This topic is addressed by recognising key benefits that are specific to VP use in HFE evaluation. In addition, challenges are recognised in the use of VP in HFE evaluation. This section contributes to this topic by answering the research question:

RQ3: What are the benefits and challenges of the use of virtual prototyping in human factors/ergonomics evaluation?

6.3.1 Benefits of the use of virtual prototyping in human factors/ergonomics evaluation

General benefits related to use of VP in PDP can be found from the case study in **P1**. This section concentrates, especially, on benefits related to the use of VP in HFE evaluation, and therefore, it synthesises findings thematically from all the case studies (**P1-P6**).

The key benefit of the use of VP in HFE evaluation is that it makes it possible for **real end-users to participate easily** during the PDP (**P1, P4, P5**). If users participate in PDP user/customer acceptance and satisfaction with the final product will increase. Participation also increases understanding of user needs and, therefore, the quality of the final product improves. This means better ergonomics and usability, and more efficient task performance. Leino (2015) agrees that the use of VP enables better integration of the HFE approach into product design and development. VP can provide cost savings, for example, by decreasing the number of physical prototypes and by decreasing time-to-market.

The use of VP is more **illustrative** than the use of more traditional design tools, such as 3D-CAD (**P1, P3, P4, P5**). It is easier for users and other stakeholders who are not familiar with 3D models to immerse themselves in a VE. It decreases the need to visualise things in users' minds. In addition, the experience in a VE can be more **interactive**, which increases the realistic experience of the use of the product (**P1, P2, P4, P5**). In a VE, realism is also increased because it is easy to add the environment in which the product is normally used. This is not necessarily an assumption when working with physical prototypes. VP makes the design of a product **more concrete and realistic**, because even large machine models can be of real size (**P1, P2, P4, P5**).

The use of VP **increases understanding** of many things (**P1-P6**). It makes it easier to understand a product's complex nature and its dimensions and functions. It also makes it easier to understand user needs, requirements, and experiences. Understanding of the use of the product may also increase. According to Ma et al. (2011), the VE is a useful tool for supporting complex product design.

When VP is used during design reviews and the participatory design approach, it brings several stakeholders together. When they have the same image of a design in front of them, it is easier for them to **communicate with each other and share knowledge (P1, P5)**. This improves the HFE features of the product, if all the different expertise is acknowledged during the design. Other studies have also found that the use of VP supports communication and interaction between different stakeholders (Bordegoni et al., 2009; Bordegoni and Caruso, 2012; Davies, 2004; Kremer, 1998; Leino, 2015; Shen et al., 2010).

There is also a life-cycle view on this. The use of VP makes it possible to **recognise the needs of different users in the product's life-cycle (P1, P4, P5)**. It is possible to consider many tasks during the life-cycle (e.g., using the same virtual prototype, it is possible to evaluate the use, assembly, and maintenance of a product). In the PDP, the benefits derive from the possibility to use VP in many design phases, from concept ideation to testing. Especially when used early in the PDP, bigger benefits could be achieved. VP makes it **easy to try out futuristic concept ideas** that it might still not be possible to create physically (**P1**).

VP is a safe alternative for evaluating HFE issues in early design phases. Especially with large machines, it could be difficult to build physical prototypes, and sometimes those prototypes do not meet all the safety regulations. For example, building a physical prototype of a maintenance platform could be difficult, but by using a virtual prototype, there is no fear of falling off the platform. In addition, the actual work tasks may include safety issues, which are easy to consider with virtual prototypes. For example, there is no fear of cutting a hand by accidently touching a machine's gearwheel in the VE. Therefore, VP supports **the evaluation of safety-critical tasks (P2, P4, P5, P6)**.

In experimental studies, users' subjective experiences or performance are under consideration. By using VP, it is easy to create several conditions with different variables for users to test. It is easy and rapid to change virtual model features during the VP session. This makes it **easy to compare different product features** (**P2, P6**).

The use of VP in HFE evaluation **supports both self-report and observational HFE evaluation approaches**. Because test participants are able to perform a task in VE, it is possible to gather their experiences by using self-report methods for example questionnaires **(P1, P2-P6)**. In addition, while test participants are performing the task, it is possible to gather observational data **(P1-P6)**.

Previous benefits were related mostly to the use of VE and MR prototypes, but DHMs provide other types of benefits. They are beneficial, especially, when evaluating **a population view (P6)**. They include different sizes of human models, so it is easy to make sure that small-size women can perform the same tasks as large-size men. This supports the "design for all" approach. In addition, when using DHM software, it is possible to use **automatic HFE evaluation methods**, such as field of view, energy expenditure, fatigue limits, and posture analysis (**P6**). These are rapid assessment methods, and design engineers could use them to enhance their understanding of HFE issues related to a design object. Perez and Neumann (2015) agree that the DHMs are useful in HFE evaluation, for example in calculating ergonomic limits, and identifying risks of injuries and musculoskeletal disorders. Despite the easy use of analytical methods, it is important to consider HFE evaluation results carefully, or even under the supervision of ergonomics experts. In addition, the use of VE/MR systems could support **easy data collection** by collecting, for example, time, errors, and distances automatically (**P2**).

It was found that VP is usable in HFE evaluation. It was possible to evaluate, among other things, visibility, posture, reach, space, use of tools, behaviour, activities, performance, larger muscle groups, assembly order, and gesture interfaces, and to compare design solutions (**P1-P6**). In summary, it can be said that all the key issues in HFE evaluation of user-task-product (Pheasant, 1996) can be considered during VP. **VP makes it easier to involve real users, to perform real tasks in a real context, and therefore, to improve the final product and its use.**

6.3.2 Challenges of the use of virtual prototyping in human factors/ergonomics evaluation

There are also challenges to consider when using VP in HFE evaluation. It can be challenging **to select suitable methods** to be used and in addition, methods are not automatically available in all cases. In DHMs **(P6),** there are different HFE evaluation methods provided in a toolkit. However, in many cases when using VP during design reviews **(P1, P5)** and user studies **(P2, P4),** there are not any HFE evaluation methods ready to apply. This requires knowledge about HFE methods. In addition, when using VP in HFE evaluations, it is important to consider **the target of the evaluation**: is it the product (Bordegoni et al., 2009; Lawson et al., 2015; Roland Örtengren et al., 2009) or the VR system (Kalawsky, 1999; Wilson, 1999). In addition, in many cases, the studies include both aspects.

It can be challenging **to select the right test participants** for the HFE evaluation. In **P1, P3-P5** there were end users and other stakeholders participating in the VP use. In **P2** and **P6,** there were research scientists and students. It depends on the research questions which kind of user groups should be applied. In addition, the mobilisation of several stakeholders can be difficult in terms of **time and from a financial standpoint**. During design reviews in **P1** and **P5,** all the company stakeholders came to the research institute's VR facilities, which is an extensive effort from the companies.

When a certain user group is used in the HFE evaluation, it is possible that **the whole population view** is not acknowledged. In **P2** and **P6,** real end users were not used, which can also have a negative effect on the results. In addition, the small number of participants may bias the HFE evaluation results. The same can happen if the user group is too homogenous or heterogeneous. In addition, if design engineers are using VR technologies by themselves during the design, it is possible that it reinforces a “design for me” approach. For example, in **P4,** design engineers acted as maintenance technicians on top of the safety platform. In this case, design engineers compared the height of safety railings against their own body sizes. This may bias the HFE evaluation results because in using this method, the design engineers do not acknowledge the heights of the general population.

It has been recognised that VP is an easy way to allow real end-users to participate in product design. However, it is always possible that especially long-term use may lead to **indirect and direct effects on users** (Viirre et al., 2014). In case studies **(P1-P2, P4-P5)**, no major simulator sickness symptoms were recognised, however, it is important to consider that it may have an effect on HFE evaluation results.

One challenge of VP use in HFE evaluation is to select **the most suitable virtuality** (Milgram et al., 1995) **and fidelity levels** (Bordegoni et al., 2009) for the virtual prototypes. If the virtual prototypes do not provide proper interaction and task performance possibilities for users, it is possible that HFE evaluation results are incorrect. For example, in **P4,** the use of a safety platform was evaluated but, it was not possible to climb the stairs on top of the safety platform. Therefore, the climbing was not evaluated in the study regardless of whether it is a critical part of the safety platform use. In addition, in **P6,** it was not possible to evaluate small muscle groups (fingers) by using DHMs, although, fingers were an important part of the gestural interfaces. It has also been seen in other studies that inconsistencies between real and virtual environments may lead to different HFE evaluation results (Hu et al., 2012; Pontonnier et al., 2014; Wu et al., 2012).

The timing during PDP is one challenge to be able to gain the benefits of VP use in HFE evaluation. In **P6,** the DHMs were used after construction of the gesture interfaces and user evaluations. This was due to research purposes, but in practice, VP is most beneficial when used in the early design phase (Chaffin, 2007; Demirel and Duffy, 2007). In addition, it is possible that the building the virtual porotype might be too **challenging and time-consuming** and is not flexible enough to support rapid iterative design. In **P5,** there was already an outdated version of the product in the design review. According to Perez and Neumann (2015), time is considered to be a motivational or deterring factor for the use of the virtual human factors tools. In addition, Berg and Vance (2016) say that the conversion process is still one of the research challenges in the use of VP in product design.

Previously in the benefits section, it was stated that the use of VP is illustrative when imagining things that do not exist yet and when performing real tasks. However, it is not always straightforward to use VP. If the stakeholder group consists mainly of design engineers **(P4 & P5),** they usually have a good understanding of 3D images and the use of VP could be an unnecessary **effort**.

One challenge is the multidisciplinary nature of VP use in HFE evaluation, which leads to a **need for versatile expertise**. Rarely one person can design VP setup by himself/herself and then perform HFE evaluation. In the use cases (**P1-P2, P4-P6**), there were people who were experts in VR technologies and people who were experts in HFE evaluation. Therefore, when using VP in HFE evaluation, it is important to consider the teams that need to be established around the topic. According to Berg and Vance (2016), there are five unique responsibility roles in VP use: maintainer, operator, user, builder, and manager.

6.4 Deployment of virtual prototyping at company level

Berg and Vance's (2016) review of VP use in product design and manufacturing shows that VP is currently actively used in industry. However, when they discussed this with companies, they found that it is challenging to start up and maintain the VR effort in companies. It is typical that all the industrial companies have learned themselves to design and use VP systems, and integrate the use into their PDP. This is because there are no VP deployment guidelines available. This issue is addressed in this thesis, because it is important for VP use in HFE evaluation: the company-level issues related to VP provide a foundation for HFE evaluation. This section contributes to this topic by answering the fourth research question:

RQ4: How should industrial companies deploy virtual prototyping?

It was discovered during the case study in **P3** that companies have different kinds of approaches when they implement VR technologies. Some companies may buy VR technologies first, and then integrate their use into their processes, and others can do vice versa: consider the processes first and then deploy the technologies. For this reason, it is important to have a holistic approach to implementing VP in companies, rather than one stepwise process that all companies should follow. The "virtual prototyping implementation model", VIRMA, was developed to address this in **P3**. It supports all kinds of companies in different situations regarding implementing VP. It helps companies to understand their current situation in adopting VP, and focuses on developing those areas that need more consideration. For example, it is possible that a company has invested in VR technology and facilities, but has not nominated human resources to take care of them. For this reason, it is possible that the VR system will remain unused. This approach highlights that it is not enough to invest in novel technologies to achieve business benefits. The benefits are obtained only by a comprehensive effort from the companies.

During the development of the VIRMA model, seven categories were identified that are critical in VP implementation by companies. The categories are based on the workshops within the two companies involved in the **P3** case study, and on the related literature. The categories are:

- understanding business impacts and opportunities of VP
- defining the current PDP
- describing and integrating VP in PDP
- understanding VR technology maturity/capabilities
- providing facilities to support VP
- nominating human resources to be responsible for VP
- provoking positive attitudes towards VP within the organisation

All the categories can be classified based on a general scale of one to five of maturity levels (five is the optimal level and one is an unstructured/basic/non-existent level). **Figure 21** illustrates an example of the maturity level of a company in implementing VP. In this example, it can be seen that the company has defined its PDP very well and has a flexible VR system that supports several design purposes. They also have experts who know how to use the VP system, and attitudes towards the use of VP are positive. Understanding business benefits and provided infrastructure are almost at maturity at level three. In this example, most work should be put into integrating VP use in the PDP, because now it is used intuitively during the design of a product. By applying VIRMA, it is possible to achieve a solid foundation by which it is possible to use VP for HFE evaluation.

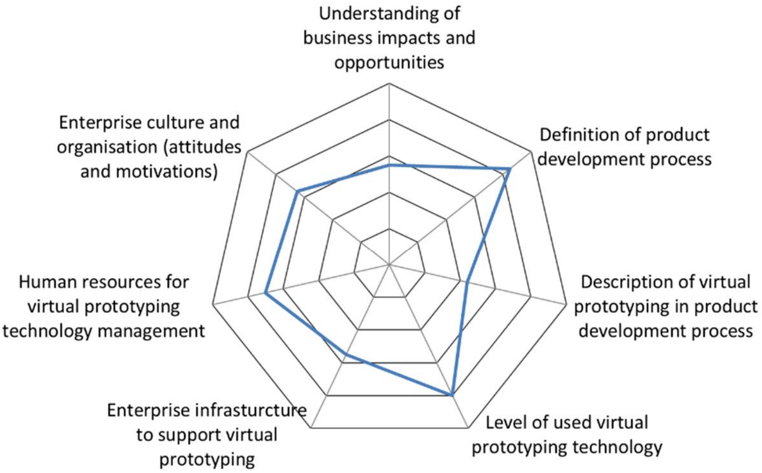


Figure 21. An example of a level in the virtual prototyping implementation maturity model (VIRMA) (**P3**).

The VIRMA model is a thorough approach for understanding key aspects of VP implementation. It considers the issues inside companies. However, other case studies (**P1, P2, P4-P6**) in this thesis were investigated in cooperation with a research partner's VE facilities. In these cases, the level of VR expertise was high, as well as the VR technology maturity level. Nevertheless, this cooperation aspect brings another branch that companies need to consider. If companies want to use subcontractors when using VP, it is easy to achieve good maturity levels in expertise and technology, but it might be challenging to integrate VP use into the PDP. In particular, timing and knowledge-sharing may become an issue.

The novelty in VIRMA is that there is no other maturity model, to our knowledge, that has VP as a central topic. Similar issues that are highlighted in the model are discussed in the study by Berg and Vance (2016). However, they concentrated more on defining the current situation, and challenges in companies, than on providing guidelines. The VIRMA model provides a holistic view of VP and enhances understanding of the key issues when deploying VP for company use. Another novelty here lies in the VIRMA model's approach. This kind of sectorial approach is more suitable for different companies than any traditional stepwise process description. It provides companies with a possibility to understand their current situation in all seven categories, and then to decide how they want to proceed with the deployment of VP. This is important because companies are very different from each other.

6.5 Summary of the results: The model of human factors/ergonomics and virtual prototyping

Previous sections addressed the research questions **RQ1-RQ4** by introducing the HFE approach, the VP design process, the VP design template, benefits and challenges of VP use in HFE evaluation, and the VIRMA model. These all consider a certain topic related to VP use in companies and in HFE evaluation: how to use VP in HFE evaluation, how to design VP systems, what the benefits and challenges of VP use in HFE evaluation could be, and what is expected from companies when implementing VP. These issues are not separate entities, but closely interconnected with each other. This is important to acknowledge when using VP in HFE evaluation. For this reason, a model of human factors/ergonomics and virtual prototyping is proposed (
Figure 22).

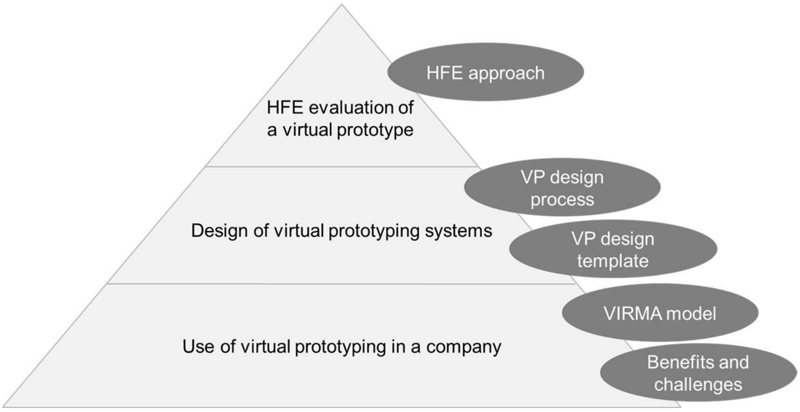


Figure 22. The model of human factors/ergonomics (HFE) and virtual prototyping (VP) describes three key elements related to VP use in HFE evaluation. The contributions of this chapter – HFE approach, VP design process, VP design template,

and virtual prototyping implementation model (VIRMA) – help in comprehending the elements.

The model includes three key elements to consider. The first element, at the bottom of the model, presents how companies need to be prepared for the use of VP. This can be achieved by using the VIRMA model. In addition, understanding the benefits and challenges that VP can bring to HFE evaluation is important. The second element describes the design and development of VP systems. The VP design process and VP design template can support this phase. The third element describes the actual HFE evaluation of virtual prototypes. The presented HFE approach supports this phase by proposing two strategies for HFE evaluation. The HFE/VP model is drawn as a triangle to illustrate correlations between the three elements: to be able to use VP for HFE evaluation, the foundation at company level needs to be in order, and the VP systems need to be designed accordingly. Only by ensuring that these two bottom elements are in order to evaluate HFE and gain valid results from it.

The novelty in this HFE/VP model is in taking a comprehensive view of the use of VP in HFE evaluation. It considers VP use broadly at a company level, and it takes a more systematic approach to VP design, and enhances understanding of HFE evaluation during VP.

7. Discussion and conclusions

The goal of this thesis was to gain an understanding of the use of virtual prototyping (VP) in human factors/ergonomics (HFE) evaluation. The research belongs to HFE discipline and the focus is in the intersection of HFE and VP. This thesis synthesises findings from six case studies made in the manufacturing industry. These case studies were published in six publications, which are included in the appendices of the thesis. This chapter describes the contributions of the research. Then it discusses the validity of the research and suggests future research topics. Finally, the chapter concludes the thesis.

7.1 Contributions of the research

This section describes the contributions of the research by research questions (**RQ1-RQ4**) and at theoretical and practical levels.

7.1.1 Contributions by research questions

The main contribution of this thesis is an HFE/VP model that can be applied when using VP in HFE evaluation. The HFE/VP model answers the research questions of this thesis: **RQ1**: What kind of approaches should be used in evaluation of human factors/ergonomics in virtual prototyping? **RQ2**: How should virtual prototyping systems be designed when using them for human factors/ergonomics evaluation? **RQ3**: What are the benefits and challenges of the use of virtual prototyping in human factors/ergonomics evaluation? **RQ4**: How should industrial companies deploy virtual prototyping?

The novelty of the HFE/VP model lies in systematising the use of VP in HFE evaluation. It systematises its use by providing a VIRMA model that identifies key components that need to be considered when companies want to implement VP **(RQ4**). This forms a basis for VP use in industry. In addition, it enhances understanding of the key benefits and challenges that can arise when using VP in HFE evaluation **(RQ3)**. This improves the understanding of the value companies can gain from using VP in HFE evaluation. Then, the HFE/VP model expands different approaches of the design of VP systems in a VP design process **(RQ3)**. The novelty of the VP design process is in extending design approaches from VE design to VP design, which means that, in particular, HFE evaluation of prototypes is acknowledged. In addition, from the VP design process, a practical VP design template is extracted. The template simplifies the design process and makes a suggestion of how, usually, quite theoretical and complex VP design approaches could be made usable in everyday life. Finally, the HFE/VP model introduces an HFE evaluation approach that could be used during VP **(RQ1)**. It is based on a traditional taxonomy of HFE methodologies. However, the novelty here is that these taxonomies (experimental and evaluation-based approaches) have not previously been adopted in such an approach during VP.

7.1.2 Theoretical contributions

This thesis contributes to the sociotechnical systems theory by introducing the HFE/VP model. The HFE/VP model supports the theory's key theme of joint optimisation of systems during the design. By using the HFE/VP model it is possible to involve users in early design phase to be able to evaluate the performance of whole human-machine systems, and not only parts of it. Eason (2014) says that it is important to apply conceptual tools and design practices to improve the delivery of sociotechnical systems.

The HFE/VP model contributes to knowledge in the HFE discipline and VR research community by illustrating a comprehensive view of VP use in HFE evaluation. It has been seen from the literature how complex and dispersed VP use in HFE evaluation can be with several individual studies (e.g., Bordegoni and Caruso, 2012a; Regazzoni and Rizzi, 2013; Roland Örtengren et al., 2009). The HFE/VP model illustrates the comprehensive view by describing three key elements of VP use in HFE evaluation. In addition, it proposes more systematic ways to adopt and use VP in HFE evaluation.

The differences between designing and evaluating VE and VP systems needs more attention in the VR research community. The HFE/VP model contributes to this topic by focusing on the key issues in evaluating a product in VEs. This topic seems straightforward, but often the research in the VR area concentrates only on developing VR systems (e.g., Kalawsky, 1999; Stanney et al., 2003; Sutcliffe and Gault, 2004). This fundamental understanding is important because the research construction is different when evaluating the HFE of the VE, or the HFE of a product, using virtual prototypes. The goals of data collection methods differ in these approaches. However, both kinds of approaches can be used during the same study. This thesis contributes to the development of HFE issues in products, and not HFE issues in VR technologies.

The HFE/VP model contributes to the HFE discipline by introducing VP as an approach to support HFE consideration early in the PDP and in a realistic context. Dul et al. (2012) requested strategic actions "*to strengthen the application of high-quality HFE*", and ISO 9241-210 (2010) requests that "*even at the earliest stages in the project, design concepts should be evaluated to obtain a better understanding of user needs*". The VP approach makes it possible to take a more proactive approach to HFE evaluation, and this supports Dul et al.'s (2012) idea that HFE is design driven. Using VP, it is easier to integrate knowledge regarding human performance in the design process. In addition, Czaja and Nair (2006) say that "*the focus in HFE is on studying performance within the context of tasks and environments*". Virtual prototypes are beneficial when providing not only the prototype of the product but also a virtual model of the environment. This type of contextual approach is often lacking from the physical prototypes in early phases of the PDP.

This thesis also contributes to the HCI discipline by enhancing understanding of digitalisation and emerging new technologies: design engineers' tools are changing from traditional PCs to interactive multimodal interfaces. In addition, the thesis enhances understanding of the design of new interaction paradigms (e.g., gesture-based interfaces) using VP.

The HFE/VP model contributes to the use of VP in cooperation and knowledge-sharing. It can contribute as an approach that can be used for knowledge-sharing, collaboration, and learning. This supports the principles of the participatory design approach (Ehn, 1993; Muller and Kuhn, 1993). In addition, it supports the theory of organisational knowledge creation by Nonaka (1994). Nonaka's (1994) theory discusses tacit (“hidden”) and explicit (“visible”) knowledge, and how the knowledge converts from tacit to explicit to tacit. A participatory approach that uses VP supports the conversion of tacit knowledge, which is hidden in the organisation, to become explicit to all.

7.1.3 Practical contributions

The HFE/VP model also makes practical contributions. VIRMA can be used as a practical tool for companies when implementing VP. There are currently descriptions of VR use processes (e.g., Berg and Vance, 2016). VIRMA is a novel approach compared to these because it takes account of the fact that companies are often different in their nature. This means that it is not possible to produce one process flowchart in which the implementation of VP is described. Companies have different PDP processes and practices. VIRMA provides a possibility for all companies to understand the key issues related to the implementation, and to recognise the issues they should develop further.

The VP design template is another practical contribution of this thesis. The novelty in it is that it tries to simplify the current VP design approaches into practical and usable form. Quite often still, there is a lack of efficient processes in companies, which include the use of VP during the PDP. Therefore, this template assists people in working systematically when designing VP systems, and it enhances knowledge-sharing between people during the VP system design process. Regardless of the several approaches to support the design and use of virtual prototypes presented in Chapter 2 (Aromaa et al., 2014a; Bordegoni and Ferrise, 2013; Chung et al., 2002; Eastgate et al., 2014; Ferrise et al., 2013; Mahdjoub et al., 2013; Wang, 2002), there is still a need to streamline the VR use process (Berg and Vance, 2016). The proposed VP design template is a derivative from the VP design model, especially to be used before design reviews. It emphasises that goal-setting for VP design reviews is important. The establishment of design review objectives is a standard procedure (IEC-61160, 2005), but when using virtual prototypes, its value increases. If goal-setting is not clear, the validity of HFE evaluation may decrease. In addition, the building of virtual prototypes requires a certain effort, and without clear goal-setting, it could just hinder the PDP.

The proposed HFE approach in VP makes practical contributions. In current research regarding the use of VP in HFE evaluation, there is not much consideration and discussion of how to select suitable HFE evaluation methods. The studies often consider the virtuality and fidelity of prototypes (Bordegoni et al., 2009; Pontonnier et al., 2013), and reliability and validity of HFE evaluation (Hu et al., 2012, 2011; Lawson et al., 2015; Pontonnier et al., 2013; Wu et al., 2012). The proposed approach gives guidance when selecting a suitable HFE evaluation approach during VP. It is a traditional approach in HFE research, but it is novel when applied in VP. The approach includes the selection of experimental and evaluation-based approaches when designing VP systems. It formalises the process and highlights key issues related to the selection of methods, participants, and prototypes (fidelity, virtuality). This supports design engineers and other experts in designing and conducting HFE evaluations during VP.

Identified benefits and challenges of the use of VP in HFE evaluation enhance understanding in industry and also in the research community. Recently, the use of VR technologies has increased in industry (Berg and Vance, 2016), but it is still a novel tool to apply. Therefore, the benefits and challenges from its use, especially in HFE evaluation, are not recognised fully yet. This thesis contributes to this by identifying key benefits and challenges.

7.2 Validity of the research

The validity of research means how trustworthy the results are, and to what extent they are not biased by the researchers' own opinions. The validity of research can be addressed in many ways. In this thesis, it is done by using four different validity categories: construct validity, internal validity, external validity, and reliability (Runeson et al., 2012; Yin, 2013).

Construct validity means that the used measures really represent what the researcher had in mind. In this research, it was important to keep in mind the difference between developing VEs and applying them. This is important when evaluating HFE issues in VP. Therefore, question construction and the interpretation of the results were done carefully. In many case studies, there were several researchers taking part in the research, and data-collection methods were discussed before applying them. In addition, multiple sources of evidence and different data-collection strategies were adopted (data source triangulation).

Internal validity is related to the causal relationship between conditions. It means that there are more factors that affect the investigated issue, but the researcher is not aware of this. To minimise internal validity issues, a simulator sickness questionnaire (SSQ) (Kennedy et al., 1993) was used. In a VE, it is possible to experience simulation sickness symptoms, and this can affect the user's performance, and therefore the results of analysis. In addition, tasks for the users in case studies were designed to be simple and easy to learn, to minimise the effects of complex task performance. Every test setup was recorded by making notes or using a video camera to find out if there were any extra affecting factors. In addition, two or more research scientists took part in the case studies. In this way, it was easier to detect any extra factors affecting the results. Even though VR technology has matured and developed over the years, it still cannot provide a full multisensory product experience (Ferrise et al., 2015). Therefore, when using VR technologies in HFE design, it is important to consider how the technology constraints affect the results (e.g., the lack of haptic feedback). These technology challenges were always documented and taken into account during the data analysis phase.

External validity concerns the extent to which it is possible to generalise the findings from the research. The case study approach investigates a specific instance in depth (Lazar et al., 2010; Yin, 2013). This is challenging when generalising the results. For this reason, four different companies were investigated in the six case studies in this thesis. All of them were industrial manufacturing companies (rock-crushing machines, underground drilling machines, cargo handling, and aerospace). Investigated work tasks in the case studies were related to assembly, maintenance, operating a machine, and tele-operating a robot system. Test participants also varied: university students, research scientists, customers, and many different stakeholders from the product life-cycle (e.g., design engineers). There were both novice and expert users. Even though the case studies focused mainly on industrial products, there was a variety of test setups, tasks, participants, and products. For this reason, the main findings from this thesis could be generalised to be of interest to other people (in the manufacturing industry).

Reliability means how well the same results can be achieved using the same instruments and methods later. As mentioned, all the case studies were done carefully, collecting all the information during the studies, and with multiple researchers working together. Cooperation improved the validity of research design, data collection, analysis, and interpretation. Investigator triangulation was used when using DHM in **P6** (two ergonomics experts did the same RULA analysis independently). The used VP systems were documented carefully because they could have had an effect on the results of the study. In addition, the documentation of the VP systems supports the possibility for other researchers to replicate the studies.

7.3 Suggestions for future research

This thesis proposed systematic ways to use VP in HFE evaluation. However, this thesis is based on six case studies and it does not cover all possible HFE evaluation methods (Stanton et al., 2005) used in VP. Therefore, it would be important to test more different kinds of HFE methods to understand which methods are applicable during VP and which can provide valid evaluation results. These validity studies could be made by comparing the HFE evaluation results gained from a VE and from a real environment.

There can be several different kinds of virtual prototypes in terms of virtuality and fidelity levels. Current studies are still diffused on the reality-virtuality continuum (Milgram et al., 1995), and there is a need for more research to fill these gaps. If this topic is studied more, it could be possible to provide detailed instructions and guidelines for design engineers to be able to select suitable virtual prototypes. The design work is often a trade-off between time and money, and therefore it is not always easy to know how much effort to put into the design of virtual prototypes to gain a suitable fidelity level. In addition, by increasing the quantity of research in this area, it would be possible to draw statements and theories on how a certain level of virtuality in prototypes supports HFE design.

Several different approaches to VP design have been proposed. However, there is not yet one that has stabilised its status in the VR research domain, and that is used by different companies in practice. Systematic approaches and guidelines are only beneficial when used. In the future, it would be desirable for the research community, as well as industry, to apply these approaches in practice, to detect their challenges, and then iteratively to develop them further.

This thesis belongs to the HFE discipline and focuses on VP use in HFE evaluation. Therefore, organisational and PDP dimensions were not considered thoroughly. However, it would be important to study companies' current practices in detail and the effect of VP on them. This way it would be possible to enhance the understanding of participants' reaction to both new technologies and new processes. This would also support the understanding of when and under what circumstance VR technologies should be used during PDP. In addition, it would be important to consider the actor network thoroughly and how the VR technology could foster information exchange as an intermediary or boundary-spanning object.

7.4 Conclusions

The main argument of this thesis is that it is possible to evaluate HFE during VP, especially when both (HFE and VP) topics are considered carefully. The thesis demonstrates this through investigating case studies and by analysing findings from them.

The thesis proposes an HFE/VP model, which includes three key elements when using VP in HFE evaluation. In addition, it describes processes and approaches to consider these elements systematically in practice. The first VIRMA model supports company implementation of VP. The VP design process describes key elements to consider when designing VP sessions. The VP design template is a practical approach to support design engineers during design. The presented HFE approach enhances understanding of the use of HFE evaluation methods and suitable virtual prototypes.

The results of this thesis help design engineers in their work, and help companies to produce better quality products that will be accepted by users. In addition, the proposed systematic models and approaches advance the research community to execute and document research studies more systematically.

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BENEFITS OF THE USE OF VIRTUAL ENVIRONMENTS IN PRODUCT DESIGN REVIEW MEETING

S. Aromaa, S.-P. Leino, J. Viitaniemi, L. Jokinen and S. Kiviranta

Keywords: design review, Virtual Environments (VEs), Human Centred Design (HCD)

1. Introduction

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. The review meetings are efficient tools for sharing information about the product and for managing knowledge exchange [Huet et al. 2007]. Knowledge can be embodied in the individuals or embedded in the processes or practices of organisations. Knowledge can be expanded on and enriched through the spiral, innovative amplification of tacit and explicit knowledge joint creation [Nonaka and Krogh 2009]. Thus it means both cultural, behavioural and organisational issues and not merely technological innovations. Consequently the knowledge process has to be incorporated into the work processes specially focusing on the knowledge work processes such as how to (1) create, (2) gather, (3) store, (4) share and (5) apply knowledge, and all this while taking into account the way people work on a daily basis. The modes of knowledge creation are contributed by collaborative interactions between individuals, teams, and information systems.

Nowadays the design review meetings lack demonstrative and interactive interface between the reviewers and the design model to be able to test manual work tasks in a natural way. Additionally, procedures for gathering, recording and sharing knowledge are usually not well organized [Huet et al. 2007; Verlinden et al. 2009] or not even arranged because the importance of the reviews for the quality, usability, manufacturing and costs of the final product is not clearly seen. 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. 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].

Although traditional tools are still used in industry there are several studies about the use of Virtual Environments (VEs) in the review meetings e.g. [Bordegoni et al. 2009, Kremer 1998]. The use of the VEs addresses to the natural feel of the task and illustrative presentation of the model. According to [D. Ma et al. 2011] the collaborative virtual assembly environment is a useful computer-aided tool for supporting complex product design where each designer can bring into their special advantages and communicate with each other. Importance of the VEs comes up specifically in allowing communication for those who are not familiar with 3D CAD tools, e.g. for the assembly workers.

According to [Bordegoni et al. 2009], virtual prototyping is particularly useful in the assessment of interaction systems used by users. This means that by engaging users to the design reviews based on Human Centred Design (HCD) approach [ISO 9241-210 2010] and participatory design improve and deepen communication, knowledge transfer, collaboration and user participation in the design process.

The participatory approach in design and development is a procedure in which the users, workers of a production process or a machine operation have the opportunity to influence the content of the design target.

Although VEs and HCD approach are beneficial for the review meetings, unfortunately the potential of the VEs (and exploited VR technology) in product design are still not fully taken in to practice in industry. Based on a literature review [Leino et al. 2012a], which summarizes the recent progress on virtual-engineering-based human-centred design and product lifecycle management, the main gaps are related to lack of practical and adapted implementations of HCD, integration of virtual engineering to product processes, bi-directional data and information flow between virtual engineering applications and data management systems (PDM/PLM), and lack of sufficient methods, tools and infrastructure of managing company content and knowledge.

This study was made within the EU project ManuVAR (Manual Work Support throughout System Lifecycle by Exploiting Virtual and Augmented Reality). The ManuVAR industrial requirements, which can be viewed as the most prominent problems of the European industries in the context of high knowledge high value manual work, were found out to be: (1) problems with communication throughout lifecycle; (2) poor interfaces; (3) inflexible design process; (4) inefficient knowledge management; (5) low productivity; (6) lack of technology acceptance, and (7) physical and cognitive stresses. Project goal is to find out methodologies and solutions to improve manual work by utilising Virtual Reality/Augmented Reality (VR/AR) technology systems. [Krassi et al. 2010]

From these observations and many years of experience of the use of VEs within industry, it has become clear that although there are benefits of the use of VEs in design reviews, it is really difficult to formulate these benefits in terms of cost, time or effort. The research questions are “How the benefits of the use of the VEs in the design review meetings can be classified?” and “What is the relation between benefits?”. These questions guide the research made in two industrial case studies presented here by describing methods, approaches and technology used for investigating the benefits in the cases. Then, results are described, discussed and finally conclusions are drawn out.

2. Methods

2.1. Human Centred Design approach

The following HCD approaches were used: (1) the design is driven and refined by user-centred evaluation; (2) the process is iterative; (3) the design addresses the whole user experience, and (4) the design team includes multidisciplinary skills and perspectives. From the iterative HCD activities in [ISO 9241-210 2010] (Figure 1), “Evaluate the design against requirements” was the one performed in this study. The participatory approach was implemented in this study in such a way that different stakeholders were actively involved.

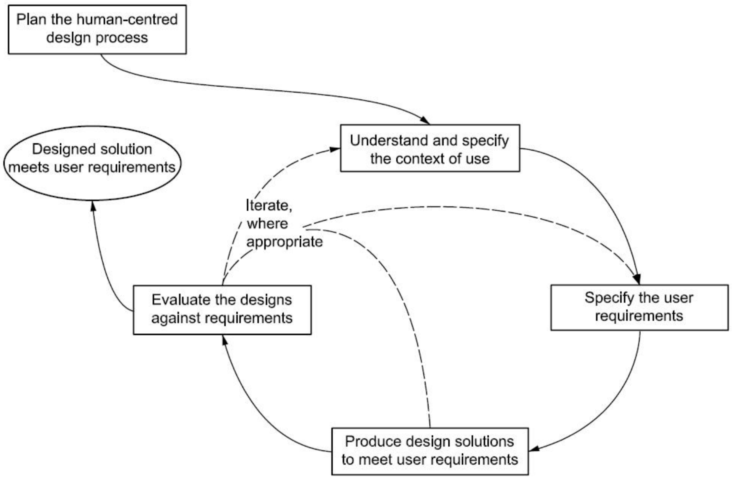

Figure 1. Interdependence of human-centred design activities

Previously mentioned HCD and Participatory Design can be considered as methods of "Design for Human" (DFH). One major principle of DFH highlights the importance of taking all manual work including lifecycle stages (manufacture, logistics, operation, maintenance, recycling, etc.) into account during the product or system design phase.

2.2. Virtual Environments

VE system (Figure 2) that was used in review meetings consists of several subsystems: (1) main visualization system with active stereographic rendering in three screens powerwall setup; (2) secondary visualization system with Head Mounted Display (HMD); (3) marker-based optical motion capture system to capture worker point of view; (4) user interface (UI) system that is a combination of gesture control, gaming controllers and basic keyboard/mouse interaction, and (5) surround audio system. The review board was provided with an overview to the system on powerwall to understand the specific context. Additionally the HMD view for the worker was also projected on one extra screen for the review board observation.

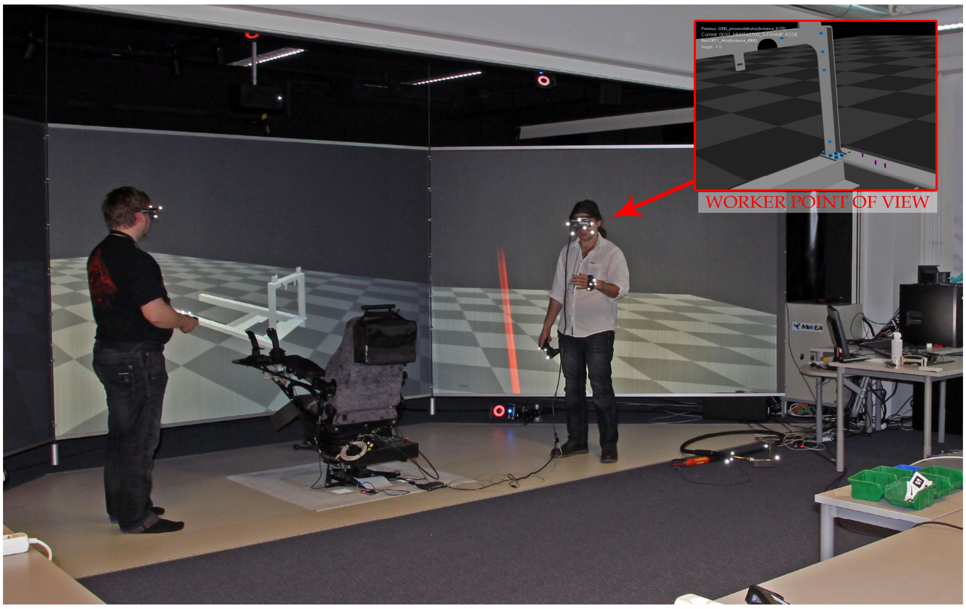

Figure 2. Virtual reality system

2.3. Product design review meeting procedure

The procedure includes three steps (1) preliminary-work, (2) actual review and (3) post-work. Before each review meeting, the preliminary work was defined and processed paying attention to the needs concerning the participants, software, hardware and other information. In the VE review meeting, the review board members gathered together to work out the actual review meeting. Following phases were conducted during the meeting:

1. A short introduction was given of the review meeting process, VR/AR tools and how to act in VE;
2. The goal, task/scenario and participants were introduced and discussed. Also role of the participants was defined (e.g. who takes notes, who uses HMD);
3. The test users were asked to perform tasks and to test the required case. The review board had free discussions. Notes were taken and small changes were made to the product model following iterative stepping;
4. Design decisions were made based on the information obtained during the meeting and expert evaluation. The meeting was documented (notes, video, pictures), saved and informed to the key persons not present in the review meeting.

Both review meeting case studies were executed at the research centre's premises in VEs laboratory.

2.4. Review meeting case studies

2.4.1. Case study 1

The purpose of the first review meeting was to present a new concept which was additional module to the existing product. There had been product design review meetings beforehand to iteratively improve the concept before this particular meeting, which was organised for the customers. Therefore, the nature of the review was about introducing the concept and how it would be assembled on site than finding out problems. The review board consisted of one product company representative, a few experts (VE system and Human Factors) and customer representatives from six different companies. One expert was using the HMD to assemble the new module and to present the idea of the concept to the customers. Although it was not the main purpose, customers were able to make comments and to suggest improvements. Customers were also allowed to try the VE system.

2.4.2. Case study 2

The purpose of the second review meeting was to show the forthcoming engine module to the productization and production experts (Figure 3). The purpose was to evaluate the assembly, maintenance, safety and structural problems, and also to discuss possible solutions. The review board consisted of an assembly worker, design engineers (mechanical/hydraulics/etc.), a manufacturing manager, assembly foremen and product development engineers - all from the same company. Also a VE expert, HF experts and the review meeting chairman were present. The assembly worker was using the HMD to observe the step by step assembly and review board was discussing and making comments. The meeting was recorded by taking pictures and notes from the discussions.

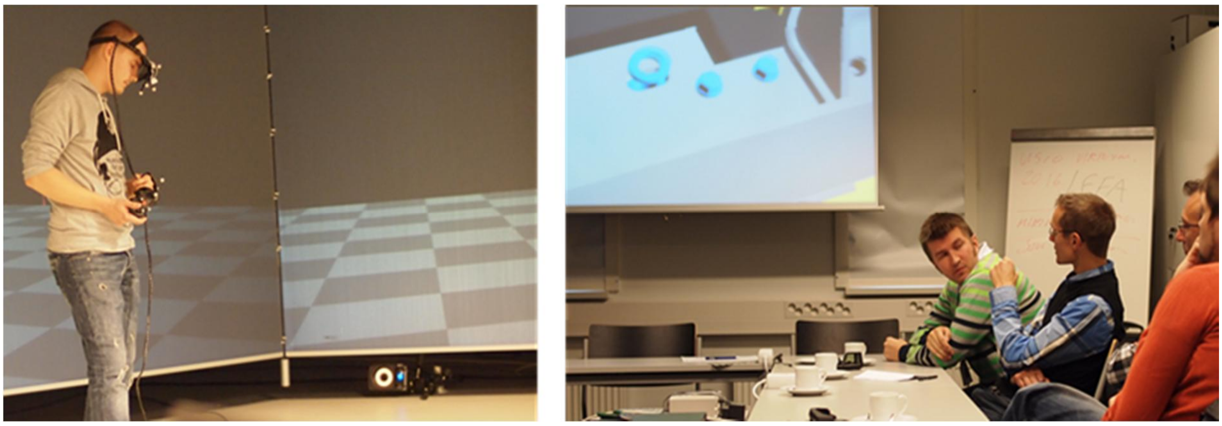

Figure 3. Engine module review meeting

2.5. Questionnaire and observation

Questionnaires and observations were used to collect information about the benefits emerged from the use of the VEs in the review meeting. Questions were related to issues e.g. how the review meeting felt as an experience, how the new VE based review process felt like when compared to the old practises, did it affect to the information transfer and whether the level and maturity of the used VEs was sufficient. The questionnaire was web-based and it was sent to the participants after meeting. A total of ten filled questionnaires were received. The observations and notes were taken during the meetings on the use and usability of the VE system, function of the review meeting process and also the product development issues in question.

3. Results

In general, the results from the interviews and observation show that the participants felt the review meeting was interesting and useful experience for them. The results based on the observations and interviews in case 1 and case 2 are presented in Table 1. The results are categorised in three key topics: (1) VE system; (2) Communication and knowledge transfer, and (3) Design process and lifecycle. In each topic, there are described main positive and negative feedback collected.

Table 1. Key results from the interview and observation on the use of the VEs in the review meeting

Key topics	Positive feedback on the use of VEs in the review meeting	Negative feedback on the use of VEs in the review meeting
VE system	• The use of VEs was illustrative • Easier to understand dimensions and functionality • User interfaces (controls) were sufficient • The implementation level of VE system was good enough for the review meeting • In general, the depth of details was sufficient for the product review	• Visualisation could have been better • Easier modified models were requested • Hide/unhide parts feature in model were requested • Simulation of the surrounding environment could improve the immersion • Zooming feature in the HMD could be good
Communication and knowledge transfer	• Increases collaboration between stakeholders, customers and manufacturing company • Enables better communication and discussions on a specific detail • Information was shared between design engineers and production/productization	• Better information recording tools needed
Design process and lifecycle	• Possible to test and to modify the design before manufacturing • Decreases need of expensive prototypes • Fewer corrections needed during the life-cycle because errors could be removed at the beginning of the process	• The review meeting process should be more systematic • Good preparations advance would make the review meeting more efficient

The improvements for the product are listed on Table 2. The improvement suggestions were collected from Case 2 review meeting's discussions and observation. Many of the improvements suggested to the product were made by the worker while walking through the assembly.

Table 2. Key findings for the product development

Findings for the product development	
Product development	• Three errors in the geometry of reviewed 3D model were found • Change request related to component layout • Change request related to 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 • Four different change request related to needs in assembly order/methods • Change request related to one safety related issue • Some feedback was collected about assembly tools and methods • Some discussions were kept about the buildup-level and module variations

4. Discussion

4.1. Benefits of the use of VEs in design review meeting

4.1.1. Emerged benefits from the two case studies

The results are generally positive and they encourage the use of VEs in the review meetings. Most of the comments were related to the quality of the VE system, communication and the product itself. It was noticeable thought that it was easier for the participants to comment on the technology improvements needed in VE/VR than the review process or the review content itself.

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

In the second review meeting, the information was shared between the design engineers and the production engineers, which was positive because the discussions 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. This *user participation and requirements* recognition are in-line with the HCD [ISO 9241-210 2010] principles. Additionally, by using this participative approach it is possible to extend good practices and to improve benefits in using VEs in manual work prototyping. Now, the existing computer-based tools to support virtual assembly either (1) concentrate on representation of the geometry of parts and evaluation of clearances and tolerances or (2) use digital human models to approximate human interaction in the assembly process [Seth et al. 2011]. The participatory approach supports also *design decision making and learning*.

Other major benefit that emerges from the use of VEs is the *visualisation and immersion*. It is relatively easy to immerse the worker into to the task without any previous experience. The worker can concentrate on the task and work naturally. Also, the user interface controls were gaming-controls, so it was easy to use them after a short instruction. According to [Bordegoni et. al. 2008], the use of VEs in the review meeting is especially beneficial when assessing interaction systems (human-machine interaction) and we confirm this finding. In the review meetings, it is also possible to *enhance designers' experience* of what the workers really experience while doing their tasks.

The two case studies also proved that it is possible to use the VE review meeting to achieve various goals in *different lifecycle phases*. The VEs make it possible to have an efficient review meeting (to verify human/worker/user/customer requirements) already at an early phase of the concept design when usually no illustrative material exists. The benefits also arise from *time and money savings* achieved later on in lifecycle e.g. (1) company can build preliminary assembly instructions based on the review meeting; (2) user acceptance will be better if based on the participatory approach; (3) assembly and maintenance will be more efficient; (4) it is possible to plan the delivery dates for sub-contractor parts; (5) bottlenecks can be found out and removed from production; (6) alternative assembly orders can be defined, and (7) the amount of physical prototypes can be decreased.

Based on these results, the use of VEs in the review meetings can also address all the manual work gap presented in the ManuVAR project [Krassi et. al. 2010]: (1) communication; (2) interfaces; (3) design process; (4) knowledge management; (5) productivity; (6) technology acceptance, and (7) human factors.

4.1.2. Benefits from the second case study

By changing the assembly order and adding a simple supportive structure it was possible to give the assembly worker more working space (Figure 4). The initial plan was to put the tank to its place as early as possible. This would cause the worker to do the assembly in a limited space between tank and engine.

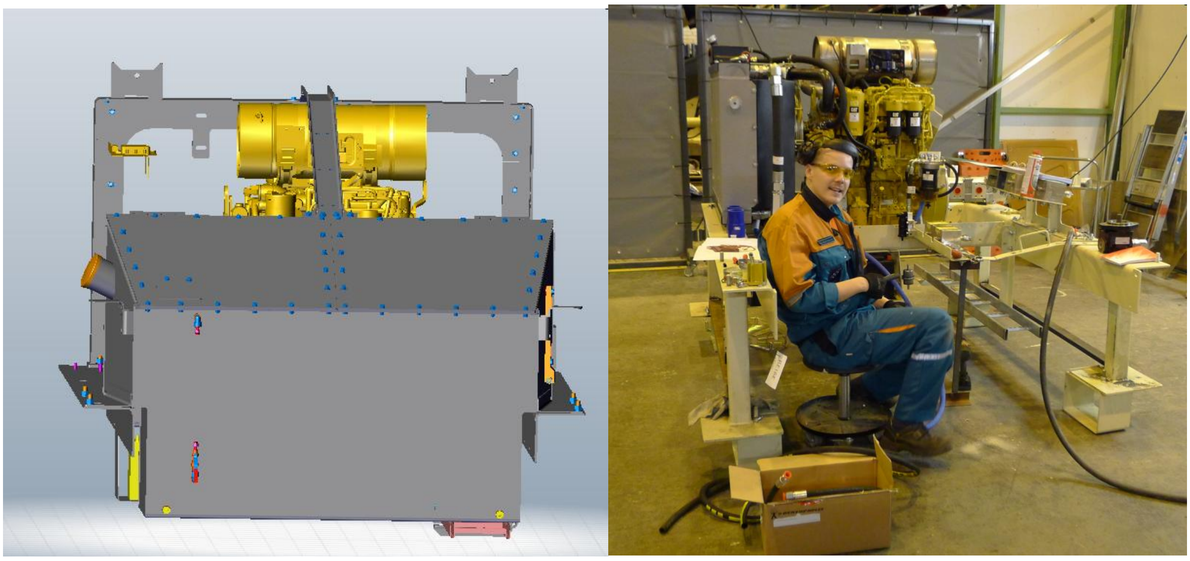

Figure 4. More working space for assembly worker by changing the assembly order

An example of what eight small design faults spotted in the review meeting mean in terms of assembly time are shown in Figure 5. Following the time line, the first bar represents the prototype manufacturing process with the VE review meeting, while the second bar represents the process where errors are spotted during the assembly instead of the early design review.

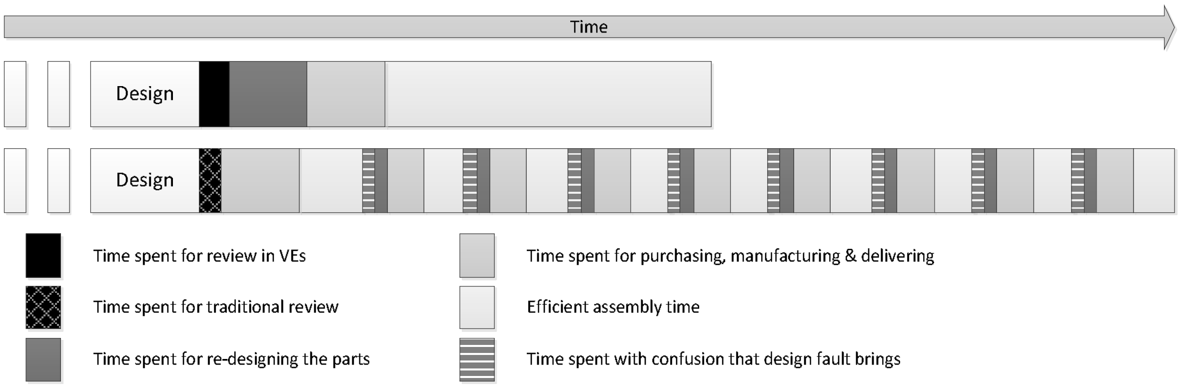

Figure 5. An example of the assembly time spent when detecting eight design errors early in VE design review meeting compared to the worst case scenario of the use of the traditional review meeting.

4.1.3. Benefits' classification and relations

Even though there are many studies done on VEs' use in the design reviews, the benefits of this use are not described sufficiently. [Bordegoni et al. 2009] mentioned a few benefits from the virtual prototyping, but for evaluating effectiveness they suggested further investigation where building a virtual prototype should be compared with building a physical prototype in terms of required time, cost and tests. Also [Kremer 1998 and Verlinden et al. 2009] are concentrating more on describing technology development in the design reviews. Additionally, the review processes are investigated e.g. [Huet et al. 2007] describes how to record knowledge in reviews effectively. This paper emphasizes the emerging benefits from the use of the VEs in the review meeting than describing yet another technology used.

When analysing the previously listed benefits it was clear that there are different types of them. The benefits are described in Figure 4 in Feature-Benefit (F-B) pyramid. Benefits are classified in three different categories based on findings: (1) VEs; (2) design, and (3) business. Additionally it is important to consider the difference and dependence between the features and the benefits. In Figure 6, VR/AR technology and HCD approach features are the enablers for achieving the benefits (immersive, interactive and visual) from the VEs use. These benefits then direct to the natural and common media for collaboration and review which forms a feature for the design. Finally, the business benefits are gained e.g. reduced costs or shorter time-to-market.

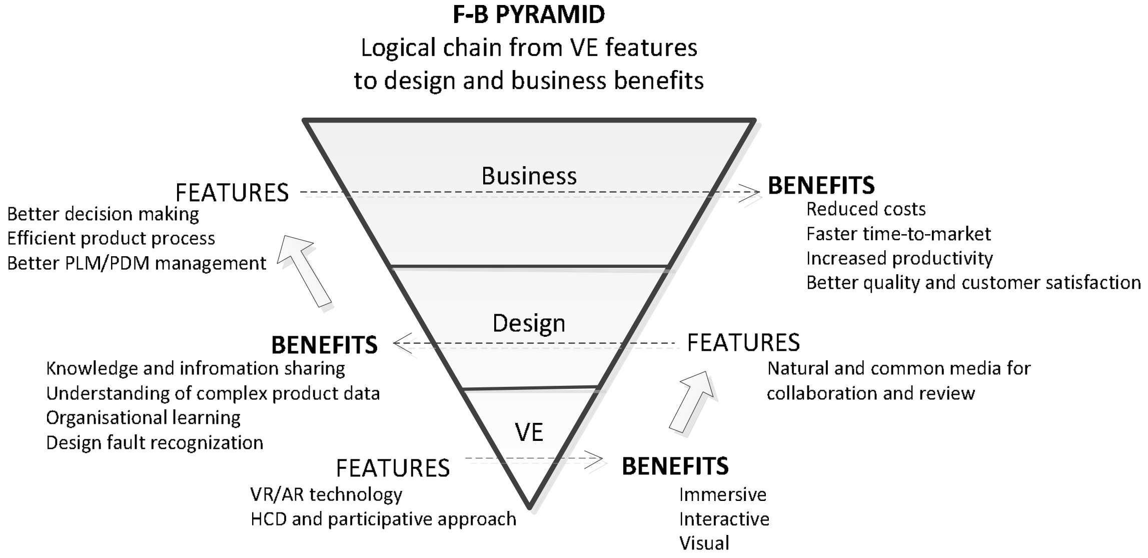

Figure 6. Feature-Benefit (F-B) pyramid describes difference between features and benefits in the case studies

This type of classification and categorisation of the benefits from the use of VEs technology in design reviews are important for the industry especially in the human –interaction context (use, assembly and maintenance). The F-B pyramid is a way to make the benefits more tangible in the theoretical and industrial context. It can also make companies' investment decisions regarding new technologies, implementation of technologies, or use of the existing VEs more straightforward. Especially the companies that operate in the areas related to human-machine interaction such as automobile or machine industry, can benefit from the presented F-B pyramid.

4.2. Challenges

When using the VEs, it is always important to consider restrictions that arise from the use of VE technology e.g. simulation sickness. It needs to be taken account how long it is possible to be in VEs (either VR or AR based) especially when using the HMD. It is also important to acknowledge the differences between each users' individual characteristics concerning eye vision, stereoscopic visual capabilities and simulation sickness. Thus need to be informed beforehand to the participants and monitored during the review.

One challenge is to decide the level of details when working within the VE system. The more details and functionality are needed, the more time it will take to do virtual models. It also means more development costs and longer time-to-market. It was also seen that technology still has constrains that affect to the immersion e.g. visualisation, simulation, haptics, challenge with large and heavy parts, and realistic forces. [Seth et. al. 2011] lists same type of technical challenges to be overcome to realize virtual assembly simulations, namely: accurate collision detection, inter-part constraint detection and management, realistic physical simulation, data transfer between CAD and VE systems, and intuitive object manipulation (inclusion of force feedback).

One often neglected challenge is how to integrate the VE review meetings to the company processes in a way that will make the design work more efficient. Companies are investing money for their own

VE systems, but they are often inefficiently used because they do not implement the new system their design process. We found out that more systematic practises in the VEs review meetings process needs to be implemented at the company level. Nowadays feedback is recorded usually into participants' minds or personal notes, and reported to the designers verbally or through an email. Due to insufficient communication, knowledge about design defects and feedback will not be shared among organisation. There are studies about the review meeting activities, procedure and knowledge management [Huet et al. 2007], but the challenge is how companies can adapt these good practises to their processes. The review board might also need training to fully understand the system and to be able to work with it.

One issue is how to link the VEs use and the information management (PDM, Product Data Management) and PLM (Product Life-cycle management) processes together. CAD-VE data exchange is one of the most important issues faced by the virtual prototyping community, especially translating identified design changes back to CAD and other CAE systems [Seth et al. 2011]. Design data is typically managed in EDM (Engineering Data Management) systems, to which, for instance, production department does not have access. Additionally, engineering structure of a product is in many cases very different to assembly or maintenance structure and task hierarchy, which causes difficulties for design evaluation from production or service point of view.

5. Conclusions and future work

This paper describes and categories benefits of the use of VEs in design review meeting collected from two industrial case studies. Main benefits are: (1) the information and knowledge sharing; (2) the user participation and requirement management; (3) the design decision making and learning; (4) the visualisation and immersion of VE systems; (5) the enhancement of designers' experience of the use of product; (6) the evaluation of different lifecycle phases, and (7) the time and cost savings. Based on this and other studies it has become clear that there are different types of benefits and classifying and defining them in e.g. cost, time or effort is difficult. This paper classifies these benefits in three categories: (1) VEs; (2) design, and (3) business, and describes relations between them.

This paper is the first step for the classifying emerged benefits. In future, more companies will be interviewed and better measurement and categorising for benefits will be developed. Another issue for the future research is to find out how to describe the benefits in a more tangible way to the industry. Finally, the VEs review meeting processes and the integration to knowledge and information management will be further investigated.

Acknowledgement

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PUBLICATION 2

New Task-Related Dynamic Field of View Analysis in Virtual Environment

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Human Factors Society Conference.

NEW TASK-RELATED DYNAMIC FIELD OF VIEW ANALYSIS IN VIRTUAL ENVIRONMENT

Aromaa, S[1], Viitaniemi, J[1] and Philippon, N[1]

[1]VTT Technical Research Centre of Finland
Tekniikankatu 1, P.O. Box 1300, FI-33101 Tampere, Finland
e-mail: susanna.aromaa@vtt.fi

This study evaluated a task-related dynamic field of view (FOV) analysis method developed to support decision making in virtual environment (VE) based design reviews. The test experiment was set up in the VE model of a crane cabin, where the operator handles containers. The FOV of the test participants was analysed in two cases for alternative cabin designs. The FOV analysis method showed promising evaluation results, however, further investigation is needed especially with respect to the harmonisation of test experiment parameters between participants.

Keywords: Field of view, FOV, visibility, virtual environment, analysis

1 Introduction

The operator's field of view (FOV) plays an important role in the vehicle design. It is critical to consider the operator's FOV already in the early design phase to ensure good usability in human-machine interaction. Studies show that the operator's FOV contributes to several factors such as performance, ergonomics and safety (Choi et al. 2009; Godwin & Eger 2009). Current FOV analyses methods are commonly based on the use of the standard light shadow bulb tests (ISO-5006 2006) or the Digital Human Models (DHM) in Virtual Environments (VEs) (Choi et at. 2009; Godwin et al. 2008; Godwin & Eger 2009; Lämkull et al. 2009). However, real operators are not widely employed in the FOV analysis. By involving real operators in the VEs, new ways are established to analyse the FOV that consider the task and the operator's performance. Moreover, involving operators supports the participative approach and can aid VE design reviews (Viitaniemi et al. 2010).

Designers need objective, numeric information of the FOV to support their decision making when comparing alternative cabin structure designs. The FOV analysis method introduced in this paper is developed to support the decision making in VE design reviews, where the operator uses a virtual machine and the review board members discuss about the design alternatives.

This paper presents a test experiment to evaluate the task-related dynamic FOV analysis method. The research questions were as follows (1) "Is it possible to compare the operator's FOV in two alternative design solutions by using this analysis method?" and (2) "Are the comparison results between each participant coherent?" The test settings and methods, study results, discussion and conclusions are presented in this paper as well as the needs for further research.

2 Methods

2.1 Virtual Environment system and models

The test experiment was set up in the VE laboratory (Figure 1) on the Virtools software platform. A 3D Rubber Tyred Gantry (RTG) crane model was used in the VE system, which consisted of: (1) the three screens powerwall and on floor screen visualisation system, (2) a marker-based optical motion capture system for head tracking, (3) shutter glasses for operator, (4) operator's control interface (joysticks), (5) a motion platform and (6) operator's cabin seat on the motion platform.

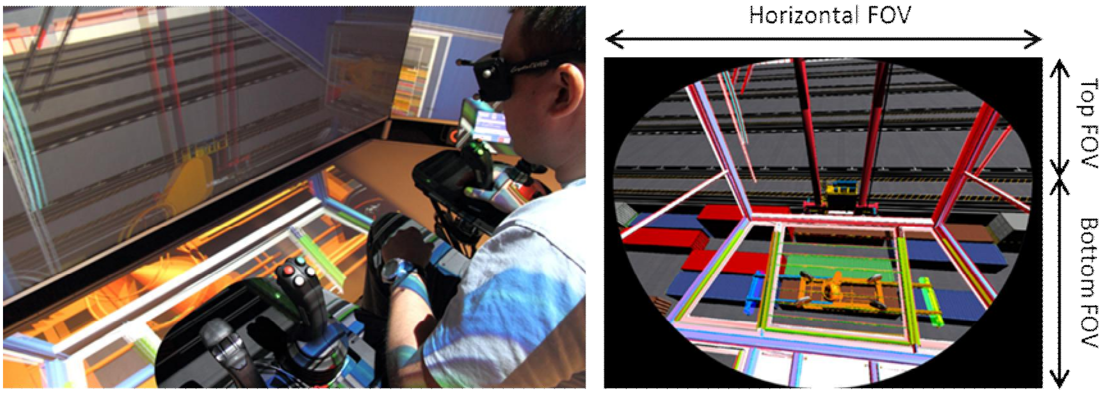

Figure 1. VE test setup showing the operator's FOV.

2.2 Test participants, task and procedure

Five participants, four males and one female, mean age 35 years (SD 4,0) and height 181 cm (SD 5,4) performed the test. Four of them had a good vision and one had eyeglasses with correction of minus 2,5. Two of them were experts on using the VEs and others were novices. One participant was an expert on the current VE application use, one was competent and three were novices. None of them had any real experience of driving the RTG crane.

The participants executed the same task with the two different cabin alternatives. The task was decomposed into the following steps: (1) drive crane up to the containers, (2) pick the first container with the spreader, (3) lift the container, (4) drive the container forward, and (5) place the container down. The spreader is a device used for lifting containers and cargo.

After the task had been introduced to the test participants, they were trained to use the controls for driving the crane and controlling the crane spreader. During the task execution, notes were made on the actions of the participants, and the test was recorded on video. The participants performed the task twice (Case 1 and Case 2), with only a small break between them. The operator's FOV (Figure 1) was recorded automatically for replay and evaluation purposes.

2.3 Test cases

The two test cases were modelled in the VE. The first case made use of an ordinary cabin structure, while the second case made use of a model in which the cabin structure was strengthened (Figure 2) resulting in a stronger masking of the operator's view. The crane spreader is also illustrated as a rectangle to simplify the figures. The left and right ends of the crane spreader were defined as target objects by aligning rectangle box models on top of them for the FOV analysis calculation purposes. The operator followed especially these target objects while performing the task. The FOV setup was fixed to 100° for the horizontal angle, 35° for the top angle and 50° for the bottom angle (Figure 1).

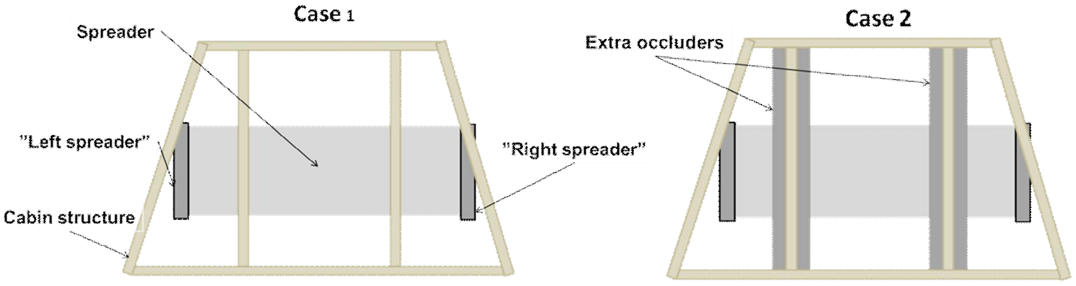

Figure 2. The difference between the cabin structures in Case 1 and Case 2.

2.4 *FOV analysis method*

The FOV analysis method is based on task related visibility and occlusion evaluation of target objects in the operator's FOV:

1. Visibility: the percentage of the visible part of the target object pixels from all the pixels of the operator's FOV (Figure 3).
2. Occlusion: the percentage of the occluded (here by the cabin structure) pixels from the visible target object pixels in the operator's FOV (Figure 3).

The method's results aid the comparison of alternative design solution's visibility, and do not give an absolute value of the visibility. For example, the smaller the occlusion percentage, the better the visibility of the target object.

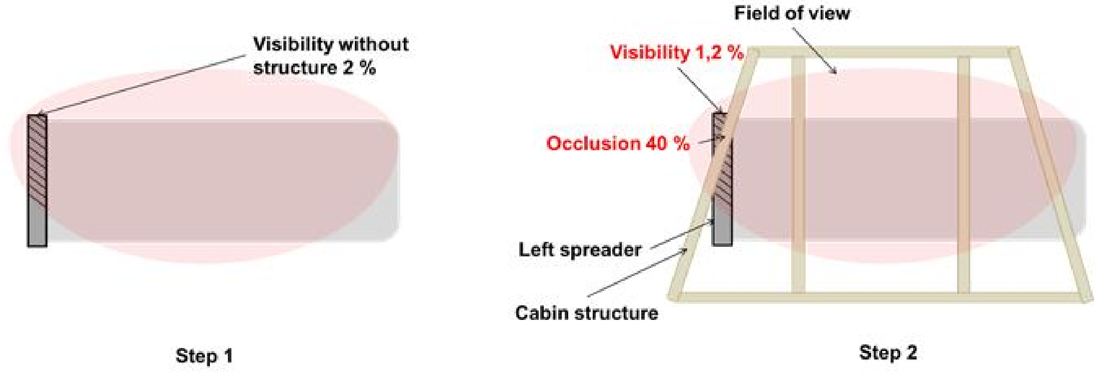

Figure 3. Step 1 involves the calculation of the visibility without occlusion, and Step 2 provides an indication of the final visibility including the occlusion calculation.

2.5 *Possible error sources in the test experiment*

Possible sources of errors that could affect to the results included: (1) no stereoscopic visualisation on the VE, (2) problems with driving the crane due to crane logic's malfunction, (3) uncontrolled spreader swing due to lack of correct anti-sway, (4) containers having random starting locations in the VE, and (4) unprofessionalism in driving a crane. Additionally, the operators' head's shadow partially obscured the floor projection, which may have affected the operator's behaviour and the task execution.

3 Results

The summary of the occlusion and visibility percentages for the target objects (the right and left spreader) are listed in Table 1. Occlusion and visibility percentages are calculated as a mean value. Additionally, average values and standard deviations for right and left spreader results are also presented in the table.

Table 1. Operator's FOV method analysis results from two cases

	Case 1				Case 2			
	Occlusion (%)		Visibility (%)		Occlusion (%)		Visibility (%)	
Partici-pant	Right spreader	Left spreader	Right spreader	Left spreader	Right spreader	Left spreader	Right spreader	Left spreader
1	17.0	14.0	0.15	0.15	21.9	24.6	0.11	0.07
2	23.8	31.1	0.14	0.25	14.3	12.5	0.17	0.14
3	9.3	12.4	0.11	0.39	23.1	27.7	0.14	0.28
4	14.1	16.4	0.14	0.35	22.0	16.2	0.11	0.21
5	16.1	19.1	0.22	0.17	14.7	17.7	0.24	0.20
Average	16,1	18,6	0,15	0,26	19,2	19,7	0,15	0,18
St.dev.	5,25	7,43	0,04	0,11	4,32	6,25	0,05	0,08

The same values are illustrated in Figure 4 for the comparison of the two test cases. The absolute values for the occlusion and visibility are not of specific importance. In Figure 4, (a) and (b) illustrate the five participants' occlusion results in the two cases. The visibility percentage results for the right and left spreader are shown in (c) and (d), respectively.

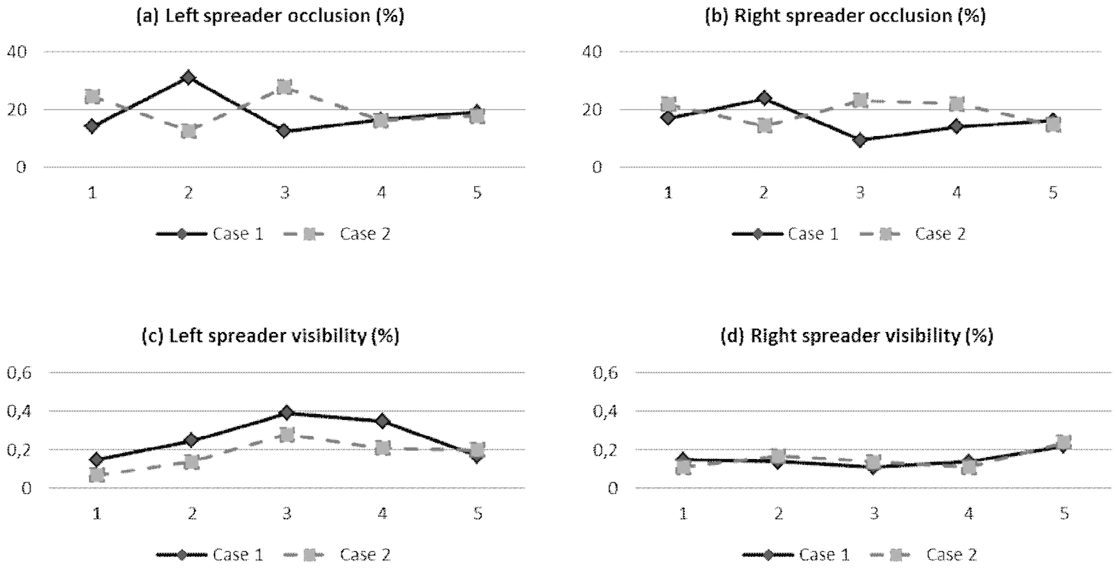

Figure 4. Comparison of the target objects' (right and left spreader) occlusion and visibility percentages for the two cases, for each of the five participants.

4 Discussion

Based on the FOV analysis method evaluation study, the occlusion percentage value in Case 1 should be smaller than in Case 2; i.e. Case 1 should have a better visibility to the target object (see Figure 2). Based on the five participants' test results, the occlusion percentage results are not sufficiently coherent to be able to say which cabin design has a better visibility. Participant 2's FOV percentages of the left and right spreader occlusion deviate compared to the other participants. From the replay of participants FOV, it was not recognised any adequate, specific reason for the deviations.

The visibility of the left and right spreader was nevertheless coherent between the participants and the cases. Thus, the results of the FOV analysis method can be regarded as being promising. Additionally, from the right spreader results it can be seen that most participants looked at the right spreader for almost the same percentage amount of time in both cases. This means that they have used different postures in Case 2 to be able to minimise the additional occlusion effect of the cabin. This also shows that the light bulb and the DHM-based FOV tests are quite static and would not account for the flexibility and the dynamic behaviour of the human. When comparing the involvement of the real participants with the use of the light bulb shadow test or the DHMs, the deviations can be found to be due to the eye movements and anthropometric differences (Choi et al. 2009).

Further investigation is needed in order to be able to make any definitive conclusions about the method's use for comparison of the two design solutions. For its further usability, it is important to ensure it supports the design process and decision making because current DHM-based tools do not provide any recommendations for the FOV settings, which demands a high knowledge (of the manikin user) of human vision and can lead to inaccurate decisions (Rönnäng et al. 2004).

Any future evaluation setup would need a more simple case, possibly with only one main target object in order to avoid the deviations in the results due to the two target objects. Additionally, the following questions need to be addressed: (1) how many operators or task repetitions are needed so that reliable results are achieved, (2) how does one manage to control operator characteristics that can affect the results, e.g. stereovision, vision, anthropometrics and experience, (3) what is the impact of different operator behaviour and performance, (4) how widely should the flexibility and dynamic behaviour of the human be taken into account, and (5) how do other variables as task, system and environment affect to the results?

5 Conclusions

This paper describes an evaluation study of the operator performance and task-related FOV analysis method implemented in the VE. The FOV analysis method has also been developed to support the decision making in the VE-based design reviews, where the operator uses a virtual machine and the review board discusses about the alternative design solutions. Especially the machine cabin design industry can benefit from the

FOV analysis method, but it could be also exploited in all human operation design, e.g. assembly and workplace design.

The use of real humans as machine operators increases the information obtained from the FOV, when compared with DHMs or the light bulb use. This is due to fact that the operators' behaviour and activities can also be analysed. However, the use of real humans also adds a series of other variables to the model and therefore it becomes necessary that several real persons perform the task, in order to achieve reliable results. This does not directly serve the VE design review meeting purposes, but such a participative approach may increase the knowledge-sharing and thereby improve the overall quality of the final solution. Further investigations are therefore also needed to ensure more objective results are obtained to support the design review process. Additionally, better support for the FOV evaluation can be obtained by using the FOV analysis method closely together with Head Mounted Displays or eye-tracking systems.

6 Acknowledgement

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PUBLICATION 3

Are Companies Ready for the Revolution in Design - Modelling Maturity for Virtual Prototyping

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INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED13
19-22 AUGUST 2013, SUNGKYUNKWAN UNIVERSITY, SEOUL, KOREA

ARE COMPANIES READY FOR THE REVOLUTION IN DESIGN – MODELLING MATURITY FOR VIRTUAL PROTOTYPING

Susanna AROMAA, Simo-Pekka LEINO, Juhani VIITANIEMI
VTT Technical Research Centre of Finland, Finland

ABSTRACT

Companies are meeting growing demands for readiness to respond rapidly to changes from the outside world. Companies actively manage and develop their competences by applying new technologies and methodologies such as virtual prototyping (VP). Nevertheless, no general, structured guidelines for VP implementation are available due to novelty of the use of virtual reality technologies in machine industry.

The purpose of our research was to improve the use of VP in companies. In this paper, we describe two company cases from the machine industry that are implementing VP for everyday use. During the research, it became clear that the companies had quite intuitive ways for the VP implementation, and they experienced many challenges. This paper describes how companies can improve VP implementation in a more structured way using the virtual prototyping implementation maturity model (VIRMA). VIRMA supports companies in improving their adaptations of VP and benefitting earlier from VP use in design.

Keywords: design process, early design phases, virtual reality, virtual prototyping, maturity

Contact:
Susanna Maria Aromaa
VTT technical Research Centre of Finland
Systems engineering
Tampere
33101
Finland
susanna.aromaa@vtt.fi

1 INTRODUCTION

Companies are meeting growing demands for readiness to respond rapidly to changes from the outside world. Companies actively manage and develop their competences by applying new technologies and methodologies such as virtual prototyping (VP). Wang (2002) defines VP as: ‘a construction and testing of a virtual prototype. Virtual prototype 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.’ Unfortunately, the potential of VP (and exploited virtual reality [VR] technology) in product design has still not been fully adopted in practice in industry. Based on a literature review (Leino and Riitahuhta, 2012), which summarizes the recent progress on virtual-engineering-based, human-centred design and product lifecycle management, the main gaps relate to a lack of practical and adapted implementations of human-centred design, integration of virtual engineering into product processes, bi-directional data and information flow between virtual engineering applications and data management systems (product data management [PDM] / product lifecycle management [PLM]), and a lack of sufficient methods, tools and infrastructure for managing company content and knowledge. It claims to be a means of assessing a company’s readiness regarding the current overall design collaboration competences to identify fundamental and urgent development needs in order to choose where to invest in its future engineering capability.

Maturity models are widely used in process improvement since they offer an effective but simple way to measure the quality and respective maturity levels of processes and their overall innovation and engineering competences. Maturity models are normative, conceptual models to assess as-is situations to outline foreseeable, consistent and claimed evolution paths towards maturity or readiness as reference models (Wendler 2012, Becker et al. 2009 and 2010, Jansson 2011, Cleven 2011, Cleven et al. 2012). Becker et al. (2009) define the maturity model as follows: ‘A maturity model consists of a sequence of maturity levels for a class of objects. It represents an anticipated, desired, or typical evolution path of these objects shaped as discrete stages.’

The recent maturity model research field has been heavily dominated by software measurement and development, software engineering domains and business process (BPM) management. The cases have been on, for example, the Capability Maturity Model (CMM) and CMM Integration (CMMI), the IT Performance Measurement Maturity Model (ITPM) or the Business Process Management Maturity (BPMM) (Wendler 2012, Becker et al. 2009, Cleven et al. 2012).

Relevant issues have included key performance indicators and process/corporate performance management, and the focus has been on process capability assessment and improvement, and on the implementation of BPM systems, though not on the implementation of the engineering software, especially the design-related systems (software and hardware) at the end-user companies. It is obvious, however, that manufacturing and service organizations have been the early adopters of maturity models, and the focus has been on the implementation of enterprise resource planning systems but not the implementation of design systems.

The purpose of our research was to improve the use of VP in companies. In this paper, we describe two company cases from the machine industry that are implementing VP for everyday use. During the research, it became clear that the companies had quite intuitive ways for the VP implementation, and they experienced many challenges. Moreover, no general, structured guidelines for VP implementation are available. This paper describes how companies can improve VP implementation in a more structured way using the virtual prototyping implementation maturity model (VIRMA). VP implementation was investigated in the companies and the challenges listed. The first model of VIRMA was described and the development iterations were started in the case companies. The initial results of the use of VIRMA are presented and some further developments highlighted.

2 DEVELOPMENT OF A VIRTUAL PROTOTYPING IMPLEMENTATION MATURITY MODEL

2.1 Background

The development of a VIRMA was based on an inductive approach and action research method. The approach ‘Procedure model for developing maturity models’ (Becker et al. 2009) was applied to the development of the VIRMA. Due to the action research, the development process was not followed literally, as it is in Becker et al. (2009) but used as a formative tool to construct the maturity model. During the research into the companies' VP implementation, several challenges and the lack of a structured implementation process were recognized. The main goal of developing this maturity model was to support the companies in their systematic VP implementation, improve their effectiveness of using VP and increase their awareness that VP is not only the use of VR technologies but also includes other elements, such as organizational, business and human resources aspects. Furthermore, it is particularly suitable for monitoring the companies' development rather than as a benchmark for assessing different companies for an equivalent comparison. Maturity models that explicitly address VP implementation could not be identified.

There were two company cases (Company A and Company B) for the VP implementation measurements. In order to characterize this research and the case studies, the 'Faceted Classification Approach' of McMahon (2012) was applied. The time episode under study took several months, and the research concerned actors from several functions and stakeholder groups within the companies. The interesting parts of the product life were the concept design and requirements formulation phases. The dimension of the issues of concern was comparatively large. The nature of the artefacts focus was one of complex interconnected human-machine systems. The degree of originality of the design application was intended for radical innovations rather than adaptive design. The degree of abstraction used in the design related mainly to visual computer simulations in virtual environments (VEs) simulators. The research approach included action research, observation, survey and interview.

During the research, there were several workshops at the two companies to identify the current level of the design processes and the VR technology used. Structured and informal interviews were used during the workshops. After describing the current status of the processes they were modelled further iteratively. Functional process diagrams (swim lanes) were used for process modelling. One company also had a simulation game that evaluated the proposed VP process model and further defined inputs/outputs. Ideas and comments were also gathered during the simulation game. Lifecycle stakeholders from design; production; purchase; supply; logistics; commissioning; operation; maintenance; customers; end-users; and business owners, such as product managers, project leaders and support process owners, e.g. CAE, PLM, IT, management, were present at the simulation game meeting. One joint benchmarking session for the companies was also held. During the session, the companies presented their current situation of applying VR technology and process development. Some future visions were also shown.

During the workshops, many challenges were detected and listed in the following categories: (1) human, (2) technology and (3) process. Human related challenges are: (1) users' attitudes towards VR technology (user acceptance, fears, interests), (2) culture changes needs time, (3) informing and involving all people in the company is difficult (when people see the benefits, they will be more adaptable), and (4) lack of resources. Technology related challenges are: (1) model updates; there is a need to convert models more easily and reduce costs, (2) creditability; it will be gained only 'case by case', and (3) interaction technologies (e.g. eye-tracking, haptics, HMD). Process related challenges are: (1) lack of a systematic approach to concept design, (2) lack of knowledge of how to manage and measure concept design, (3) handling networks, (4) knowing how to use VP (there is a need for instructions on when to use VP and what to evaluate), and (5) no clear plan on how to implement VP.

2.2 Maturity model for virtual prototyping implementation in companies

The categories described in the maturity model are based on the company cases and challenges presented here, our previous experience, findings from literature, and approaches/theories such as the value chain model from Porter (1985), the design theory (Hubka and Eder 1988) and relevant guideline fundamentals regarding systems engineering (ISO/IEC 15288, 2008). Moreover, Ameri and Dutta's (2005) definition of PLM as a business solution that integrates organizations, processes, methods, models, IT tools and product-related information was used. The categories are (1) understanding business impacts/opportunities, (2) product process including lifecycle, (3) virtual prototyping process, (4) virtual prototyping technology, (5) enterprise infrastructure, (6) human resources and (7) enterprise culture and organization. For every category, there is quality assurance to ensure that the maturity levels attained are not based only on, for example, existing technology but are also fit for the purpose.

Table 1. Virtual prototyping implementation maturity model (VIRMA)

	Unstructured	Repeatable but intuitive	Defined	Managed and measurable	Optimal
Understanding business impacts/ opportunities	No connection to business value	Few successful cases implemented	Benefits for the company defined	Strategic goals and roadmap defined; benefits monitored, evaluated and measured	Fully known benefits and business impacts; value for business recognized; continuous process development
Product process including lifecycle	No visible process	Few processes recognizable	High-level process definitions	Processes implemented and defined in detail	Methods and tools for processes defined
Virtual Prototyping (VP) process	VP has no connection to the design processes	VP is used intuitively as part of the design process	The use of VP has been described in the company processes	The use of VP as part of the processes is managed and the benefits can be measured	Processes are refined and iterated to the level of best practice; the methods and use of VP are embedded in daily the practices
	Basic components	Repeatable	Usable	Flexible	Optimal
Virtual Prototyping technology	2D or simple 3D visualization systems	Low-end VP system	Tailored VP system for company needs	Flexible VP system that supports several design purposes	Flexible VP system that fully supports all design needs
Enterprise Infrastructure	Poor facilities for VP available; case-specific modelling	Dedicated, isolated facilities for VP; one-directional model pipeline	Modules of infrastructure have been defined; most of them have been implemented; bi-directional model pipeline exists	Modules of infrastructure are implemented and measured; implemented efficient bi-directional model pipeline	Perfect and dynamic infrastructure for VP; includes information modelling and integration with PDM/PLM
	Non-existent	Policy	Knowledge	Active	Optimal
Human resources	No one has been nominated to be responsible for the VE system	One person is responsible for the VE system	One or two persons is/are responsible for the system; designers know the system	A few persons are responsible for the use of the system; designers (and others) know how to apply the system to the design and their work	A few persons are responsible who can use the system; the whole company knows how to use it in design
Enterprise culture and organization	Negative attitude towards VP; benefits	Some people see the potential and use the	The culture is positive and the potential of VP	The VP system and benefits are understood;	The whole company sees the potential

	hard to describe	system	is seen; The company is actively marketing the system; organizational change management is defined	active culture of knowledge creation around VP	and benefits and also promotes the use outside the company; the value network model is defined

All categories can be classified based on a general scale of one to five of maturity levels (Table 1). The basic maturity levels of the VIRMA model are based on the general maturity models, such as CMM and CMMI. The maturity levels are defined from unstructured/reactive/non-existent to an optimal/flexible/proactive level even though different designations are used for the categories. Basically, this means that there are categories from the simple use of VR technology in one type of case to multi-purpose use (e.g. for requirement definitions, sketching concepts, reviewing design) in well-managed complex systems (e.g. networks). The maturity levels for business and processes are (1) unstructured, (2) repeatable but intuitive, (3) defined, (4) managed and measurable, and (5) optimal. Technology and infrastructure have maturities called: (1) basic components, (2) repeatable, (3) usable, (4) flexible, and (5) optimal. For human resources and organization, the maturity levels are (1) non-existent, (2) policy, (3) knowledge, (4) active, and (5) optimal.

2.3 Company maturity level

Currently, Company A has adopted and implemented a virtual simulator of VP (Figure 1). It is an immersive, virtual environment in which projectors are directed at the four walls of a room-sized cube. The company bought the equipment and installation from the simulator provider company. All model updates still come from the simulator company. Current VP use has not yet been implemented at the detailed process or methodology level. The process has been defined as a high-level, stage-gate process, which is followed in new product development (NPD) projects. Currently, there is not a specific process definition for using VP. The aim is also to integrate VP into the NPD process.

Figure 1. Virtual environment in Company A

In the case study of Company A, VP was applied at the concept design phase. It was used to capture end-user (operator) needs and for the validation of the requirements specifications. The concept of the cabin is designed by mechanical engineering. The concept design of cabins includes alternative layouts, main dimensions, user interfaces, control devices and materials. The detailed design is done separately. The cabin dimensions are highly limited by the working environment and ergonomic/safety standards. The company follows systems engineering processes in automation software engineering but not really in mechanics or mechatronics system design. The concept documentation includes definitions of layout and functions. After the concept decision, industrial designers take care of the form.

Company A is very experienced at using multi-body system (MBS) dynamics simulation in engineering, but the virtual environments and simulators are a new technology for them. The MBS simulation is used in concept design to compare alternative concepts and to optimize tasks (hydraulics-mechanics). Model and simulation data management is based on file folders. Figure 2 shows the results of Company A’s maturity level measurements when implementing VP. It shows that the company is starting to take further steps in all areas but that it is still at quite an average level.

The understanding of business benefits as well as impacts and opportunities related to virtual environments is just beginning to grow because of the short period of experience. The approach of the implementation is based on pilots in product design and development departments. The enterprise culture and infrastructure have therefore not yet reached higher maturity levels. The awareness of the need to connect VP to product processes and data management grew during the pilots projects.

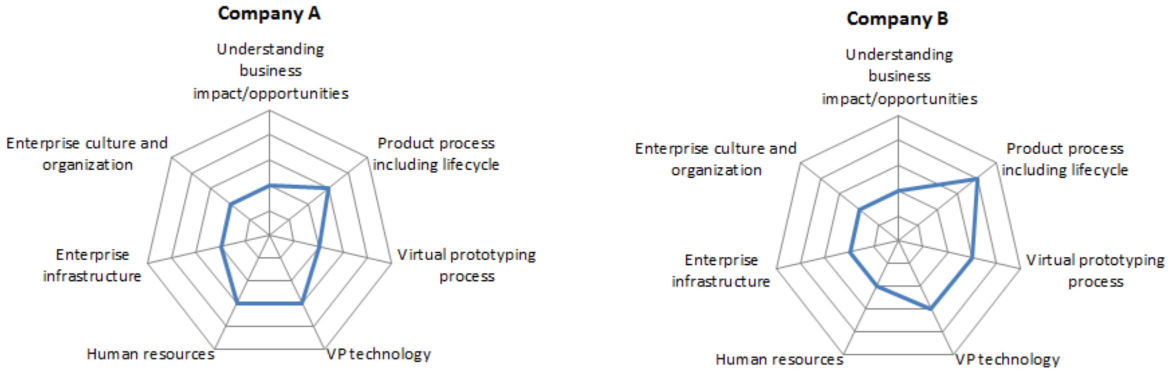

Figure 2. Virtual prototyping maturity level of Company A and Company B

Company B is currently implementing and developing new concept design processes as part of the PLM implementation. It has well-defined NPD processes, and the use of the VP integration is described in part in them. The concept design is emphasized in the new process definition. The process implementation has a top-down approach, i.e. the higher level process is implanted first, and it then goes towards more detailed definitions. As part of the process development, the VP project is also ongoing. The processes are at company corporation level, but the research case, in practice, focuses on developing the VP environment at a new facility into which it is moving.

Currently, simulators (virtual environments, VEs) are not used systematically as part of any process. Concept design is a separated process in which VE is the media for supporting communications within design reviews and requirements validation. Model-based systems engineering is an active topic at the company. Nevertheless, the interest in modelling and simulation has mainly focused on internal product properties, such as function and strength. MBS and other CAE tools have been used extensively there. However, in this research ‘external’ product properties (like ergonomics and safety) are the most interesting because of the focus on the concepts of user interfaces, which is a new approach for the company. Another question that has arisen is what is needed at the level of the product specifications and models for evaluating a concept.

Company B has a good level of maturity for implementing VP at the product process level (Figure 2) because it has been adopted in the PLM implementation. Currently, the company is implementing a new VR technology system that will improve the level of maturity in this area. The maturity of business understanding, cultural and organizational as well as infrastructure and human resources issues, is at a lower level because of the stronger emphasis on pilots in product design and at the development department. There is already awareness of the need to expand VP within all aspects of enterprise.

3 DISCUSSION

Figure 2 is a good illustration of the situation in the companies during the VP implementation. It can direct the development work in companies to help them gain earlier benefits from the use of VP in design. It also highlights seven categories that are directly connected to the VP implementation. A VIRMA has been developed during the research into the two company cases' VP implementation. The goal of the research was to improve the use of VP in industry, and the VIRMA was developed alongside this.

The two industry cases differed from each other: one company had installed and used the virtual environments system first and then begun to develop the processes further. The other company had done it mostly vice versa: first it had made the process changes at the theoretical level (not yet in practice) to describe how to use VP in concept design and then it had adopted the VR technology system. The maturity model approach for measuring the implementation level is good because it does not take a stance on which approach is best, only what the level of maturity is.

During the research, the companies' motivation for the VP adaptation was discovered. The companies saw that rapid and agile concept modelling and simulation incorporated with verification and need/requirement validation was needed. Early feedback on the design was seen as important, and they agreed that this led to better quality products and shorter time to market. The VP also makes more radical concept experiments and 'what if' questions possible. The companies also saw Systems Engineering and Requirements Engineering disciplines that should be regarded here.

The companies felt that some competitors were further ahead in applying new technologies and they wanted to narrow the gap. Moreover, it can be said that there is a certain 'wow' factor when talking about virtual reality technology, and this affects the companies' images. An eagerness to learn more and to go forward in the R&D sector also motivates companies. The aim is better use of 3D data.

The companies could see the same benefits of using VR technology in design as listed in Aromaa et al. (2012). They also thought that VP helped with the complexity of products and in perceiving modularity. The need for large real-time multi-discipline (mechanics, control, hydraulics, energy, environment, etc.) dynamics simulations in which users were involved was also recognized. The use of VP makes good design possible and therefore improves value for the customer.

Based on Becker et al. (2009), several iterations are needed when developing maturity models. The initial iterations for VIRMA were made during this research but several iterations are still needed, especially in developing quality assurance and measurement methods.

4 CONCLUSIONS

This paper describes a virtual prototyping implementation of a maturity model (VIRMA) for implementing VP into companies' design, especially in the mobile machine domain. It also shows the companies' maturity levels and lists possible challenges during the implementation. VIRMA consists of the following categories: (1) understanding business impacts/opportunities, (2) the product process including the lifecycle, (3) the virtual prototyping process, (4) virtual prototyping technology, (5) enterprise infrastructure, (6) human resources, and (7) enterprise culture and organization. The maturity of the companies seemed to be at a level at which there was an interest and capability to adapt to the new technology. The technology implementation is therefore not seen as a big challenge, but the rapid and agile use of it is a concern. The main challenge was the change of processes and the way of working. Three main types of challenges were recognized: human, technology and process related.

Currently, the use of VP systems in companies in the machine industry is quite novel, and there is therefore not much guidance or many processes for its implementation. VIRMA supports companies in improving their adaptations of VP and benefitting earlier from VP use in design. Using VIRMA, it is easy to measure the current maturity level in companies and to define further development steps for the VP implementation. VIRMA was defined during the research in two company cases. It is still under development and needs more iteration cycles, testing in several companies and validation.

However, not many companies in this area use VP yet.

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PUBLICATION 4

Suitability of Virtual Prototypes to Support Human Factors/Ergonomics Evaluation During the Design

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Suitability of virtual prototypes to support human factors/ergonomics evaluation during the design

Susanna Aromaa [a], [*], Kaisa Väänänen [b]

[a] VTT Technical Research Centre of Finland Ltd, Tekniikankatu 1, 33101 Tampere, Finland
[b] Human-Centered Technology (IHTE), Department of Pervasive Computing, Tampere University of Technology, Korkeakoulunkatu 6, P.O.Box 589, 33101 Tampere, Finland

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ABSTRACT

In recent years, the use of virtual prototyping has increased in product development processes, especially in the assessment of complex systems targeted at end-users. The purpose of this study was to evaluate the suitability of virtual prototyping to support human factors/ergonomics evaluation (HFE) during the design phase. Two different virtual prototypes were used: augmented reality (AR) and virtual environment (VE) prototypes of a maintenance platform of a rock crushing machine. Nineteen designers and other stakeholders were asked to assess the suitability of the prototype for HFE evaluation. Results indicate that the system model characteristics and user interface affect the experienced suitability. The VE system was valued as being more suitable to support the assessment of visibility, reach, and the use of tools than the AR system. The findings of this study can be used as a guidance for the implementing virtual prototypes in the product development process.

1. Introduction

A virtual prototype is a computer simulation of a physical product that can be presented, analysed and tested from various aspects. The process of constructing and testing a virtual prototype is called virtual prototyping (VP) (Wang, 2002). In recent years, the use of VP has increased in the product development process due to the improved availability and lowered prices of VP technologies (Choi et al., 2015). However, companies do not necessary know how to use VP technologies effectively, and for that reason they do not gain the full potential from it.

Virtual prototyping supports the evaluation of human factors/ergonomics (HFE) already in the early design phase. According to the principles of human-centred design (HCD) ISO 9241-210 (2010) and participatory design (Muller and Kuhn, 1993) of interactive systems, it is crucial to involve end-users and other stakeholders in the design and evaluation of technological products. International Ergonomics Association (IEA, 2000) defines HFE as “the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance”. Similarly, “Practitioners of ergonomics and ergonomists contribute to the design and evaluation of tasks, jobs, products, environments and systems in order to make them compatible with the needs, abilities and limitations of people” (IEA, 2000). According to Dul et al. (2012), HFE seeks to improve performance and well-being through systems design.

Virtual prototypes can be different in their level of virtuality and fidelity. Milgram et al. (1995) have developed a reality–virtuality continuum which is a continuous scale ranging between the completely virtual, virtuality, and the completely real, reality. Using the definition by Kalawsky (1993), virtual environment (VE) uses virtual reality (VR) technologies in order to provide human beings with the means of manipulation and sensory modalities. In practice, it means that humans are able to navigate in the VE (e.g. move from one place to another), manipulate objects (e.g. turn a steering wheel) and get sensory feedback (e.g. visual or auditory). The term mixed reality describes environments between virtual and real. An example of mixed reality is augmented reality (AR), which means that the user is able to see the real world, with virtual objects superimposed upon or composited with the real world (Azuma, 1997).

Several studies (e.g. Bordegoni et al., 2009; Bullinger and Dangelmaier, 2003; Cecil and Kanchanapiboon, 2007; Karkee

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[*] Corresponding author.
E-mail address: susanna.aromaa@vtt.fi (S. Aromaa).

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et al., 2011; Kremer, 1998; Kim et al., 2011; Kulkarni et al., 2011; Lawson et al., 2016; Park et al., 2009; Seth et al., 2011) state that VP has been considered as a powerful prototyping solution to overcome the shortcomings of conventional prototyping methods. They conclude that the production of a physical prototype is costly and time-consuming and, therefore, the reduction of the number of physical prototypes would shorten the time to market. Mujber et al. (2004) summarise the benefits of virtual reality in manufacturing applications in three categories: design, operations management and manufacturing processes. The benefits at technological, design and business levels are described by Aromaa et al. (2012). In addition, Leino (2015) models the business and organisational value of VP.

In the prototype fidelity domain, there are related studies that do not apply virtual reality techniques but compare, for example, computer and paper prototypes (Boothe et al., 2013; Lim et al., 2006; Sauer and Sonderegger, 2009; Sauer et al., 2010). These studies show that the main usability issues can be identified with prototypes of different fidelity levels. Some usability issues, however, cannot be evaluated using these prototypes, and therefore, Lim et al. (2006) state that it is important to determine what aspects need to be evaluated before building low-fidelity prototypes.

Perez and Neumann (2015) requested consideration of VP tools in supporting the integration of HFE issues in the design of new workplaces. They identified the importance of the utility of the VP tools from the ergonomists' and engineers' points of view, also listing categories to be considered, such as time, cost, training, difficulty to use, trustworthiness, graphics, flexibility, usefulness, and report presentation. Other approaches to support the development and usability of VP systems have been suggested by Stanney et al. (2003); Sutcliffe and Gault (2004); Eastgate et al. (2014). In addition, Jia et al. (2012) proposed a method for the design of more usable and efficient virtual training systems. Canuto da Silva and Kaminski (2015) proposed a procedure for the selection of virtual and physical prototypes in the product development process.

According to Ma et al (Ma et al., 2011), the collaborative VE is a useful tool for supporting complex product design. Therefore, VP can be used to support communication and interaction between different stakeholders during design reviews (Aromaa et al., 2012; Bordegoni et al., 2009; Bordegoni and Caruso, 2012; Kremer, 1998; Leino, 2015; Shen et al., 2010). Huet et al. (2007)claim that design reviews are efficient tools for sharing information about the product and for managing knowledge exchange. In addition, the use of VP during the HCD is a complex task and therefore approaches to support the use of virtual prototypes in HCD have been developed (Barbieri et al., 2013; Bordegoni et al., 2009, 2014; Broberg et al., 2011; Ferrise et al., 2013; Hall-Andersen and Broberg, 2014; Mahdjoub et al., 2013).

The use of VP in HFE evaluation has been studied in several research projects such as those by Wilson and D'Cruz, 2006; Bullinger and Dangelmaier, 2003; Park et al., 2009; Bordegoni et al., 2009; Karkee et al., 2011. It seems that the fidelity of the prototype does not affect the subjective evaluation of the usability of the product, but it affects the task performance and therefore the HFE evaluations. Bruno and Muzzupappa (2010) discovered that VR techniques are valid alternatives to traditional methods for the usability evaluation of product interfaces, and that the interaction with the VE does not invalidate the usability evaluation itself. However, in VEs users may become fatigued more quickly, require more time and greater effort and experience more discomfort and more task difficulty than in a real environment (Hu et al., 2011). Therefore, Wu et al. (2012) discovered that the results from the 1991 revised NIOSH Lifting Equation RWL tool were significantly larger in a virtual prototype than in physical prototype. Pontonnier et al. (2013) compared assembly tasks in a real environment and in VEs with and without haptics. They discovered that the mechanical limitations of the haptic device lowered the sensation of presence and resulted in an increase in the difficulty compared to real environment and VEs without haptics. Lawson et al. (2015) compared virtual and physical prototypes and discovered that virtual prototypes had lower validity and reliability than physical ones for identifying entry and exit issues in passenger vehicles. Gavish et al. (2013) studied the use of VR and AR training for industrial maintenance and assembly tasks. They found that the AR system was suitable for training but the VR system's suitability needed to be evaluated further. Nee et al. (2012) review the use of AR applications in design and manufacturing.

Digital human models (DHMs) can be used for proactive analysis of HFE in design (Chaffin, 2005; Demirel and Duffy, 2007). Lämkull et al. (2009) found that DHMs have been proven to correctly predict HFE issues for standing and unconstrained working postures. In addition, DHMs can provide information to designers, for example, about workers' reach, clearance, vision, posture and strength capabilities (Feyen et al., 2000; Sanjog et al., 2015). Nevertheless, the functionality of DHMs still needs improvement (Chaffin, 2007; Lämkull et al., 2009). In this paper, however, we discuss only real users using virtual prototypes (see a mixed prototyping framework in Bordegoni et al., 2009).

Despite the research carried out in the area of VP, there is not enough knowledge of the efficient use of VP in HCD. In particular, the question regarding which type of virtual prototypes should be used in HFE evaluation remains open. Therefore, companies who use VP in design are unable to gain full potential from it. The purpose of this study was to evaluate the suitability of VP to support HFE evaluation during the design phase. Two virtual prototypes, augmented reality and virtual environment, were selected to be tested in this study. They were chosen because both technologies can be used to visualise new design solutions such as a maintenance platform for machines. The goal was to find out differences between different fidelity level prototypes in the reality–virtuality continuum. The findings of this study can provide guidance for the preparation and use of virtual prototypes in HFE evaluation. The paper is organized as follows. Section 1 presents related work. Section 2 describes the design of the study. Section 3 provides results from the tests. Section 4 discusses collected results and Section 5 draws conclusions.

2. The study design

2.1. Experiment design

The goal of the study was to evaluate the suitability of VP to support HFE evaluation. A semi controlled between-group experiment was employed in the study. Nineteen participants from a company that offers minerals processing solutions and services took part in the experiment. They were designers or other stakeholders from a product lifecycle of the maintenance platform of a rock crushing machine. They all deal with HFE issues such as performance and well-being during the design process. The independent variable was the type of a virtual prototype: AR prototype and VE prototype. The two experiments will be called AR test/AR system and VE test/VE system for the remainder of this paper. Dependent variables measured in this experiment were the suitability of the virtual prototype for the HFE evaluation, and the overall assessment of the design object. In addition, subjective workload was evaluated.

2.2. Participants

Nine people from the company participated in the AR test. Six subjects were design engineers, one an assembly worker, one an assembly designer and one a project leader. All the participants were males and stakeholders from the product lifecycle and have an understanding of the maintenance task and its requirements regarding HFE issues. Their average age was 34 years (age range: 25–47 years) and their average time in their current employment was 8 years (range: 1–20 years). Their average height was 1.83 m (range: 1.70–2.03 m). Four people had never used VR technologies before, four had tried VR technologies before and one had used VR technologies more frequently.

Ten people from the company participated in the VE test. They were different from the test subjects participating in the AR test. All of them were males and design engineers. They had an understanding of the maintenance task and its requirements regarding HFE issues. Average age was 37 years (age range: 29–56 years) and their average time in their current employment was 10 years (range: 3–30 years). Their average height was 1.85 m (range: 1.74–1.98 m). Six people had never used virtual reality technologies beforehand. Four of the test subjects had tried VR technologies before.

2.3. Data collection and analysis

Questionnaires were used as data collection method in this semi-structured experiment. Participant demographics and consent forms were collected first. Next, the questionnaire about the overall assessment of a design object (a maintenance platform) was used. The questionnaire included three open questions regarding the design issues, development ideas and required information for design decision making. Participants also verified the design object on a Likert scale from one (strongly disagree) to five (strongly agree). In addition, participants explained their selection on the Likert scale. Next questionnaire was related to the suitability of the current system for HFE evaluation during the design. The questions were based on HFE checklists such as Karwowski (2006) and related to the maintenance task at hand. Participants selected on the Likert scale (one as not at all and five as very well) how well the system supported HFE evaluation. An unweighted NASA-TLX (Hart and Staveland, 1988) questionnaire was used to collect the experience of subjective workload during the use of the system. In addition, an adopted simulator sickness questionnaire (SSQ) (Kennedy et al., 1993) was used in the VE system but not in the AR system, because the AR system was not considered to be an environment that could provide SSQ symptoms in a given time frame. In applied SSQ, a four point Likert scale from none to severe was used to collet symptoms before and after the test. A content analysis was applied for qualitative data analysis and T-test in SPSS was used for the statistics.

2.4. Virtual prototypes and the test situations

The design object reviewed in the test was a maintenance platform attached to a mobile rock crushing machine. This was an upgrade for the existing machine. The purpose of the maintenance platform is to provide a safe, ergonomic and efficient workspace for maintenance workers. This study investigates the use of two different virtual prototypes (AR and VE) from the reality –virtuality continuum. The prototypes are described in more detail in the following.

In the AR test, the system includes a virtual model of the product (the maintenance platform), the real rock crushing machine, a virtual frame and a cover, a real environment, three different postures of a digital human model (DHM) and a real participant. The environment is not authentic because the machine is located outside in the backyard of the factory. The weather was bright and sunny. The temperature was around five degrees and there was a cold wind. Participants were able to stand next to the real machine but could not climb on the virtual maintenance platform (Fig. 1). The models of the maintenance platform and DHMs do not have dynamic model characteristics. A user interface consists in the means of manipulation and sensory modalities. The means of manipulation were provided by buttons to show and hide models; move and scale the machine model for tracking purposes, and lock and release tracking. Different view angels could be achieved by walking around. Only visual feedback was provided as sensory modalities. Used hardware and software were iPad, Unity 3D and AR tracking with Qualcom Vuforia (Unity add-on component).

In the VE test system, the model included a virtual model of the product (the maintenance platform), a virtual model of the rock crushing machine, a virtual environment, three different postures of DHM, a real participant and 3D models of hands and shoes (Fig. 2). The models of the maintenance platform, the machine and DHMs did not have dynamic model characteristics. A participant's head, hands and feet were tracked, and therefore the participant was able to move hand and shoe models in the VE. The participant was able to stand next to the rock crushing machine or on top of the maintenance platform. He/she was able to walk around. A user interface consists of the means of manipulation and sensory modalities. The means of manipulation were provided to the participant by using verbal commands to show and hide DHMs, and to change the standing location (the Wizard of Oz approach). The participant was also able to move around. Only visual cues were provided as a sensory modality. Therefore, haptic feedback was not provided. Nevertheless, the participant was able to estimate collisions by using his/her hand and to look when it touched e.g. the railings of the maintenance platform. The hardware and software used were a head-mounted display (HMD) (Oculus), tracking (Vicon), Unity and Middle VR.

2.5. Test procedure

The AR study was conducted at the company facilities and the VE study in a VR-laboratory. At the beginning, there was an introduction to the project and the test to participants. The participants' goal was to review the possibility of performing two maintenance tasks on the maintenance platform: (1) a visual check of a feeder of the rock crushing machine, and (2) attempt to open a bolt in the machine frame. The use case was an upgrade model of a maintenance platform for a mobile rock crushing machine. Next, a consent form and the participant demographics were collected. After gathering initial information, the participant went to the test area (outside or VR lab) and was given a short introduction to the use of the AR system or the VE system. The participant was able to try the system for a while. In the AR system, the participant placed the maintenance platform in the right place, checked if it was possible to perform the maintenance tasks mentioned in the introduction and ended the task. In the VE system, the model of the maintenance platform was already in the correct place. After reviewing the maintenance task, the participant was asked to complete Nasa-TLX with unweighted scores, and other questionnaires about the overall assessment of a design object and the suitability of the system used for HFE evaluation. The interviewer wrote down the answers to the open questions and explanations of the selected Likert scale results. In addition, a modified SSQ was collected before and after the test with the VE system. The whole test took around 45 min in total including data collection.

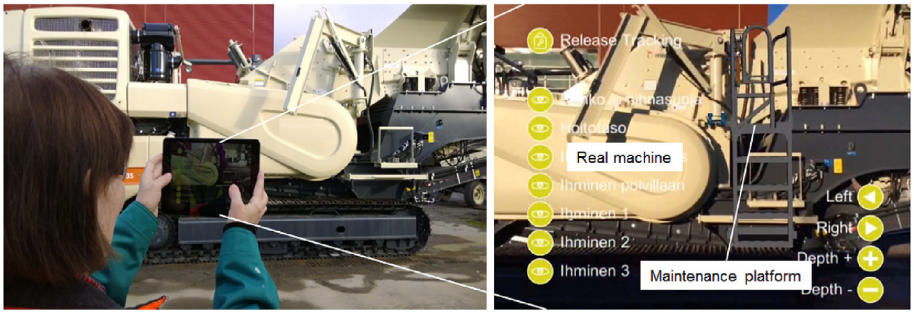

Fig. 1. The augmented reality system for reviewing the maintenance platform. A participant is holding a tablet PC in her hand on the left-hand side. On the right-hand side is a screenshot from the tablet PC: a 3D model of a maintenance platform is augmented on top of the real machine.

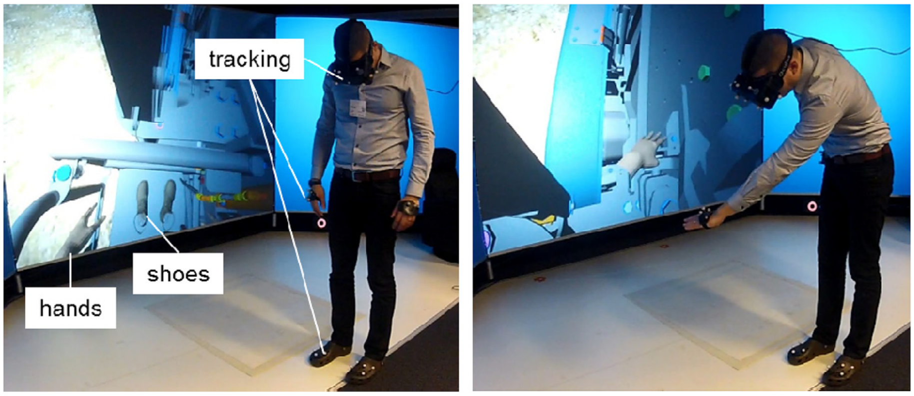

Fig. 2. The virtual environment system for reviewing the maintenance platform. Other people were able to see where the participant is looking from the screen behind.

3. Results

T-test was used to analyse differences between the two virtual prototypes in: overall assessment of the maintenance platform, suitability for the HFE evaluation, and subjective experience of workload and simulator sickness. Results indicate that both AR and VE prototypes were suitable to support HFE evaluation. However, the VE system was valued as being more suitable to support visibility and reach evaluation, and the assessment of the use of tools.

3.1. *Overall assessment of the maintenance platform with the virtual prototypes*

Seven people ($n = 9$) said that they did not find any design issues from the maintenance platform while they used the AR system e.g. “I didn't find any design issues because I wasn't able to see things I would have wanted” (male design engineer, 47 years of age). Five test subjects said that they did not come up with any new ideas of how to improve the maintenance platform. Some other comments were also made such as a participant who would have wanted more information about the maintenance platform e.g. material choices, measurements (e.g. a railing height), attachments and dynamics (e.g. how the port opens). The participants felt that many things which are needed in design decision making were left uncertain, e.g. the correct placement of the maintenance platform, how the maintenance worker fits into the platform, is he/she able to reach the targets, and how other parts move near the platform.

The use of a VE system provoked more comments about the design issues than the AR system. Three ($n = 10$) people said that they did not find any design issues with the maintenance platform. Four people mentioned that it was easy to see the feeder in the machine. Four people said that they were able to reach the bolt and perform the task. However, seven people said that the maintenance platform was tight and small: “The platform is small for big man” (male design engineer, 47 years of age). Four also mentioned that the reach distances in some cases are too long, e.g. when putting tools on the maintenance platform from the ground. When asked how to develop the maintenance platform, five people commented that the maintenance platform is OK. Nevertheless, five people commented that the maintenance platform could be bigger, and three people that the platform could be located a little lower. Four people would have wanted more information about design constraints: “I'm not able to say how to develop the maintenance platform further because I don't know all the constraints that are affecting the design” (male design engineer, 32 years of age). Three people did not require more information. Some other single comments were made about moving e.g. climbing stairs, going through the gate, kneeling on the platform.

With both prototypes, participants agreed that the maintenance platform is good, safe and efficient to work on the Likert scale (Table 1).

3.2. *Suitability of the virtual prototypes for the human factors/ergonomics evaluation*

The suitability of the virtual prototypes for the HFE evaluation was analysed with the questions from the HFE checklists as in Karwowski (2006). Totally, eleven questions were asked related to the maintenance task performed on the maintenance platform. In data analysis, two questions regarding visibility were put together as one to conclude a one HFE feature. The same was done to the two questions regarding reach issues.

Table 1
The overall assessment of the maintenance platform, ($p < 0.05$).

	AR ($n = 9$)	VE ($n = 10$)	t	p
	M (SD)	M (SD)		
The maintenance platform is good	3.78 (0.67)	3.70 (0.95)	0.204	0.840
The maintenance platform is safe to use	4.33 (0.71)	4.50 (0.71)	0.513	0.615
It is efficient to work on the maintenance platform	3.67 (0.71)	3.90 (0.74)	0.702	0.492

Both systems received more than the mean value on the Likert scale in visibility, climbing, enough room, postures, use of tools and reach (Table 2). In addition, the VE system received the mean value in task performing time. Below the mean were environmental factors, force and task time (in the AR system). There was a significant difference in the visibility scores for the AR system ($M = 3.3$, $SD = 1.3$) and the VE system ($M = 4.8$, $SD = 0.4$) conditions; $t(22) = -5.66$, $p = 0.000$. There was significant difference in the reach scores for the AR system ($M = 3.39$, $SD = 0.78$) and the VE system ($M = 4.45$, $SD = 0.61$) conditions; $t(36) = -4.721$, $p = 0.000$. In addition, there was significant difference in the use and carry tools for AR system ($M = 3.22$, $SD = 0.83$) and VE system ($M = 4.20$, $SD = 0.79$) conditions; $t(17) = -2.62$, $p = 0.018$. Postures ($p = 0.059$) and climbing ($p = 0.068$) were not statistically different but the values were close.

3.3. *Subjective experience of workload and simulator sickness*

There was no significant difference between the AR and VE systems in subjective workload (Fig. 3). Both systems were below mean value on the NASA-TLX scale (0 low demand, 100 high demand). In general, VE system received higher scores on mental, physical and temporal demand, but lower scores on performance, effort and frustration compared to AR system. None of these results were statistically significant. However, performance was close ($p = 0.054$).

An adopted SSQ was used in the VE test to find out if negative symptoms appear. If the symptoms are moderate or severe, they can affect the performance and experience of the participant. However, there were no severe symptoms after being in VE (mean values between 1.00 and 1.44). The biggest change was in general discomfort but this was not significant either (before $M = 1.11$, after $M = 1.44$). The AR system was not so immersive, and therefore SSQ was not used in the AR test.

4. Discussion

Results indicate that VP can be used to support HFE evaluation during the design. The significant differences between the use of AR and VE systems for the HFE evaluation are related to the system model characteristics (fidelity, virtuality, dynamics, statics, etc.), and how the means of manipulation and sensory modalities (haptics, aural, etc.) are provided.

The system model characteristics impact the suitability of the virtual prototypes for the HFE evaluation. A significant difference in visibility would have been even more different if the DHMs had not been provided in the AR system. By comparing the DHM's head location to the machine's frame, participants were able to estimate whether a maintenance worker is able to see targets. In addition, the significant difference would have decreased by providing more information e.g. DHMs' field of views to the tablet PC in the AR system. This same analogy can be found from the results of the posture evaluation. It is remarkable that there was no significant difference between the AR and VE system when evaluating the postures. This is because DHMs with three static postures were provided in the AR system to support participants' HFE evaluation. In addition, the use of DHMs increased the reach evaluation results ($M = 3.39$) in the AR system. However, reach was significantly different between the AR and VE systems. These findings suggest that it is important to provide required design information in some form to support design decisions making.

A natural and interactive interface with the context in use supports the HFE evaluation in VP. Based on the findings, the VE system was more natural and interactive than the AR system. A significant difference in visibility results was due to the fact that the participants were able to stand on the maintenance platform and see the feeder and other parts properly. In addition, in the VE system participants were able to use their own hands to see how far they can reach and also visually check whether their hands cut the model parts. Therefore, it was significantly better to do the evaluation of reach distances in the VE system. However, designers should remember that they are comparing the system dimensions against their own body size and this is not covering a whole population. The VE system also supported the evaluation of carrying and using tools (a significant difference from the AR system). In the VE, participants were able to perform tasks and act in the context. They were able to reach the maintenance platform from the ground and put the tools on top of it even though the tools did not exist virtually or physically. They were also able to imagine the use of tools while opening the bolt in the maintenance task. In the AR system, the interaction with the maintenance platform was limited because participants needed to keep the tablet PC in their hands

Table 2
The suitability of the AR and VE systems for the human factors/ergonomics evaluation, ($p < 0.05$).

By using this system I was able to evaluate …	AR ($n = 9$)	VE ($n = 10$)	t	p
	M (SD)	M (SD)		
the visibility of the feeder, the crusher and the frame bolt.	3.33 (1.03)	4.80 (0.41)	5.656	**0.000**
the load of the working postures.	3.11 (0.33)	3.7 (0.82)	2.080	0.059
the room for different working postures.	3.56 (1.01)	4.00 (1.05)	0.934	0.363
the reaches to the frame bolt from above and between railings.	3.39 (0.78)	4.45 (0.61)	4.721	**0.000**
the ergonomics and safety when climbing stairs.	4.00 (0.71)	3.20 (1.03)	1.947	0.068
the force needed to open the frame bolt.	2.00 (0.71)	2.10 (1.29)	0.206	0.839
the use of tools, and carrying them.	3.22 (0.83)	4.20 (0.79)	2.627	**0.018**
environmental effects (e.g. dust, noise, temperature).	2.67 (0.87)	2.20 (0.92)	1.136	0.272
the time spent opening the frame bolt.	2.78 (0.67)	3.00 (1.33)	0.451	0.658

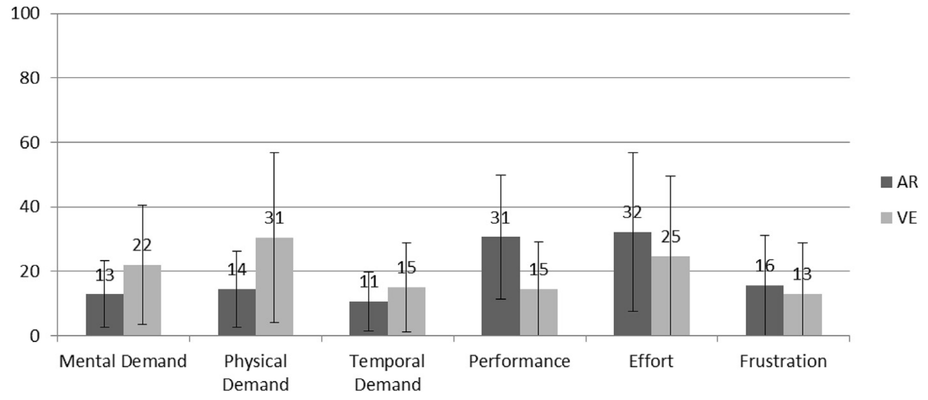

Fig. 3. Subjective workload after using the AR and VE systems.

and only a visual feedback was provided. In addition, the AR-technology was not robust enough to support more free movements. The image in the tablet PC was also small, so when you stood next to the rock crushing machine you were able to see only a small part of the maintenance platform. Therefore, participants tended to look at the maintenance platform from further away from the machine.

Other sensory modalities, in addition to the visual feedback, are required to better evaluate environmental factors, force and task time. The participants felt that the virtual prototypes were less suitable for the evaluation of environmental factors (e.g. noise, lighting) (AR M = 2.7; VE M = 2.2), force (AR M = 2.0; VE M = 2.1), and task time (AR M = 2.8; VE M = 3.0), from all HFE factors listed. Two different environments were provided: an outdoor environment and a virtual environment. However, none of these were real rough mine environments with noise and dust. Haptic and aural feedback was not provided in both cases and in the AR system the natural interaction with the maintenance platform was limited. However, sometimes the use of haptics does not increase the feeling of presence. Pontonnier et al. (2013) discovered that the mechanical limitations of the haptic device lowered the sensation of presence and an increase in the difficulty was reported compared to real environment and VEs. The results of the evaluation of the time required for the task could have been influenced by the fact that the participants were not required to perform the task step-by-step. Therefore, it might have been difficult to evaluate the time spent. According to Sauer and Sonderegger (2009), the task completion time may be overestimated when a computer-based prototype is used as compared to paper prototype.

Based on the subjective workload evaluation result, it can be seen that both systems were very usable and workload was not high. There was no significant difference between the systems. However, it can be seen that the use of a VE system was mentally, physically and temporally more demanding. Six participants (n = 10) had not used the VEs before and this can have affected the results. Hu et al. (2011) compared VE and physical prototypes and also discovered that more effort is needed to perform a task in a VE than in a real environment. In addition, as a result of using HMD, participants felt more immersed and therefore experienced some SSQ symptoms. On the other hand, the use of the AR system required more effort, performance and was more frustrating. One reason for this could be the technology readiness and usability of the AR system. In addition, the experience was different within the AR system; it required more imagination and lacked natural interaction. This could have generated more frustration.

The different prototypes did not affect the overall assessment (good, safe and efficient to work) of the maintenance platform. This supports the findings from the studies made about the system model characteristics of the prototype (not virtual prototypes, but e.g. computer vs. paper prototypes). In these studies, the fidelity level does not affect perceived usability, and therefore reduced fidelity prototypes are generally suitable to predict the product usability of the real appliance (Boothe et al., 2013) (Sauer and Sonderegger, 2009; Sauer et al., 2010). In addition, it also supports the Bruno and Muzzupappa (2010) discover that VR techniques are valid alternative to traditional methods for product interface usability evaluation and that the interaction with the virtual interface does not invalidate the usability evaluation itself.

This research had limitations that may have affected to the validity of the results. The AR system had technology challenges: the 3D model in the tablet PC was not stable and it vibrated on the screen sometimes. In addition, it was not possible to freely walk around and view the maintenance platform model from different perspectives because the rotation in the AR system did not work correctly. Another validity issue may derive from the use of the between group setup and the difference in professions of the participants. However, all of the participants were stakeholders that usually could have participated in a design process at some point.

5. Conclusions

The purpose of this study was to evaluate the suitability of the VP to support HFE evaluation during the design. Two different prototype systems (AR and VE) were tested in a between-groups set up. Design engineers and other stakeholders evaluated the suitability of the prototypes to support the HFE evaluation.

Results indicate that both AR and VE prototypes were suitable for the assessment of visibility, climbing, postures, space, reach and use of tools. However, the VE system was valued as being more suitable to support the assessment of visibility, reach, and the use of tools than the AR system. To assess HFE factors such as environment, force and time, more sensory modalities, are required in addition to the visual feedback. Moreover, results show that the system model characteristics can impact the suitability of the virtual prototype for the HFE evaluation. A more natural and interactive interface with the context of use can support the HFE evaluation.

It is challenging to use complex systems such as virtual prototypes in the design process. The findings of this study can provide guidance for the use of virtual prototypes in HFE evaluation. In addition, when using virtual prototypes in design, it is not always important to go for high fidelity and high virtuality prototypes. It is more important to use virtual prototypes that provide enough details and information to make good design decisions.

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PUBLICATION 5

Virtual Prototyping in Design Reviews of Industrial Systems

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Virtual Prototyping in Design Reviews of Industrial Systems

Susanna Aromaa
VTT Technical Research Centre of Finland
Finland
susanna.aromaa@vtt.fi

ABSTRACT

Virtual prototyping (VP) is increasingly applied during product development processes in industry. This paper investigates if the use of VP supports design reviews and identifies critical issues related to it. In addition, it illustrates a systematic approach for VP design review preparation. Studies were conducted on two cases in the rock crushing industry. Data was collected by observations and using questionnaires. Based on results, VP was seen to be suitable for supporting design reviews and cooperation between participating stakeholders. In addition, it enhanced the first-hand experience of the use context for design engineers. The use of the systematic approach for the preparation of VP design reviews highlighted the importance of the goal setting for the review meetings: it can improve or decrease the quality of the VP design review results. The systematic approach to VP design review preparation can be used by industry and also by the research community.

CCS CONCEPTS

• **Human-centered computing → Virtual reality** • *Human-centered computing → User centered design* • *Human-centered computing → Participatory design* • *Human-centered computing → Interface design prototyping*

KEYWORDS

Virtual prototyping, design review, human-centred design, participatory design

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1 INTRODUCTION

Industrial work context is becoming more complex due to digitalization and automation. This provides challenges, especially to human-machine interactions, and requires proactive approaches to consider not only a worker but a whole working context during design [1]. Virtual prototyping (VP) can be seen as one solution to support early human-machine interaction design in realistic contexts.

Traditionally, design engineers have used approaches in which three-dimensional 3D-CAD models of parts are reviewed on two-dimensional (2D) computer screens [5]. In recent years, however, the use of VP has increased in product development processes due to the improved availability and lowered prices of VP technologies [2]. Virtual reality (VR) technologies are being actively used in industry to support decision making and to enable innovations [3]. According to [4], a collaborative virtual assembly environment is a useful tool for supporting complex product design where each designer can bring their special advantages and communicate with each other. The utility of VP comes up, especially in allowing communication for those who are not familiar with 3D-CAD tools [5]. This can happen, for example, when different stakeholders participate to design reviews. The use of VP technologies to support design review meetings has been discussed in several studies such as [3, 6, 7].

Regardless of the positive experiences from VP use during design reviews it is still challenging to prepare VP design reviews systematically and execute them efficiently. Perez and Neumann [12] identified nine characteristics that were of critical concern to virtual human factors tools users (engineers and ergonomists) including time, cost, training, difficulty to use, trustworthiness, graphics, flexibility, usefulness, and report presentation. There are also other research challenges related to VP use in industry such as an easier model conversion process [3]. Lawson et al. [13] recommend future developments of VP technologies in the automotive industry, for example, for gaining a greater range of virtual contexts. In addition, it is challenging to illustrate, gather, record and share knowledge during the design reviews [9, 11]. For these reasons, there is still a need to understand the critical issues of VP design reviews better, and to pursue more systematic and standardised use of VP.

The goal of this study was to investigate the applicability of VP in design reviews and to gain insights from industrial settings. The research questions were: “Does VP support design reviews from the participants' viewpoint?" and "What are critical issues related to using VP in design reviews?". Chapter 2 presents related work regarding VP and design of virtual prototypes. Chapter 3 illustrates used methods and study design. Chapter 4 illustrates results from the cases. Discussion of the findings is in Chapter 5, and finally, Chapter 6 concludes the research.

2 RELATED WORK

2.1 Design reviews

Design review meetings are important milestones within a product development process. They ensure that the design is assessed from many different viewpoints such as performance, safety, endurance, robustness, lifecycle costs and ergonomics [8]. The design review process includes planning, organization, actual meeting and reporting [8]. The design reviews are efficient tools for sharing information about the product and for managing knowledge exchange [9]. Knowledge sharing and creation can be contributed to by collaborative interactions between individuals, teams, and information systems [10].

2.2 Virtual prototyping

According to [14] a virtual prototype is a computer simulation of a physical product that can be presented, analysed and tested from various aspects. The process of constructing and testing a virtual prototype is called VP. Virtual prototyping makes it possible to evaluate the product in an early design phase. It is also said that VP saves time and money compared to physical prototyping [5]. Seth et al. [5] pointed out that by using VP it is possible "to address various aspects of the product life cycle such as ergonomic, workstation layout, tooling design, off-line training, maintenance, and serviceability prototyping".

VR technologies can be used during VP. According to [15], a virtual environment (VE) uses VR technologies in order to provide human beings with the means of manipulation and sensory modalities. Practically, it can be said that humans are able to navigate in the VE (e.g. walk), manipulate objects (e.g. lift a tool) and get sensory feedback (e.g. see and hear). Virtual prototypes can be different in their level of virtuality and fidelity. According to [16], a reality-virtuality continuum is a continuous scale ranging between the completely virtual and the completely real.

Virtual reality technologies are being applied widely in design reviews and assembly tests of products [2]. Bordegoni et al. [6] have effectively used VP for the rapid design review of new products (e.g., washing machines). Kremer [7] has used virtual reality tools in design reviews of mechanical products. The opinion stated in the publication was that they are especially suitable for design reviews and product configuration. Santos et al. [17] have presented a unique effort in hardware and software research and development to facilitate collaborative mixed reality design reviews in indoor and outdoor scenes with mobile users. Aromaa et al. [18] have listed the benefits of the use of VP during design reviews, for example, user participation and information and knowledge sharing. Bordegoni and Caruso [19] have used VP in case studies in the car interior design sector. Choi et al. [20] have introduced an approach and tools for virtual prototyping design review. Ferrise et al. [21] have also proposed three prototyping strategies (real, virtual and mixed) to support design engineers of a multisensory experience of products. According to [2], future research topics regarding manufacturing and VR technology should be focusing on the development of the whole product development processes with dynamic integration between each element. This means that also the related standards need to be constantly developed and extended. In addition, the VP systems should be tested more often in the real context as exemplified in [18]. The suitability of VP to support design reviews is researched in many of these studies by proving the concept in case studies [6, 7, 20]. In [19], the usability of the VP system and its usefulness in collaboration were evaluated in empirical study. However, the research participants were students and therefore real stakeholders' opinions were not investigated.

Virtual prototyping is beneficial in making it possible to evaluate human factors/ergonomics (HFE) issues even in an early design phase [6, 22–25]. According to [6], virtual prototyping is particularly useful in the assessment of interaction systems used by users. This means that by engaging users in design reviews based on human-centred design [1] and participatory design [26, 27] principles it is possible to improve and deepen communication, knowledge transfer, collaboration and user participation in the design process. The participatory approach in design and development is a procedure in which the users, and workers of a production process or a machine operation have the opportunity to influence the content of the designed system. According to [28], VR is a valid tool to support participatory design, because it facilitates collaboration among designers and users. Davies [29] has studied the adaptation of VP for participatory design of work environments. Leino [30] says that from a design methodology viewpoint, VP enables a better use of a participatory design approach. In addition, VP combined with human-centred and participatory design methodologies enables more systematic and holistic consideration of HFE aspects [30].

2.3 Design of virtual prototypes

There is a possibility to use many different variations of VP systems during the design process (e.g. virtuality, fidelity); these issues affect testing and, especially, HFE evaluation. Therefore, it is important to pay attention to how virtual prototypes are designed. This section presents some of the currently existing systematic approaches for virtual prototype design.

Aromaa et al. [32] proposed a framework for virtual prototyping in human-machine interaction design to be able to systematically construct and test virtual prototypes (Fig. 1). However, the use of the approach was not thoroughly tested in the cases reported in [32]. The framework combines human, interface and system model elements. The human interacts with the system model through the interface. In addition, it includes a test model element that can contain different data collection and analysing methods (e.g., HFE, comfort, user experience).

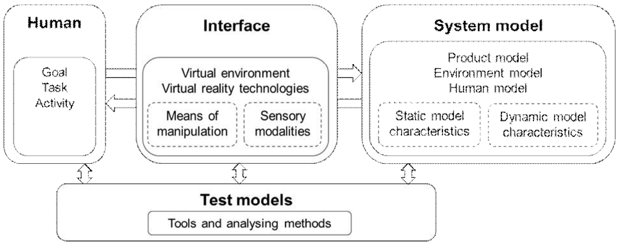

Figure 1: An adapted framework for virtual prototyping in human-machine interaction design from [32].

Virtual environment development structure (VEDS) has been used to support the development of VEs in industrial use, industrial training and education [31]. Its main steps are: preparation, analysis, specification, building, implementation and evaluation. VEDS is a thorough framework with goal setting and constraints, requirement analysis, task and user analyses, appropriate interface guidelines, predictions of task performance, an iterative design/test cycle, and an evaluation process. However, as the framework is thorough it might be challenging to use it during iterative and rapid design phases.

Mahdjoub et al. [33] have introduced the concept of intermediary objects (IOs) and proposed a framework to define a structure for the objects. They see a virtual prototype as one type of IO. The structure includes seven interrelated models: product model, product use model, interaction model, support tools model, rules and interaction model, evaluation model and convergence situation model.

The interactive virtual prototype (iVP) is introduced by [34]. They define the iVP as the conversion of a virtual prototype into multisensory functional models. The iVP is a combination of functional sensorial models accessed by means of a multimodal and multisensory input/output interaction environment. Ferrise et al. [34] emphasize that the interaction and interface modules are required when the user uses the virtual prototype.

There are also different aspects to consider when designing virtual prototypes. A reference framework for mixed prototyping [6] represents a two-dimension prototype and a user that can be either real or virtual. The framework also includes interaction that can be direct or mediated. Further, a multisensory interaction model has been proposed to consider multiple senses which are involved in the perception of virtual objects [35].

When designing virtual prototypes it is also important to consider their usability. Stanney et al. [36] introduced a systematic approach to design and evaluate a VP system's usability (MAUVE). Kalawsky [37] has also introduced a tool (VRUSE) to evaluate the usability of virtual interfaces.

As a summary, these proposed virtual prototype design approaches have good qualities but have been tested only in rare cases. There should be more research studies of the applicability of them to develop them further. This would support their systemisation and standardisation for use in everyday practices during product development processes.

3 METHODS

Two VP design review cases were studied within the same industrial company, Metso Minerals, Inc. Participants were different between the cases apart from one person who was in both. The purpose was to use the systematic approach to VP design review and find out the industrial participants' subjective experience of the VP's suitability to support design reviews. Data was analysed by applying the qualitative thematic analysis approach [38]. This chapter describes the used systematic approach to VP design reviews, and the study design and setup in cases.

3.1 Systematic Approach for Virtual Prototyping Design Review

Aromaa et al.'s [32] framework for virtual prototyping was selected as a basis for a systematic design of VP design reviews. Many of the previously presented approaches contained the same aspects and were overlapping. However, this model was comprehensive and simple enough to be tested rapidly in industrial settings. It was further extended to create a template to support the systematic preparation of a VP design review. This is a relatively basic tool for the design engineers but its novelty is in the simplification of the approaches to a practical and usable form. In addition, it forces people to work systematically when designing VP systems and enhances knowledge sharing between people involved in the VP system design.

The template can be used in preparation of VP systems for design reviews and also for other experiments. The template includes general information: a date, a goal of the design review and a description of a design object. In addition, it includes more detailed information based on the framework (Fig 1) [32]. In the approach, a human means a real participant/user including their tasks and activities. A system model means both static and dynamic model characteristics and can include product, environment and human models. For an interface, definition of sensory modalities (what a user can see, touch, etc.) and means of manipulation are needed (how a user can move and interact). It is also important to know which software and hardware are used. Test models are important from an evaluation and review point of view (e.g. was the design suitable for its purposes). These issues should be discussed with different stakeholders and filled in before design reviews.

3.2 Case 1: A Maintenance Platform for a Rock Crushing Machine

3.2.1 Case description. The design object reviewed in this case was a maintenance platform attached to a mobile rock crushing machine. This was an upgrade for an existing machine. The purpose of the maintenance platform is to provide a safe, ergonomic and efficient workspace for maintenance workers.

3.2.2 Planning the VP design review. Before the actual design reviews, a company representative (project leader), a virtual reality lab expert and a human factors expert (evaluation responsible) discussed how the system should be built. They filled in the template (Table 1) together. The system model included a virtual model of the product (the maintenance platform), a virtual model of the rock crushing machine, a virtual environment, three different postures of the digital human model (DHM), a real participant and 3D models of hands and shoes. The models of the maintenance platform, the machine and DHMs did not have dynamic model characteristics. A participant's head, hands and feet were tracked, and therefore a participant was able to move hand and shoe models in the VE (Fig. 2). The participant was able to stand next to the rock crushing machine or on top of the maintenance platform. S/he was able to walk around. The user interface consisted of a means of manipulation and sensory modalities. The means of manipulation were provided to the participant by using verbal commands to show and hide DHMs, and to change the standing location (Wizard of Oz approach). The participant was also able to move around. Only visual cues were provided as a sensory modality. Therefore, haptic feedback was not provided. Nevertheless, the participant was able to estimate collisions by using his/her hand and see when it touched, e.g. railings of the maintenance platform. The hardware and software used were head-mounted display (HMD) (Oculus), tracking (Vicon), Unity and Middle VR. The design engineers' goal was to understand the user's point of view when performing a maintenance task. They assessed HFE issues such as task performance, space, safety and reach.

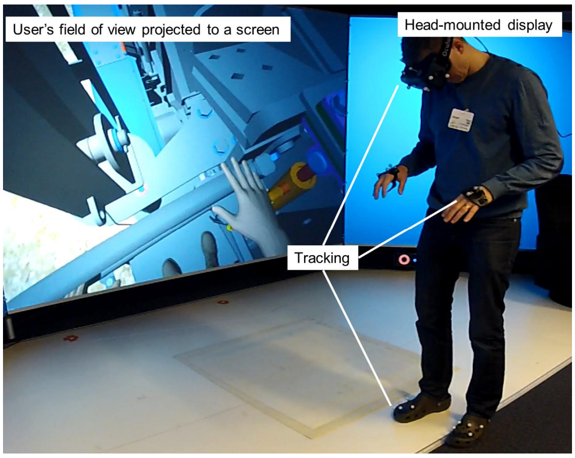

Figure 2: A participant reviewing a maintenance platform.

3.2.3 Participants. Ten people from the company participated in the design review. All of them were males and design engineers. Their average age was 37 years (age range: 29–56 yrs).

3.2.4 Data collection. Data was collected using observation and questionnaires. A consent form and the participant

Table 1: A plan for virtual prototyping design review in Case 1.

Date	19 January 2015	
Goal	To evaluate the maintenance platform. Purpose of the maintenance platform is to provide safe, ergonomic and efficient workspace for maintenance workers.	
Design object	The design object reviewed in the test was a maintenance platform attached to a mobile rock crushing machine.	
Human	Task/activity	The participants' goal was to review the possibility to perform two maintenance tasks on the maintenance platform: (1) visual check of a feeder of the rock crushing machine, and (2) try to remove a bolt from the machine frame.
System model	Static model characteristics	- A virtual model of the maintenance platform - A virtual model of the rock crushing machine - A virtual environment - Three different postures of digital human model - 3D models of hands and shoes - Pre-determined standing positions: ground and on top of the maintenance platform
	Dynamic model characteristics	- Head, hands and shoes are tracked
Interface	Sensory modalities	- Visual cues
	Means of manipulation	- Participant used verbal commands to show and hide DHMs, and to change the standing location. - Participants are able to walk around
Technology	Virtual reality technologies	- Head-mounted display (HMD) (Oculus) - Tracking (Vicon), - Unity - Middle VR
Test models	Evaluation methods and tools	- Assessment of the human factors / ergonomics issues - Is it possible to perform a maintenance task? - Is it safe to work on the maintenance platform? - Is there enough room to operate? - Are the reach distances acceptable?

demographics were collected. The questionnaires included questions about an overall assessment of a design object (here a maintenance platform); the possibility to detect all necessary factors, and the possibility to generate new design solutions. In addition, participants evaluated how well the VP system supports design review and does it increase communication and interaction during the design review. A Likert scale from one (strongly disagree) to five (strongly agree) was used in all questions. Participants were also able to further elaborate their selections. An adopted Simulator sickness questionnaire (SSQ) [39] was used to collect symptoms before and after the test with a four-point Likert scale from one (none) to four (severe).

3.2.5 Test procedure. The study was conducted in a VR-laboratory. In the beginning, there was an introduction to the project and a test for participants. The participants' goal was to review the possibility of performing two maintenance tasks on the maintenance platform: (1) a visual check of a feeder of the rock crushing machine, and (2) to try to open a bolt in the machine frame. In this experiment only one person at a time was using a virtual prototype, although in a normal design review there are also other stakeholders present. A consent form and the participant demographics were collected in the beginning. Next, the participant got a short introduction to the use of the VE system. The participant was able to try the system for a while. After reviewing the maintenance task, the participant was asked to fill in questionnaires about the overall assessment of a design object and the suitability of the system used for design review purposes. In addition, a modified SSQ was collected before and after the test with the VE system. The whole test took around 45 minutes in total including the data collection.

3.3 Case 2: Noise Encapsulation for a Rock Crushing Machine

3.3.1 Case description (Table 2). A design object reviewed in

Table 2: A plan for virtual prototyping design review in Case 2.

Date	18 November 2016	
Goal	To evaluate the noise encapsulation and to see a current status of virtual reality technologies.	
Design object	The design object reviewed in the test was a noise encapsulation of a mobile rock crushing machine.	
Human	Task/activity	- The participants' goal was to review the noise encapsulation - One participant in the virtual environment at a time, and other stakeholders around a table viewing the projector
System model	Static model characteristics	- A virtual model of the noise encapsulation - A virtual model of the rock crushing machine - A virtual environment - Virtual models of hands - A virtual model of a user's helmet - A virtual floating camera model - Pre-determined standing positions: 11 waypoints (home (where the user is starting, ground level), 0–9: ground near ladders, ground underneath maintenance platform, on the maintenance platform, on the walkways on top of the machine))
	Dynamic model characteristics	- Head and hands are tracked - Lighting is adjustable (day and night) - Waypoint markings on the ground can be hidden - Different camera views are shown on the projector (virtual environment around the user or first-person view). The placement of the cameras is able to be changed. - Camera handles are highlighted when grabbed by the user's hand
Interface	Sensory modalities	- Visual cues from head-mounted display (HMD) and projector
	Means of manipulation	- Participant used verbal commands (VR expert uses keyboard) to change (teleport) the standing location, hide/show waypoints and change lighting - Participants are able to walk around inside the tracked volume - Participants can move cameras by hand - VR expert can create camera, move it or change the view which is projected to the projector by using HTC Vive controller
Technology	Virtual reality technologies	- HMD (HTC Vive) - HTC Vive controller - Leap Motion hand-tracking sensor - Unity - Projector
Test models	Evaluation methods and tools	- Assessment of the assembly and general feasibility of the product

this design review was a noise encapsulation of a mobile rock crushing machine engine. This was an upgrade for the existing machine. The purpose of the noise encapsulation is to reduce noise emissions to the environment.

3.3.2 Planning the VP design review. The template (Table 2) was filled in by a company representative, a VR lab expert and a human factors expert. They discussed via email and phone how the system should be built up before the actual design review. The system model included a virtual model of the product (the noise encapsulation), a virtual model of the rock crushing machine, a virtual environment, virtual models of hands, a virtual model of a helmet, a virtual model of a camera and 11 pre-defined waypoints. The models of the noise encapsulation and the machine did not have dynamic model characteristics. It was possible to change the lighting of the environment between day and night. In addition, it was possible to project different camera views on screen for others to see. A participant's head and hands were tracked, and therefore the participant was able to move hand models in the VE (Fig. 3). The participant was able to stand next to the rock crushing machine or on top of the machine on the waypoints. S/he was able to walk around inside the tracked volume. A user interface consisted of a means of manipulation and sensory modalities. The means of manipulation were provided to the participant by using verbal commands to change the standing location, hide/show waypoints and change lighting. A VR expert carried out these commands using a keyboard. Only visual cues were provided as a sensory modality: a HMD view for participants and a screen view for other stakeholders. The hardware and software used were HMD (HTC Vive), HTC Vive controller, Leap Motion hand-tracking sensor, Unity and the projector. Test model included the assessment of the assembly and general feasibility of the product.

3.3.3 Participants. Eleven people participated in the design review. Ten were from the company and represented roles such as design engineers, design managers, project leaders, development managers, mechanical engineer and technicians. In addition, one entrepreneur from a subcontracting company was present. They all were males and the average age was 43 years (age range: 30–55 yrs).

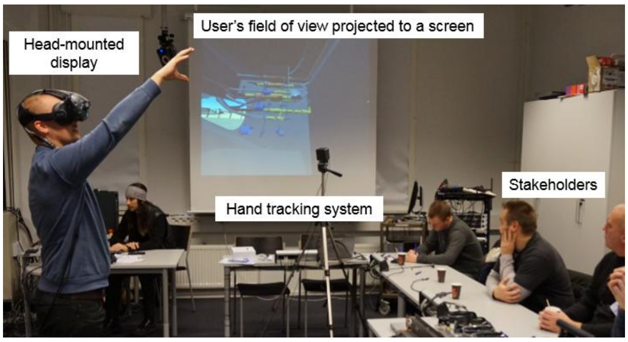

Figure 3: A participant reviewing a noise encapsulation with other stakeholders.

3.3.4 Data collection. Data was collected using observations and questionnaires. A consent form and participant demographics were collected in the beginning. The questionnaires included questions referring to the overall assessment of a design object (here a noise encapsulation); the possibility to detect all necessary factors, and the possibility to generate new design solutions. In addition, participants evaluated how well the VP system supports design review and whether it increase communication and interaction during the design review. A Likert scale from one (strongly disagree) to five (strongly agree) was used in all questions. Participants were also able to further elaborate their selections. The simulation sickness symptoms were evaluated by one question: "Did you feel any negative symptoms when you were in the VE (e.g., sickness, headache, eye symptoms)?". A three-point Likert scale (from 1=no symptoms to 3=severe symptoms) was used. If symptoms developed participants elaborated on them.

3.3.5 Test procedure. The design review was conducted in a VR-laboratory. In the beginning, there was an introduction to the project and the study setup for participants. The participants' goal was to see the current status of the VR technologies and review the model of the noise encapsulation. The review was performed in two groups: in the first group there were four participants and in the second group were seven participants. One participant at a time was able to try out the VE system. Others were able to see a first-hand view of the participant or other views that the virtual camera could provide from a projection screen, and discuss them while one of them was using the system. There was no detailed review plan provided but it was said that they could review the model from different points of view (e.g., tightness, assembly, maintenance). A consent form and participant demographics were collected in the beginning. The durations of the design reviews were around 30 for the first group and 60 minutes for the second group. After reviewing the noise encapsulation, participants were asked to fill in the questionnaire.

4 RESULTS

The results from the case studies are presented in this chapter.

4.1 Case 1

The participants felt that the used VE system supported the design review purposes well (mean value, M=4.6, standard deviation, SD=0.52) (Fig. 4). They said "it felt like really being next to the machine" (design engineer, 47 years) and that it "added value" (design engineer, 29 years). They agreed that they could compare the machine against their own body measurements and it was more illustrative than 3D-CAD on a computer. For example, they have used human manikins to evaluate size and distance within 3D-CAD. However, this approach gave a better understanding of the user experience than human manikins. It can be said that the use of VP supported the goal of the design review because it was easy to evaluate the visibility and reach distances. In addition,

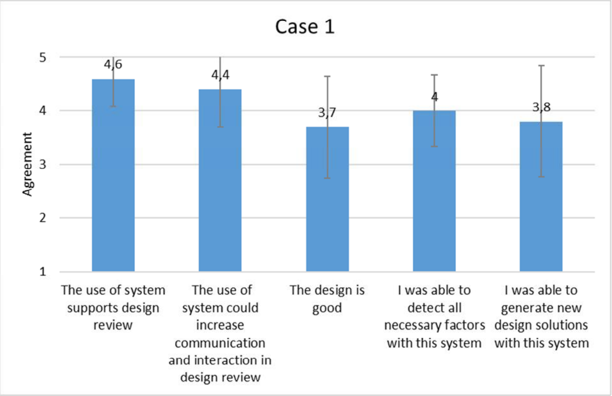

Figure 4: Mean values and standard deviations of the suitability of the VP system for the design review (5=strongly agree, 1=strongly disagree).

they said that it could be beneficial, especially, in detecting critical issues in early phases of the design process.

Participants agreed that the use of the VE system could increase communication and interaction in design reviews (M=4.4, SD=0.70). It brings different stakeholders together and improves communication, especially from those who are not experts with 3D-CAD tools (e.g., assembly and maintenance workers). It was also said that the discussion could go deeper than when the review is done next to a real machine: there is no need to imagine how things would look like. VE can provide a more interactive and realistic experience: “it is different than staring at the screen and trying to think” (design engineer, 32 years). The communication could be even better if there were several HMDs that participants could use at the same time.

The participants agreed that the design of the maintenance platform is good (M=3.7, SD=0.95). Three (n=10) people said that they did not find any design issues with the maintenance platform. However, some comments came up while using the VE system. Four people mentioned that it was easy to see the feeder in the machine. Four people said that they were able to reach the bolt and perform the task. Seven people said that the maintenance platform was tight and small: “The platform is small for a big man” (design engineer, 47 years). Four also mentioned that the reach distances in some cases are too long, e.g. when putting tools on the maintenance platform from the ground. Three people said that the platform could be located a little lower. Four people would have wanted more information about design constraints: “I’m not able to say how to develop the maintenance platform further because I don’t know all the constraints that affect the design” (design engineer, 32 years).

Participants felt that they were able to inspect all necessary factors quite well (M=4.0, SD=0.67). However, they requested two dynamic model characteristics that were not currently available: manipulating the bolt and opening the gate of the maintenance platform. It was also mentioned that it was not possible to climb the stairs to the maintenance platform. Haptic feedback was not provided, and therefore, it was not possible to feel if body parts touched the machine. In addition, without collision detection it was possible to move anywhere and for that reason some design constrains might remain unnoticed. However, participants said that it was possible to evaluate collisions visually by using virtual hand models. Because the VP technology was new to some participants they felt that it takes a couple of times to get used to it. It was also said that it would have been interesting to see material flows inside the machine (which is impossible to do in real life).

Most of the participants were not able to come up with new ideas during the experiment (M=3.8, SD=1.03) because it was a novel situation and the design of the maintenance platform had gone through several reviews already. However, they felt that it could support the innovation phase in design. ”It is possible to innovate with the VE, and I got immediately an idea to turn the bolt the other way around” (design engineer, 29 years).

An adopted SSQ (four-point Likert scale) was used in the test to find out if negative simulator sickness symptoms appeared. If the symptoms are moderate or severe, they can affect the performance and experience of the participant. However, there were no severe symptoms after being in the VE (mean values between 1.00–1.44). The largest change was in general discomfort, but this was not significant either (before M=1.11 SD=0.32, after M=1.44 SD=0.53).

4.2 Case 2

Participants agreed that the use of the system supports design reviews (M=4.5, SD=0.52) (Fig. 5). Seven (n=11) participants said that the system increased the reality of the model and provided a better understanding of its proportions. It was easier to perceive reach dimensions with the system than measuring them in a 3D-CAD: “it is easier to see where your hands can reach than measuring dimensions from a model” (mechanical engineer, 39 years). However, the VE system lacked support for design review in the sense that the used model version was old already. The new version of the noise encapsulation was not converted to the VE system yet.

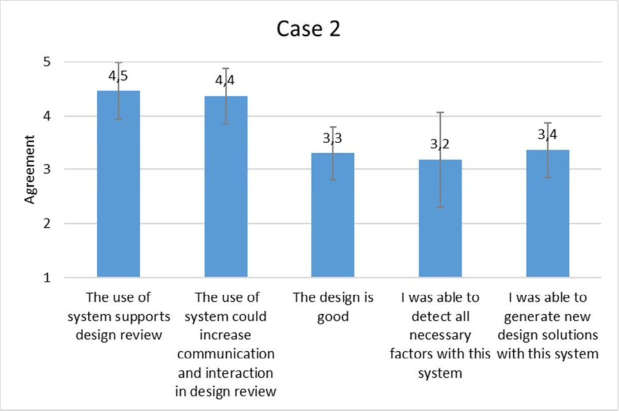

Figure 5: Mean values and standard deviations of the suitability of the VP system for the design review (5=strongly agree, 1=strongly disagree).

The use of the system supported communication and interaction (M=4.4, SD=0.50). The participants felt that it provoked more active participation: “You have to participate” (development engineer, 30 years). Everyone is able to see the same things with same perspective. However, one participant said that it was more illustrative for the HMD user than other people who were sitting around the table.

The participants agreed that the model of noise encapsulation was good (looked air-tight) but still requires some development (M=3.3, SD=0.48). Three participants wondered how it is possible to assemble the noise encapsulation. It might be challenging because it is located on top of the large machine “How is it possible to lift and assemble the noise encapsulation” (head of design, 49 years). In addition, they missed some parts in the model, which can affect the assembly (e.g., lifting points and inlets).

Participants did not agree nor disagree that they were able to detect all necessary factors with this system (M=3.2, SD=0.87). They said that on some level it was possible but some static model characteristics were missing or were incorrect in the virtual prototype. This made the participants feel that the model was approximate and they could not trust the correctness of the model. The participants commented also that it would have been easier to analyse assembly if the parts would have had dynamic characteristics such as move/hide parts to simulate the assembly. To be able to see the machine from every angle the participants requested more pre-defined standing points, especially for the other end of the machine. It would have been easier to navigate (use verbal commands) if standing points were marked with numbers. The participants wanted more contrast because the colour of the model was so grey that it was difficult to see details clearly. One designer said that it would be easier to evaluate the model first in 3D-CAD and afterwards with the VE.

The participants agreed that it could be possible to create new design ideas by using VP (M=3.4, SD=0.50). However, the used design review time was short and the purpose was more to try out the new VE technologies. However, some new ideas came up because it was possible to see the machine from inside.

Simulator sickness symptoms were gathered with the question “Did you feel any negative symptoms when you were in the VE (e.g., sickness, headache, eye symptoms)?” with a three-point Likert scale (M=1.5, SD=0.52). A few people said that they felt dizziness and a lack of balance. One said that he felt the same type of dizziness than when standing in high places in real life.

5 DISCUSSION

In general, the participants felt that the use of VP could support the design reviews. The participants felt immersed in the VE system and were able to reach targets and compare the machine’s measurements against their own body size. By doing this, they gained a better understanding of the proportions of the model. It also made the design more concrete: they were able to visually check the feeder and perform the actual tasks of a maintenance worker. The participants also thought that the system could increase communication and interaction during the design review because everyone has the same view of the design. Studies [19, 30] agree that VP can be used to support communication and interaction between different stakeholders. In general, design reviews are important opportunities to make key design decisions and design experiences explicit [9]. In addition, these shared experiences support the creation of organizational knowledge [10]. The participants also felt that it added value compared to traditional design tools such as 3D-CAD.

The systematic approach to VP design review [32] was useful because it was fast and easy to use. In both cases, it forced everyone to have a common understanding of what happens beforehand, and that all required applications are implemented. It also worked well as a memo of the VP design review. However, it was not always easy to separate the system model and interface characteristics. In addition, the meaning of “test models” can be unclear because there are two possibilities for the evaluation: a user is evaluating the product’s HFE in VE or the HFE expert is evaluating the user. The template was comprehensive but it is important to remember that it concentrates especially on issues related to VP. In addition, the normal design review process needs to be applied (e.g. selection of the design review team members) [8].

Based on the two cases, it was obvious that in design reviews, especially those that apply VP, the goal definition is the most important thing to execute properly. It affects task definition, system model creation, interface, technology and testing methods. In the first case the test setup was prepared in more detail. There was a goal statement to evaluate the maintenance platform and a task was also defined in detail. In the second case there was not a precisely defined goal. The general purpose in the review was to see the status of the current technology and also to review the noise encapsulation. Due to the lack of a clear goal (review plan), the second design review meeting was not beneficial regarding development of the product and decision making. In addition, some essential parts and details were missing from the virtual model and there was too little time to do the review. Therefore, design issues (good, detect all factors, generate new ideas) were valued lower than in the first case (Fig. 4 and Fig. 5).

System model static and dynamic characteristics need to be correct for design review purposes. This means that models of design parts under evaluation need to be at the required detail level. For example, if participants are evaluating the suitability of a maintenance platform to support maintenance work, the model needs to be the right size and a participant needs to be able to stand on top of the platform. Again, if the evaluation target is the assembly of the maintenance platform, the model needs to have more detailed information such as bolts and pre-defined assembly order (possible to show/hide parts in the right order). In the second case in this paper, participants felt that they were lacking some details in the model (e.g. lifting points and inlets), and therefore were not able to review the design as a whole.

Trustworthiness issues have arisen in many VP design reviews and are related to the correctness of the system model. In these cases, the company has sent the model to the research partner whose VR expert converted and optimized the model for VE software. During optimization it is possible that some important information could be left out. Therefore, design engineers have difficulties in trusting that the model is correct when they review it in VE. However, correctness is necessary for making proper design decisions. This issue could be addressed by a design engineer working in close cooperation with the VR expert or the whole conversion and optimization process could be done by the design engineer him/herself. According to [3] this conversion process is still one of the research challenges in the use of VP in product design.

The human-virtual prototype interaction in the VP design review requires consideration. In this study there were two different examples of the use of the VP. In the first case there was only one participant using the HMD at a time, and in the second case there were other stakeholders present also. If other people participate, visual cues should also be provided for them (e.g. by using projectors). It is also important to consider the interface aspects, such as how participants are able to act and move around. In the both cases participants were able to walk in a tracked volume and use waypoints to teleport them to a different location. The participants used verbal commands and a VR expert changed waypoints from a keyboard. In [31] were listed some usability issues to consider when designing virtual prototypes: “(1) forms of representation; (2) modelling of avatars; (3) supporting navigation and orientation; (4) understanding and enhancing presence and involvement in VEs; (5) requirements for cues and feedback; (6) minimizing any side and aftereffects, and (7) providing interface support and tools for interactivity”.

VEs are seen as especially beneficial when providing a possibility to test tasks in their real context. In both of these cases, the design object is quite large and therefore, building physical prototypes takes time and effort (it is not possible to make rapid paper prototypes). The clear task definition in the first case supported the design review well. In the second case, tasks were not defined and therefore what to evaluate it was not so clear. In addition, the participation of real end-users would improve the quality of VP design reviews because they have real context knowledge.

The optimization of effort and time is a key issue during the VP design review. In these cases, the keyboard was used as a means of manipulation in the VE. It was used because it is easy and fast to apply and does not require learning from the participant: participants are able to use verbal commands and the VR expert is using the keyboard. The creation of dynamic model characteristics is another time-consuming task. Therefore, it is important to understand what dynamics are really required and what is not needed. In the second case, it would have been easier to evaluate the assembly if there would have been dynamics characteristics (e.g., show/hide elements). According to [12], time is considered as one motivational or deterring factor for the use of the virtual human factors tools.

Timing is also a challenge when using VP design reviews during product development processes. In the first case, the design of the maintenance platform was almost final. It meant that the design was already iterated several times and therefore the VP design review did not reveal any new major issues. In the second case, the timing was better in the sense that the design was not in later phases. However, another problem occurred: the next geometry version of the product already existed but the older version was used in the VE.

From the managerial point of view, it is important to provide suitable facilities for the use of VP systems, and also support the collaboration and getting together among different stakeholders. In addition, it is important to integrate the VP use in company processes and aim towards positive attitudes on VP use in organisation’s culture.

The systematic approach supported the preparation of VP design reviews in these two industrial cases. In addition, it could supplement research related to VP. Currently, there is a lot of valuable and interesting research in the area of VP but unfortunately, sometimes test procedures and virtual models are not described clearly enough for others to replicate. One reason for this is that the research area is challenging due to the different virtuality levels of the systems [6, 16].

Limitations that may have affected the validity of the results may derive from a qualitative research approach. It is also possible that the adapted framework to support VP design review [8] is not comprehensive enough. In the future, the systematic preparation approach could be iteratively developed further, and other exploitation possibilities that VP can provide for traditional design review processes (e.g. for documentation) should also be considered.

6 CONCLUSIONS

The purpose of this research was to study the suitability of the use of VP to support design reviews and identify critical issues related to that. In addition, a systematic approach to VP design reviews was presented. Two VP design review cases were studied related to a maintenance platform and a noise encapsulation of a rock crushing machine. In total, 21 stakeholders, mainly design engineers, participated in the design reviews and their opinions on the suitability of the VP for design reviews were evaluated.

Participants felt that the use of VP supports design reviews because it provides a common understanding of the design object (same visual cues), and also supports communication and interaction. In addition, the VP provides design engineers a first-hand experience of the use context. This is not always the case when using 3D-CAD or physical prototypes.

Results indicate that the preparation of design reviews, when using VP, can have an effect on the review outcome’s quality. Therefore, it is important to have a well-defined goal and to consider how much effort should be put into model design. The timing of the VP design reviews and the conversation and optimization processes can decrease the value of the VP design reviews. In addition, user interfaces and system models’ static and dynamic characteristics need to be considered thoroughly.

The systematic preparation approach of the VP design reviews presented in this paper can be applied in different industry sectors that are using VP in their product development processes. In addition, it is useful when designing virtual environments for testing various research topics within the research community.

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PUBLICATION 6

Digital Human Models in Human Factors and Ergonomics Evaluation of Gesture Interfaces

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Digital Human Models in Human Factors and Ergonomics Evaluation of Gesture Interfaces

SUSANNA AROMAA, VTT Technical Research Centre of Finland Ltd.
NIKOS FRANGAKIS, National Technical University of Athens
DOMENICO TEDONE, Thales Alenia Space Italia
JUHANI VIITANIEMI, VTT Technical Research Centre of Finland Ltd.
IINA AALTONEN, VTT Technical Research Centre of Finland Ltd.

Gesture-based interfaces are becoming a widely used interaction modality in many industrial applications. Therefore, it is important to guarantee usable and ergonomic interfaces for workers. The purpose of this study was to investigate whether the use of digital human models (DHMs) by human factors/ergonomics (HFE) experts can complement the user evaluation of gesture interface prototypes. Two case studies were conducted, in which gesture-based systems for remote robot control were evaluated. The results indicate that the use of DHMs supports the findings from self-reported HFE evaluations. However, digital human modeling still has some limitations. For example, in this study, it was not possible to evaluate small muscle groups (e.g. fingers). We argue that adaptation of the DHMs could be a rapid and simple alternative for supporting the HFE design of gestures.

CCS Concepts: • **Human-centered computing~User studies** • **Human-centered computing~Virtual reality** • **Human-centered computing~Gestural input** • *Human-centered computing~Empirical studies in HCI*

KEYWORDS

Human factors and ergonomics, gesture interfaces, digital human model, virtual prototyping

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1 INTRODUCTION

Gestures have become an important interaction technique in many multimedia systems, for example in public displays [41,63], mobile devices [50,59], virtual environments [6,17,29] and robot controls [1,57,62]. When adapting gestures in an industrial work context, it is important to consider the comfort and ergonomic aspects of user-system interaction. In a recent Eurobarometer survey [16], workers considered ergonomic risks — repetitive movements or tiring or painful positions — to be the second greatest occupational risk after stress.

Many studies regarding human factors/ergonomics (HFE) in gesture interface design have evaluated the aspects of stress, performance time or the number of errors made (e.g. [23,24,55]). However, these attributes form quite a narrow interpretation of HFE — defined as "*the scientific*

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discipline concerned with the understanding of interactions among humans and other elements of a system… in order to optimize human well-being and overall system performance" [25].

There has been some discussion about the lack of established guidelines for gestural interaction in design [45,46]. According to [9], an international standard for the testing procedure of gestural interfaces does not yet exist, nor a guideline for their ergonomic design. Delamare et al. [13] concluded that there is a need for gesture guiding systems to promote the use of gesture interaction. In addition, most publications deal with the technical issues of gesture interfaces, whereas only a few consider HFE issues [6]. In the industrial work context, it is important to make sure that new interfaces do not cause physical or mental fatigue which may lead to sickness absences.

In general, a more proactive design and analysis of HFE is required when designing and developing interactive systems. Virtual prototyping (VP) with digital human models (DHMs) has been introduced in industry to facilitate more efficient design processes. A virtual prototype is a computer simulation of a physical product that can be presented, analysed and tested according to various aspects. Construction and testing of a virtual prototype is called VP [64]. According to [2], DHMs are computer models of people that can be used as substitutes for 'the real thing' in ergonomic evaluations of computer-based designs. DHMs have mainly been used in the design of aerospace [51], automotive [20,58] and industrial workplaces [8,30,49]. However, DHMs could also be used when designing novel interaction modalities, such as gesture-based control systems.

The research question of this study was whether the use of DHMs by HFE experts can complement user evaluation of gesture interfaces in the area of tele-operated robots. Two case studies were carried out using different gesture interfaces: a 'sensor-based system' and a 'computer vision-based system'. These two interface types were different enough to provide versatile HFE evaluation feedback. The paper is organized as follows: first, the previous related work is introduced. Then the case studies are presented by describing the used systems and methods and the results. Finally, the results from the two case studies are discussed and conclusions are drawn.

2 RELATED WORK

Gestures are a prominent interaction technique in many multimedia systems. Gestures can be defined as "*actions human do all the time*" [34] or "*body movements which are used to convey some information from one person to another*" [60]. Different approaches to the gesture vocabulary design exist. Two categories for choosing the gesture vocabularies are presented in [43]: a technology-based and a human-based one. A design approach introduced in [66] is based on eliciting gestures from non-technical users for surface computing. Another approach for gesture vocabulary design considers both human- and technology-based factors [55]. Two studies [4,61] have offered guidelines on how to develop gesture-based systems. According to [8], two types of motion-tracking solutions for gesture-based systems exist on the market: computer-vision-based and inertial sensor-based systems.

Many studies, such as [6,43], emphasize the importance of HFE evaluation of gestures. The topic has been investigated in some gesture design studies. Hoggan et al. [23] evaluated the completion time and the ergonomic failure rate of multi-touch pinch gestures. The Borg scale of perceived exertion [5] was used in [55] to describe the level of stress. Typically, the studies evaluated stress by holding one gesture for a certain amount of time [55]. In [53], a subjective discomfort rating was used in gesture development; however, the authors did not precisely delineate the method. Chuan et al. [10] proposed usability heuristics for testing gestural interaction. Their heuristics are related to gesture learnability, gesture cognitive workload, gesture adaptability, and gesture ergonomics. In addition, the relationship between movement time, distance, and accuracy for people engaged in rapid aimed movements when using pointing devices has been studied in [18,54].

HFE issues to consider during the design, testing, and evaluation of any human-system interactions include (1) anthropometric, biomechanical and physiological factors (e.g. body size); (2) factors related to posture (e.g. enough room, working height); (3) factors related to manual material handling (e.g. lifting, carrying); (4) factors related to the design of tasks and jobs (e.g. task allocation); (5) factors related to information and control tasks (e.g. information presentation), and (6) environmental factors (e.g. noise, vibration) [27]. Usability approaches used in interface design evaluate the ease of use of the interfaces, and topics related to learnability, efficiency, memorability, errors and satisfaction [42].

When designing gestures, it is important also to consider the risk of musculoskeletal disorders (MSDs). "*Awkward postures, repetitive work or handling heavy loads are amongst the risk factors that may damage the bones, joints, muscles, tendons, ligaments, nerves and blood vessels, leading to fatigue, pain and MSDs*" [15]. Particularly, the neck, lower back and upper limbs (shoulder, elbow, wrist, and hand), are vulnerable to MSDs [15]. It can be said that factors contributing to the existence of MSDs include poor posture and exposure to vibration and mechanical shocks [37]. Approaches for evaluating exposure to risk factors for MSDs include self-reports, observational methods and direct measurements [12]. Self-reports from workers can be used to collect data on workplace exposure to both physical and psychosocial factors by using methods such as diaries, interviews and questionnaires [12]. Simple observational methods for recording and assessing workplace exposure are such as Ovako working posture analysis (OWAS) [26], National Institute for Occupational Safety and Health lifting equation (NIOSH) [65], Rapid upper limb assessment (RULA) [40], and Rapid entire body assessment (REBA) [22]. There are a wide range of direct methods that rely on sensors, which are attached to the worker for the measurement of exposure (e.g. electromyography (EMG)). This paper focuses on the use of self-reports (interviews, questionnaires) and simple observational methods (RULA).

DHMs can be used for the evaluation of HFE issues during the early design phase. It is possible to analyze a wide variety of HFE, including injury risk, timing, user comfort, reachability, lines-of-sight, energy expenditure, fatigue limits and other HFE related parameters. Chaffin [56] classified digital human modeling into two categories: cognitive/performance digital human modeling and physical digital human modeling. Cognitive/performance DHMs concentrate on modeling aspects of human-machine interaction. Physical DHMs focus on evaluating working postures and work-related MSDs. In physical DHM there are two types of human models: biomechanical models which calculate forces and moments in body parts (e.g., LifeMOD, SIMM, MADYMO, and Santos), and computer manikins which are more human-like and function in a computer-generated environment (e.g. Jack [3,52], Ramsis, Safework, HumanCAD). This paper focuses on the use of human-like computer manikins which can be used during the design of human-system interaction.

An ergonomic assessment performed with DHMs needs to be valid and reliable in order to be able to predict real life issues. According to [67], results from HFE analyses are the same when postures of the DHMs are manually set up or gathered using a motion tracking system. In addition, DHMs have demonstrated correct prediction of ergonomics issues for standing and unconstrained working postures [49]. Fritzsche's study [19] further indicates that DHM simulations can provide good estimates of the workload in real-life tasks and that there is a correlation between the DHM simulation assessment and workers' perceived exertion. Nevertheless, Ma et al. [31,32,33] and De Magistris et al. [35,36] criticized that the ergonomic analysis tools of DHMs are too static.

In summary, it can be said that HFE evaluation is an important part of gesture interface design. Therefore, the traditional completion time and error rate measurements should be enhanced with other HFE evaluation methods. As mentioned above, DHMs can be useful in enhancing the HFE evaluation of human-system interaction. In general, DHMs have been used in the evaluation of gestures, but their use in gesture interface design has not been studied widely.

3 CASE STUDIES

In order to investigate whether the use of DHMs can complement the user evaluations of gesture interfaces, a case study approach was adopted. In the case studies, two different gesture interfaces were evaluated with a similar research setup. In both case studies, self-report (body discomfort and NASA-TLX [21]) and observational (RULA [40] within the DHM software Jack) methods were used. Jack software includes many HFE assessment methods, such as fatigue analysis, lower back analysis, manual material handling, metabolic energy expenditure, NIOSH, OWAS, predetermined time standards, RULA, static strength prediction (SSP) and a force solver. Due to the nature of the gestures in this study and available analysis methods in Jack software, RULA was selected to be most applicable to detecting awkward postures that may lead to MSDs. RULA was adopted because it evaluates physical work-related upper limb disorders (e.g. postures of the neck, trunk and upper limbs). Self-report methods were selected due to their insights into experienced load obtained when using gestural interfaces. The purpose was not to make a comparison study between self-report and observational approaches, and therefore the same methods were not used within both. The purpose was to assess whether the use of DHMs by HFE experts can complement user evaluation of gesture interfaces.

The gesture interfaces were a sensor-based system and a computer vision-based system. Gestures which were evaluated with the DHM were in the sensory-based system: wrist bend down, wrist bend up, wrist twist right and wrist twist left, and in the computer vision-based system the gestures were: arm forwards away from the torso, arm backwards away from the torso, rotate forearm right and rotate forearm left. The following sections describe the two case studies separately. In both cases, the user evaluation and expert evaluation setups and the results for each case study are described. Finally, the findings from both case studies are discussed in the discussion section.

3.1 Case Study 1: Sensor-Based System

3.1.1 Methods. **Technical setup**. The technical setup included two main sections: the setup supporting the robot system and the setup supporting the user. The setup for the robot system was composed of two main components: (1) a four-wheel drive (4WD) remote controlled car and (2) the robotic arm, a Lynx al5d, which includes three main links and an actuator (Fig. 1, right). The remote visual monitoring hardware was composed of a non-stereoscopic pan tilt camera, the Tenvis JPT3815W. The camera, mounted on an aluminium construction 40 cm above the rover, provided head motion and coupled visuals to an Oculus Rift head-mounted display (HMD) worn by the user (Fig. 1, left). The view of the camera was projected into the HMD. The participant used the camera view to operate the robot. The robotic arm was mounted on the rover and received power from an internal 6-volt battery, placed in the 4WD rover. All the cables of the motors of the robotic arm were connected to the controller, which was also mounted on the back of the rover. This controller was also connected to the motors of the 4WD rover.

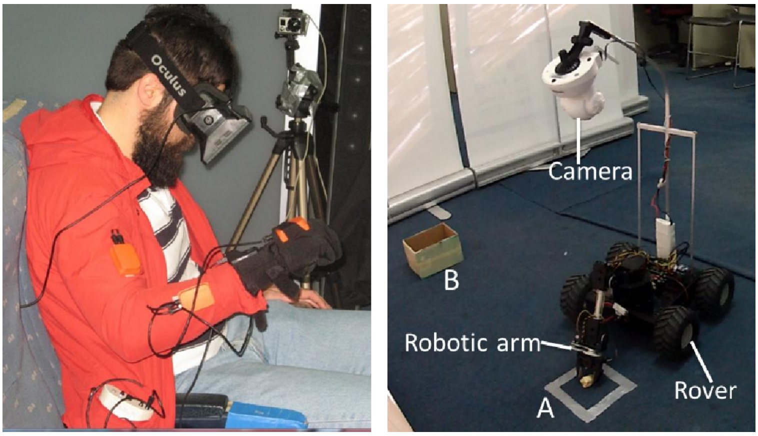

Fig. 1. The sensor-based system is on the left and the remotely operated robot system is on the right.

In the sensor system (Fig. 1, left), there was one main computer connected to the rover through an Xbee wireless adapter. The user was also wearing a special jacket with Xsens inertial sensors mounted on the sleeve. These sensors were connected to each other and with the main PC so as to compute the user's arm position and orientation. Finally, the user wore a data glove manufactured by 5DT, for selecting between the different modes of movement: rover movement, robotic arm movement and gripper movement. The main computer had additional displays to support the test execution showing e.g. the HMD visuals for the main facilitator. The sensor system includes the metaphor of drifting the robotic arm to its desired position: for example, in order to move the robotic arm all the way to the left, the user could make several repetitive movements from right to left. Each time the user reached the left-most position, s/he would open up the hand (to instruct the robotic arm to cease movement) and move the hand all the way to the right, close the hand and repeat the movement to the left. This provided fine movement to the robotic arm.

Participants. The participants were ten university researchers and students (8 males and 2 females). The average age was 30 years (range: 23–36 yrs.). All participants were right-handed.

Data collection and analysis methods. Participant demographics were collected with a questionnaire, and participants signed consent forms. This study used both mental and physical self-report methods. An unweighted NASA-TLX [21] was used to measure mental workload during the use of gesture-based control systems. The NASA-TLX includes six subscales which assess mental demand, physical demand, temporal demand, effort, performance, and frustration level in a 21 vertical tick marks scale. In this study, the scale used was 0 to 100. For the physical workload evaluation, the experience of discomfort in a certain area of the body was assessed. In this case, the body discomfort was evaluated with the question" Did you feel any strain/pain in your neck or hands, or somewhere else?" In addition, two questions were asked: "Were you able to act in a natural manner?" and "Did you notice any mistakes/errors that affected the task performance?" A qualitative approach was adopted for the data analysis in order to gain insight into the users' perceptions of the interaction.

Test procedure for user studies. The user's task in the test was to operate the robot system remotely using right-hand gestures. The aim was to move a small object with the robot system from location A to B (Fig. 1, right). The task included driving the rover next to the object, moving the robot arm to a specified position, picking up the object with the robot arm gripper, steering the system next to a box and dropping the object into the box. During the task performance, the participant sat on a chair.

The test started with an introduction, completion of the consent form and the collection of demographic data from the participants. Next, the test participants put on the equipment and had ten minutes of training. The actual task performance had a 15-minute time limit. After completing the task, the participant filled in the questionnaires and answered the interview questions.

Human factors/ergonomics evaluation with a digital human model. The expert evaluation with DHMs was made after the user studies with the help of video recordings from the studies. This study focuses on the use of human-like computer manikins that can be used for the HFE evaluations. A DHM simulation system Jack® [3,52] was used during the virtual prototyping of the sensor-based system. It was selected because it focuses on improving the HFE of a human-technology interaction and therefore also addresses MSDs. The posture analysis RULA [40] was adopted because it evaluates physical work-related upper limb disorders. Two HFE experts manually put the DHM into operating postures with the Jack software. They performed the analysis separately. Both experts used video material collected from the user tests to support the creation of correct postures in DHM.

For this study, four basic gestures were chosen from both control systems for the DHM analysis because these are the most representative of all used operating gestures. The four basic control gestures were: (1) robot moving forward; (2) robot moving backward; (3) robot turning left, and (4) robot turning right (Fig. 2). The sensor-based system uses a relative zero point to operate the robot, requiring more extreme wrist angles to achieve different commands. Finger postures were part of the robot control gestures, but during digital human modeling they were excluded from the analyses (even though they have an effect on the load to other body parts). Finger postures were excluded because the RULA analysis in the Jack Task Analysis Toolkit cannot evaluate finger positions. In addition, the study was limited to the right hand posture evaluation and did not consider head, trunk or leg postures.

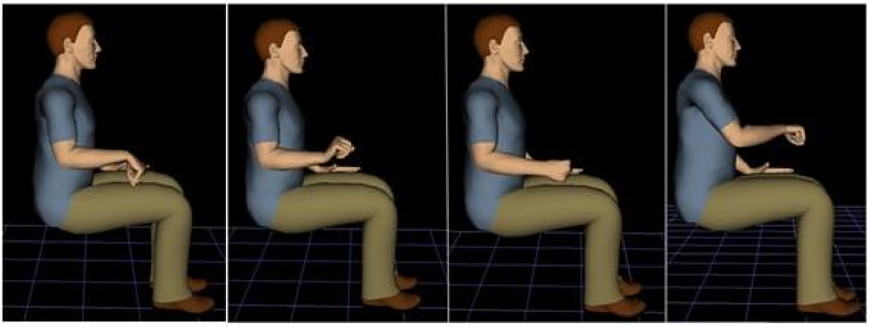

Fig. 2. Sensory-based system gestures, from the right, operate the robot system forwards, backwards, right and left.

The used Jack was an ANSUR male P50, with custom stature and weight (176 cm and 78 kg). The mean RULA value was calculated from both HFE experts' evaluations and from all four different gesture postures (n=8) to simulate the whole task performance. In this study, the body group B (neck, trunk, legs) posture score was given a value of 1 with no added muscle and force scores because those body parts were not included in the analysis. In group A of the RULA analysis, the upper arm scores can vary between values from 1 to 6, the lower arm from 1 to 3, the wrist from 1 to 4, and the wrist twist from 1 to 2. The final wrist and arm score, calculated as a sum of its parts, can vary from 1 to 7. In this study, in group A, the used muscle and force scores were given a value of 0 for normal, non-extreme use and an intermittent load of less than 2kg.

3.1.2 Results. There is no threshold level in the NASA-TLX for high workload [21]. However, some suggestions for the general workload thresholds have been proposed, for example, 40±10 (out of 100) [11], 50-55 [38,39] and over 50 [68]. In this case, the mean value of the effort (67.0, SD=15.1) was over the threshold level (Fig. 3). This means that participants were required to provide too much mental (e.g. thinking) and/or physical activity (e.g. controlling) during the operation. This can also be seen from the mental (M=53.5, SD=23.0) and physical (M=52.5, SD=22.8) demand levels. In addition, the performance was rated high (M=49.5, SD=33.5). It can be deduced that many participants did not feel successful when performing the given task. Temporal demand was below the threshold level. In addition, the frustration was rated to be low, which means that participants must have felt quite content using the system.

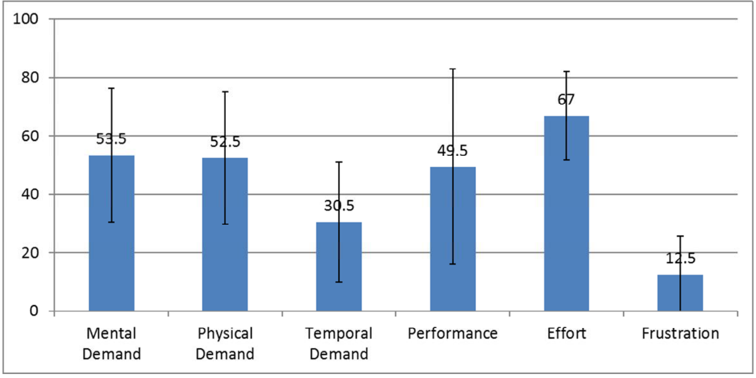

Fig. 3. The NASA-TLX results for the sensory-based system.

In this case, body discomfort was assessed with an open question. Four people (n=10) did not feel any discomfort during the task performance. However, four people reported discomfort, especially in the wrist area after the test. In addition, discomfort in the forearm, upper arm and shoulder was mentioned.

Half of the participants felt that they were not able to perform the task well. They reported that it was difficult to perform accurate positioning with the rover and to move the robot arm accurately. Furthermore, the movement of the rover had an effect on the field of view of the camera. The other half felt that they succeeded or almost succeeded to perform the task. One said that the correspondence and the reaction of the robot arm and rover was quite good. Most of the participants in this setup felt that they could act in a natural manner, especially after getting familiar with the logic of the system. One felt that s/he had to do awkward things with his/her hand but after a while, the rules made sense. The participants mentioned some system-related errors which they thought could have affected their task performance, for example when turning the rover to the left, the rover did not follow the user’s gesture. Other errors included a loss of connection; battery problems; a detached sensor on the glove; delays in the movement of the robot; calibration of the arm; and the mode change from robot control to rover control mode. Two people also requested more training to be able to avoid the mistakes.

The RULA scores for the sensory-based system are shown in Table 1. Based on the results, the upper arm is in the relaxed position range. The score reflects that the lower arm is raised. The wrist is bent all the time and the wrist twist score is rather high (M=2, SD=0). The grand score was 2.6. In RULA, the recommendation is between scores of two and three. The posture is acceptable when the grand score is 1–2, whereas further investigation may be needed and changes required when the grand score is 3–4. However, the level 3–4 is still considered as a low risk value.

Table 1. Mean values and standard deviations of RULA analysis results for the sensory-based system.

	Mean value	**STDEV**
Upper arm	1.3	0.46
Lower arm	2.0	0.00

	Mean value	STDEV
Wrist	2.1	0.83
Wrist twist	2.0	0.00
Body group A total	2.6	0.52
Body group B total	1.0	0.00
Grand score	2.6	0.52

3.2 Case Study 2: Computer-Vision-Based System

3.2.1 Methods. **Technical setup.** In the computer-vision system the setup supporting the robot system was the same as in Case 1, whereas the setup supporting the user was different (Fig. 4). The arm of the user in this setup was constantly tracked with a Kinect depth camera, which was connected to the main PC for computing the user's arm position and orientation. The user wore a data glove manufactured by 5DT to operate the robot system. The user's hand was mapped to the robotic arm's end effector (i.e. gripper position), providing an absolute translation of position. This means that when the user held his/her hand all the way to the left then the robot arm was also held all the way to the left. If s/he moved the hand all the way to the right, the arm would also move all the way to the right. This provided rapid movement of the robotic arm, but with less accuracy.

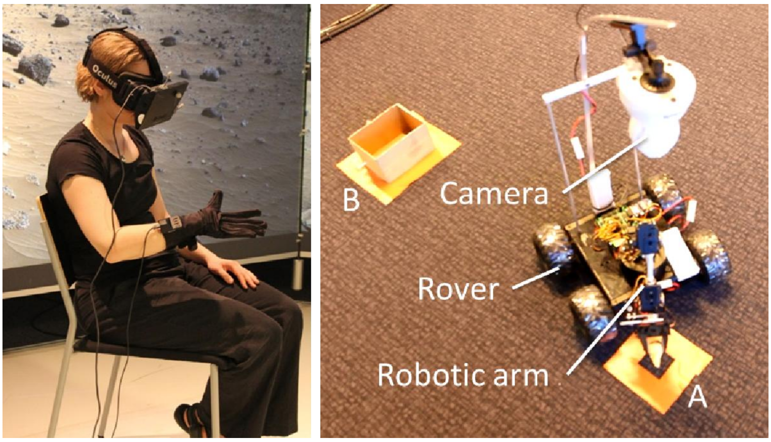

Fig. 4. The computer vision-based system is on the left and the remotely operated robot system is on the right.

Participants. Nine research scientists (5 males and 4 females) took part in this case. Average age was 36 years (age range: 29–57 yrs.). All participants were right-handed. All the participants were different from those in Case 1.

Data collection and analysis methods. Participant demographics were collected with a questionnaire, and the participants signed consent forms. In this case also, the unweighted NASA-TLX [19] was used to measure mental workload during the use of the computer vision-based system. The physical workload was evaluated using a map of the upper body to collect information about areas of discomfort before and after the test. The body-map areas were adapted from [28,37] and a 7-point Likert-scale was used (1=no discomfort, 7=severe discomfort). In addition, two open questions were asked: "Were you able to act in a natural manner?" and "Did you notice any mistakes/errors that affected the task performance?" For the data analysis, a qualitative approach was used. In addition, a T-test in SPSS was used for statistical analyses of the body-map results.

Test procedure for user studies. The test procedure was the same as in Case 1.

Human factors/ergonomics evaluation with a digital human model. The virtual prototyping setup was the same as in Case 1. The computer vision-based system, however, uses an absolute approach and uses mostly the elbow joint to achieve different gestures (Fig. 5).

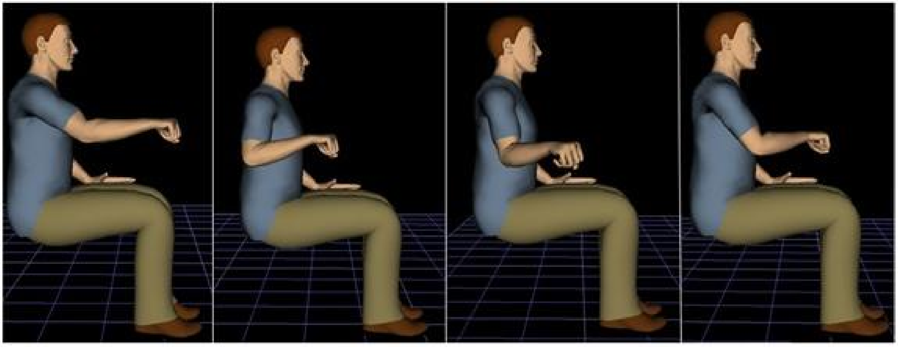

Fig. 5. Computer vision-based gestures, from the right, operate the robot system forwards, backwards, right and left.

3.2.2 Results. On the basis of NASA-TLX analysis (Fig. 6) of the computer vision-based system, the effort score (M=57.2, SD=17.5) affected the mental workload most. This means that participants felt much effort was needed in order to perform the task. The frustration score (M=50.6, SD=25.2) also reached the threshold level. The participants clearly felt annoyed and frustrated during the task performance. This might also have had an effect on the rather high performance rating (M=47.2, SD=20.6). It implies that many of the participants would have wanted to be more successful with the task performance. Mental demand score should also be considered, because it was close to the threshold level (M=46.7, SD=25.1). Physical demand (M=28.3, SD=17.3) and temporal demand (M=27.2, SD=21.5) were evaluated as rather low.

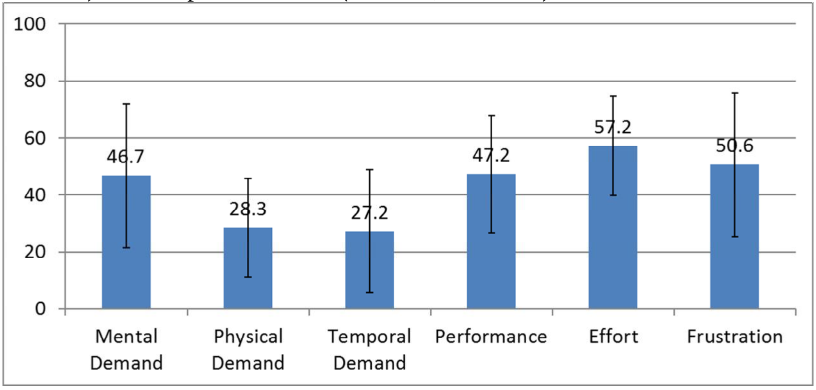

Fig. 6. The NASA-TLX results for the computer vision-based system.

Body discomfort was assessed before and after the task performance by using the body map questionnaire with Likert on a scale from 1 to 7. Participants felt increased physical fatigue especially in the shoulder, upper arm, elbow and hand areas. There was a significant difference in right shoulder discomfort for the before (M= 1.11, SD=0.33) and after (M=3.44, SD=1.74) conditions; t(8.6)=3.95, p=0.004 (p<0.05) (Table 2). This means that participants felt more discomfort in their right shoulder after performing the task. In addition, the score in the upper arm was also noticeably increased; scores for before conditions were (M=1.0, SD=0.00) and for after (M=2.56, SD=2.07); t(8.0)=2.3, p=0.054.

Table 2. Discomfort in body parts before and after performing the task with the computer vision-based system (1=no discomfort and 7=severe discomfort, p<0.05).

	Before	**After**		
	MV (STDEV)	**MV (STDEV)**	**t**	**p**
Hand	1.3 (1.0)	1.7 (1.1)	0.667	0.514
Wrist	1.0 (0.0)	1.1 (0.3)	1.000	0.347
Forearm	1.0 (0.0)	1.2 (0.7)	1.000	0.347
Elbow	1.3 (1.0)	1.7 (2.0)	0.447	0.661
Upper arm	1.0 (0.0)	2.6 (2.1)	2.256	0.054
Shoulder	1.1 (0.3)	3.4 (1.7)	3.951	**0.004**

When asked about the experience of acting in a natural way, the participants gave contradictory comments. Some of them felt that they were able to act in a natural manner: it was easy to concentrate on the task, and “There was nothing unnatural” (female, 40 years). In addition, it was natural to move to the next step in the task. However, a few participants felt that they could not act naturally. Switching between the modes was the main source of confusion: sometimes it was difficult to remember which mode was on. The participants also reported that the motion range was rather large, as it was unnatural to move only the arm and not the whole body. One participant said that the glove did not bring any added value and s/he would have preferred to use a keyboard instead. Another participant suggested that when using absolute positioning, it could be helpful to have an indicator in the virtual environment of the previous position of the arm.

The RULA analysis results are presented in Table 3. In this case, the score reflects that the upper arm was more raised (to 20-45 degrees). The lower arm was also raised. The wrist was almost in a neutral posture when considering bending postures, but the wrist twist got a high value (M=2.0, SD=0). The grand score was 2.9 in this case. This suggest that further investigation could be needed and changes could be required (when the grand score is 3–4). The body group B was given the value 1 because neck, trunk and legs were not analysed (as in Case 1).

Table 3. Mean values and standard deviations of RULA analysis results for the computer vision-based system.

	Mean value	**STDEV**
Upper arm	2.1	0.64
Lower arm	2.5	0.53
Wrist	1.1	0.35
Wrist twist	2.0	0.00
Body group A total	3.4	0.74
Body group B total	1	0.00
Grand score	2.9	0.35

4 DISCUSSION

On the basis of the results of this study, it appears that the use of DHMs by HFE experts could supplement the user evaluation of gesture interfaces. It can be said that both *user evaluation and expert evaluation with DHM gave similar results*. In Case 1, the participants mentioned that they felt fatigue mostly in their wrist area. In the RULA analysis, performed by HFE experts with the DHM, the wrist scores were also higher than the upper arm scores. The results were consistent with those found in Case 2, in which the participants commented that their fatigue increased especially in the shoulder and upper arm areas during the use of the computer-vision system. The RULA scores also showed higher mean values with the arm.

The overall results from the NASA-TLX and RULA were similar: they both suggest that further investigation is needed to ensure better HFE. The overall workload results from the NASA-TLX, 44.3 in the sensor-based system and 42.9 in the computer vision-based system, are near the threshold level of 50±10 recommended by [11,38,39,68] and the RULA results, the average grand score of 2.6 in the sensor system and 2.9 in the computer-vision system, are near to the range of 3-4, which suggests that further investigations are needed. Other studies [19,49,67] have also reported *that it is possible to gain valid HFE evaluation results by using DHMs*.

In general, the case studies showed that when designing *gesture interfaces, it is important to consider mental and physical HFE issues* in addition to the traditional performance measures (e.g. time, errors). The use of NASA-TLX in the user evaluation of the gesture interfaces revealed issues that might not have been noticed if only performance evaluations (such as in [23,24]) had been used. In both cases, there were no major differences between the mean values of the self-evaluated performance. However, with the sensor-based system (Case 1), the participants felt they needed to work hard (both mentally and physically) in order to be able to perform the task. With the computer vision system (Case 2), however, the participants experienced more mental than physical demand, and were more frustrated with the use of the system. In addition, it was seen from the results that gestural interfaces could increase the physical load (for example there was a significant increase in discomfort in the shoulder area in the computer vision-based system). Therefore, it is important to pay attention broadly to HFE issues when designing gestural vocabularies, and not to focus solely on time and error measures. The evaluation of MSDs is an important issue especially when designing applications to be used in an industrial work context.

4.1 Implications for the Digital Human Model Use in Gesture Interface Design

This section discusses implications for gesture interface design. It critically discusses both the benefits and challenges that need to be considered when DHMs are used in gesture interface design.

What kind of gestures: Experiences from this study indicate that DHMs are particularly suitable to evaluate gestural interfaces requiring the use of larger muscle groups (e.g. wrist and arm motions). This is an important issue to consider because many gestural interfaces also include finger postures, and these HFE issues should also be considered. If the used DHM cannot support the evaluation of small muscle groups, the use of other HFE methods is required during the gesture interface design.

What kind of applications: In this study, gesture interfaces were developed for the remote operation of a robot. However, it was seen that DHMs could be used in the design of gesture interfaces in many application areas, such as in public displays, mobile devices, virtual environments and robot controls. For example, by using DHMs and RULA analysis, it would be possible to define correct heights for the raised arm when using public displays. In addition, heights could be assessed with different sizes of humans by applying anthropometrical data from DHM software. However, as discussed earlier, if applications require gestures with small muscle groups, the used DHMs may not be applicable.

Types of users*:* In this study, gesture systems were developed for industrial use in remote operation of the robots. However, DHMs could be used to design interfaces for many different user groups (e.g. industry, leisure, public), as DHMs include anthropometric libraries, which can be used to acknowledge different sizes of humans (e.g. small woman and large man). It supports the "design for all" approach by considering the population view.

What to evaluate: When using DHMs in gesture design, it is important to consider what kind of HFE evaluation methods can be applied. In this study, only one observational method was applied (RULA) from DHM. Therefore, the study does not provide a comprehensive view of all the methods that DHM software can provide. When selecting suitable methods for this study, many of the methods in the Jack software were not considered to be usable. The purpose of the DHMs during product development is often to give an overall view of the HFE issues in human-machine interaction (e.g. visibility, load, space). Therefore, it does not concentrate on the evaluation of one particular issue (e.g. posture) with several methods (e.g. RULA, OWAS, self-reporting). In HFE evaluation of gesture interfaces, this can be a restricting factor for the use of DHMs.

Product development process*:* It is important to consider at what time during the product development process DHMs are applied. In this study, DHM was used after user studies to evaluate gestures. However, the best benefits from the use of DHMs can be achieved when DHMs are used in the early design phases when a real product does not yet exist [7,14,19]. DHMs could be adopted to gesture interface design in the gesture selection phase.

The HFE experts agreed in this study that the virtual prototyping (VP) of gesture interfaces is rapid and easy: Prototyping of the gesture systems was fast because there was no need to model products and the environment in addition to a human model. This is important because other researchers [47] have reported that time and the difficulty of use of VP tools can be a motivational or a deterring factor when applying them. VP could also be suitable for the design of gesture interfaces because no haptics is required. The use of haptic feedback can be challenging when using VP in the design of human-system interactions [48].

How to use in gesture selection: There are two approaches to how DHMs can be adopted for the selection of suitable gesture vocabularies. It is possible that a design team can set suitable gestures and evaluate HFE issues by using DHMs in a way similar to that used in this study. However, as seen in this study, the expert approach can lead to gestures which are selected only on the base of technical feasibility of gesture recognition rather than on HFE issues, such as learnability, efficiency, memorability, error coverage and usability [44]. Another possibility is to use test subjects in the selection of the easiest gestures and track their motions to the DHM software. This could improve the user acceptance and would include the users' task knowledge of real work in gesture interface design.

Required expertise*:* Despite the coherent HFE evaluation results between the self-report and observational methods in this study, it is always good critically to consider the DHM results. In this study, both HFE experts got a value of 2 with the RULA for the wrist twist in the vision-based system evaluation (Case 2). This means that the wrist is twisted near the end of the motion's range. However, gestures in the vision-based system were based mainly on the elbow joint and did not use bending or twisting of the wrist. This highlights the issue that the person who uses DHMs should have some experience of the HFE analysis methods in order to be able to critically analyze the results.

4.2 Study Limitations and future research

The study had limitations that need to be considered. The usability and maturity of the technology are issues to consider. Especially in the sensor-based system studies, the participants needed to repeat motions occasionally several times before the system registered the gestures. This may have caused more use of extended wrist postures and therefore, more discomfort and fatigue. In addition, sometimes it was necessary to hold the posture for an extended period of time due to technical issues (in both systems). This can cause more static strain. However, the results still indicate that if the sensor-based system were to be used for long periods of time, the first symptoms would probably appear in the wrist. Other validity issues may derive from the low number of HFE experts performing the RULA analysis with the DHM. In addition, if the postures had been modelled using a motion tracking system and not manually put into the DHM, the results might have been more robust. However, the two HFE experts returned similar results from the analysis. Furthermore, the participants were students and researchers, which are not the most likely end-user groups for this kind of remote operation systems. It is also important to remember critiques [45,46] of the naturalness and usefulness of the gestural interaction, especially when designing gestures for work conditions.

In this study, NASA-TLX was used to measure the mental workload, and the body discomfort questions were used to identify the physical workload. In future, it would be interesting also to use other self-report and expert HFE evaluation methods, such as the Borg scale of perceived exertion [5], and to determine whether they could give similar results. In addition, it would be important to use postures tracked from real users when evaluating HFE with DHMs.

5 CONCLUSIONS

The purpose of this study was to investigate whether the use of DHMs by HFE experts can complement user evaluation of gesture-based interfaces. In addition, the need for a comprehensive HFE evaluation (not only time and error) during the design of gestures was discussed, especially when adopting ubiquitous multimedia systems for the industrial work context. Based on this study, it appears that the use of DHMs could support the HFE evaluation. The results of the DHM posture analyses were in agreement with the test participants' experience of the fatigue in their wrist and arm. With both the studied gesture-based control systems, further investigation is proposed, because participants felt discomfort in their shoulder or wrist area according to which system was used.

The use of virtual prototyping in terms of digital human modeling provided a rapid means of evaluating gesture interfaces. It was demonstrated that it is possible to use DHMs during the design of new interaction techniques. This is an addition to the more traditional use of DHMs in workplace design in domains such as aerospace and automotive industry.

ACKNOWLEDGMENTS

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Title	**Virtual prototyping in evaluation of human factors and ergonomics of human-machine systems**
Author(s)	Susanna Aromaa
Abstract	Industrial work is evolving due to the digitalisation and complexity of the systems. This creates challenges for workers in performing their work tasks well, and with their well-being considered. These challenges can be addressed by investing in improving issues in human factors/ergonomics (HFE) during the design of human-machine systems. In recent years, the use of virtual prototyping (VP) has increased in the product development process due to the matured and low-cost technologies. In addition, VP has proven to be useful in the design of work systems targeted at users. However, the design and use of virtual prototypes to support HFE evaluation is not a simple task. It is important to enhance the understanding of this topic, and to adopt systematic approaches in the use of VP in HFE evaluation. The goal of the thesis is to understand how to use VP in HFE evaluations when designing human-machine systems. The research of this thesis belongs to the field of HFE but it also contributes to the human-computer interaction (HCI) discipline by enhancing the understanding of digitalization and emerging new technologies in a work context. A case study approach was adopted for the research: six case studies were investigated and all of them were related to VP use in the evaluation of HFE. Case studies included topics such as suitability of virtual prototypes to support HFE evaluation, benefits and challenges of the use of VP in HFE evaluation, a systematic preparation of VP design reviews, and systematic deployment of VP in companies. Mainly qualitative data analyses were used, but quantitative measures were also applied. The thesis identifies critical issues related to VP use in HFE evaluation, and proposes an HFE/VP model. The model guides design engineers and research scientists through the critical steps when using VP in HFE evaluation. It supports the deployment of VP for company use, and provides instructions for designing VP systems to be used in HFE evaluation. The model proposes an HFE approach that can be adopted during VP. In addition, the understanding of key benefits and challenges of the use of VP in HFE evaluation are identified. This thesis contributes to both the research community and industry: the HFE/VP model includes practical and theoretical contributions that can be used when researchers are studying the use of virtual prototypes, and in industrial companies during product development. In research, the contribution of this thesis is in the intersection of the research fields of HFE/HCI and virtual reality.
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Nimeke	**Virtuaaliprototypoinnin hyödyntäminen ihmisen ja koneen välisen vuorovaikutuksen arvioinnissa**
Tekijä(t)	Susanna Aromaa
Tiivistelmä	Teollinen työympäristö muuttuu digitalisoitumisen myötä monimutkaisemmaksi ja haastavammaksi. Työntekijöille voi tuottaa vaikeuksia käyttää monimutkaisia järjestelmiä tehokkaasti ja siten, että heille ei aiheudu siitä ylimääräistä kuormitusta. Ratkaisevaa on ihmisen ja koneen välisen vuorovaikutuksen hyvä suunnittelu. Virtuaaliprototypoinnin (VP) hyödyntäminen tuotekehityksessä on lisääntynyt teollisuudessa viime vuosina. VP-teknologioiden laskeneet hinnat ja kehittyminen ovat osasyy tähän. VP on erityisen hyödyllinen suunniteltaessa monimutkaisia ihmisen ja koneen vuorovaikutuksia. Vaikka VP:n käyttö onkin lisääntynyt viime aikoina, on vielä tarve kehittää sen systemaattista käyttöä erityisesti ergonomian (human factors / ergonomics, HFE) arvioimisessa. Tämän väitöskirjan tavoitteena on tutkia VP:n käyttöä erityisesti ihmisen ja koneen vuorovaikutuksen arvioinnissa, jolloin otetaan huomioon käyttäjien tarpeet liittyen mm. ergonomiaan ja käyttökokemukseen. Tavoitteena on ymmärtää keskeiset tekijät käytettäessä VP:a ergonomian arvioinnissa. Tämä väitöskirja kuuluu ergonomian (HFE) tieteenalaan. Se on keskittynyt ennakoivaan ergonomian kehittämiseen suunnittelun aikana ja arvioi erityisesti käyttäjän ja koneen vuorovaikutusta. Väitöskirjan kontribuutio ulottuu myös ihmisen ja tietokoneen vuorovaikutuksen tutkimuksen tieteenalaan (human-computer interaction, HCI) auttamalla ymmärtämään digitalisoitumisen ja uusien tietoteknisten työkalujen käyttöä suunnittelijan työssä. Väitöskirja perustuu tapaustutkimukseen. Siinä kuvataan kuusi erilaista tapaustutkimusta, ja ne liittyvät VP:n hyödyntämiseen ergonomian arvioinnissa suunnittelun aikana. Tapaustutkimusaiheet liittyivät mm. virtuaaliprototyyppien soveltuvuuteen tukemaan ergonomian arviointia, mahdollisiin hyötyihin ja haasteisiin VP:a käytettäessä ergonomian arvioinnissa, systemaattiseen VP:n suunnitteluun ja systemaattiseen VP:n käyttöönottoon yrityksissä. Väitöskirjassa on käytetty sekä laadullisia että määrällisiä aineiston arviointimenetelmiä. Tämä väitöskirja tunnistaa kriittisiä aiheita liittyen VP:n käyttöön ergonomian arvioinnissa ja kuvaa HFE/VP-mallin sovellettavaksi siinä. Mallin avulla suunnittelijoiden ja tutkijoiden on helpompi hyödyntää VP:a ergonomian arvioinnissa. Malli tukee VP:n käyttöönottoa yrityksissä ja VP:n suunnittelua. Mallissa on otettu käyttöön ergonominen lähestymistapa, joka perustuu kokeelliseen ja evaluointipohjaiseen tutkimukseen. Myös merkitykselliset hyödyt ja haasteet VP:n hyödyntämisessä ergonomian arvioinnissa on tunnistettu. Tämän väitöskirjan kontribuutio hyödyntää sekä tiedeyhteisöä että teollisuutta. Molemmat voivat käyttää väitöskirjassa esitettyjä systemaattisia lähestymistapoja virtuaaliprototyyppien rakentamiseen ja käyttöön ergonomian arvioinnissa. Erityisesti tutkimustyö ergonomian ja VP:n rajapinnassa hyötyy tästä väitöskirjasta.
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Virtual prototyping in evaluation of human factors and ergonomics of human-machine systems

Industrial work is evolving due to the digitalisation and complexity of the systems. This creates challenges for workers in performing their work tasks well, and with their well-being considered. These challenges can be addressed by investing in improving issues in human factors/ergonomics (HFE) during the design of human-machine systems. Virtual prototyping (VP) has proven to be useful to support the design of work systems targeted at users. However, there is a need to enhance the understanding of this topic, and to adopt systematic approaches in the use of VP in HFE evaluation.

The goal of the thesis is to understand how to use VP in HFE evaluations. As a result, the thesis identifies critical issues related to VP use in HFE evaluation, and proposes an HFE/VP model. The model guides design engineers and research scientists through the critical steps when using VP in HFE evaluation.

This thesis contributes to both the research community and industry. It contributes, especially, to the intersection of the research fields of HFE and virtual reality. The HFE/VP model includes practical and theoretical contributions that can be used when researchers are studying the use of virtual prototypes, and in industrial companies during product development.

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