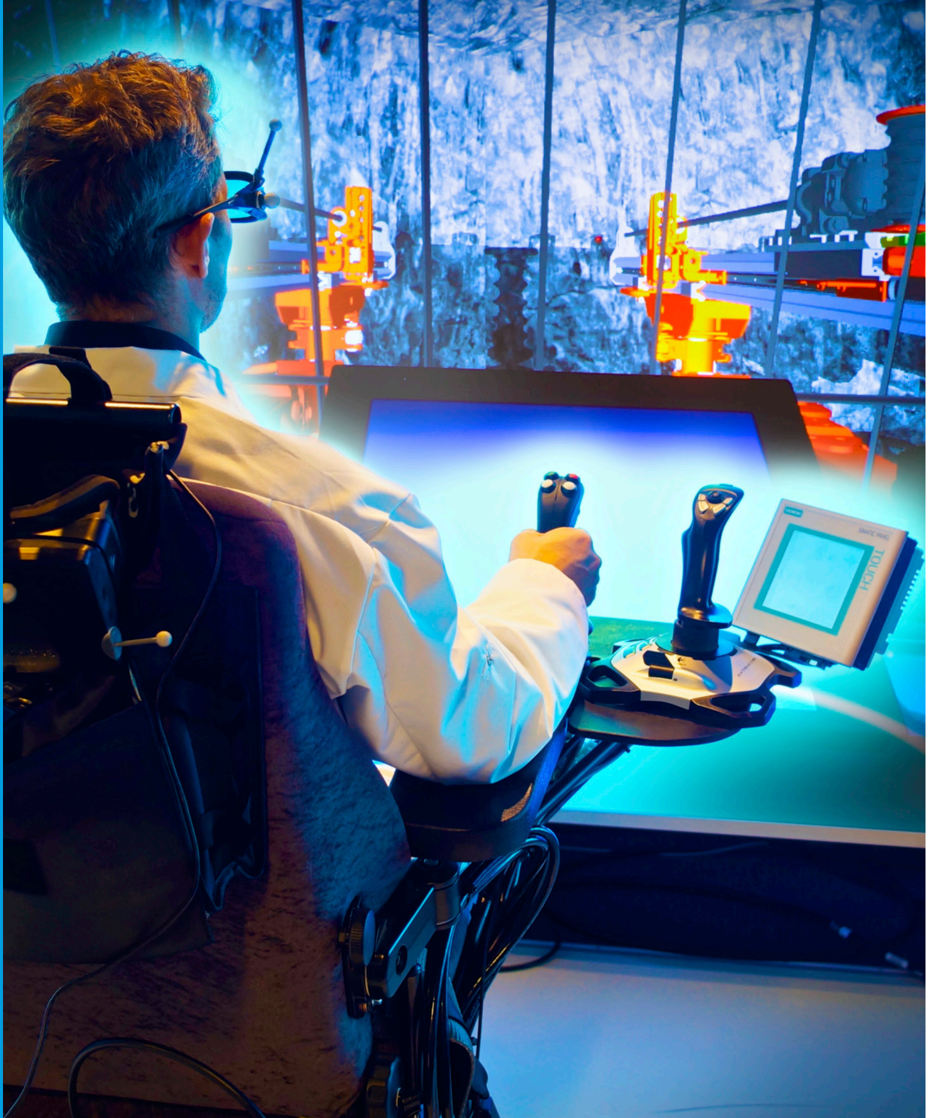

TECHNOLOGY • RESEARCH HIGHLIGHTS • VISIONS • SCIENCE
185

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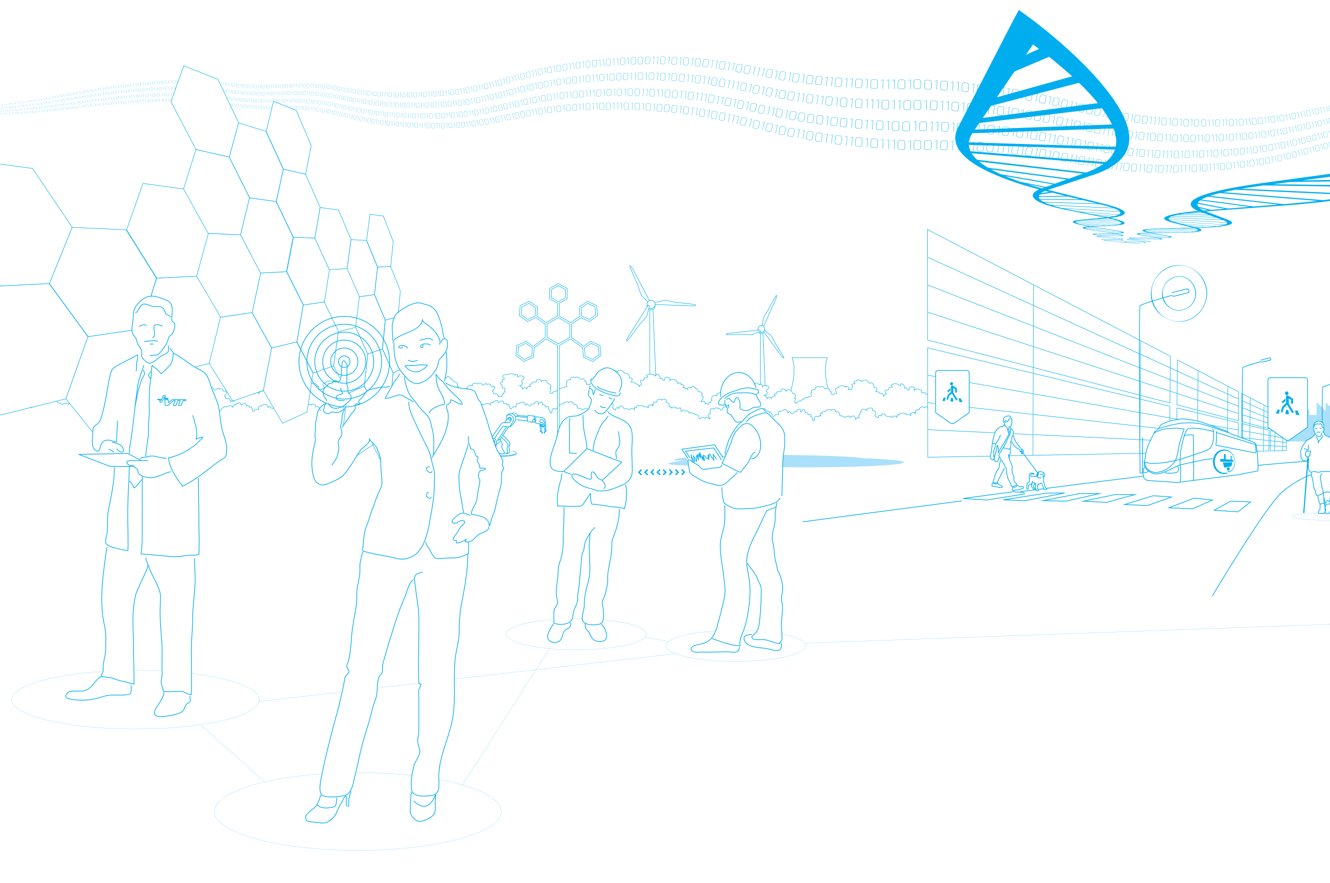
Susanna Aromaa | Simo-Pekka Leino | Juhani Viitaniemi

VTT



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Preface

This publication is part of the EFFIMA-LEFA research project under FIMECC (Finnish Metals and Engineering Competence Cluster) (2009–2014) funded by Tekes – the Finnish Funding Agency for Innovation. The main target of the project was to take a significant step towards user-centred R&D of mobile machines. User-centred R&D is made possible in particular by developing real-time virtual environments and simulators. User-centred R&D improvements enable usability, safety and life cycle efficiency to be achieved.

The research partners were Lappeenranta University of Technology/Lab of Intelligent Machines (project leader), VTT Technical Research Centre of Finland and Tampere University of Technology/EDE. Industry partners were Sandvik Mining and Construction Oyj, Cargotec Finland Oyj, MeVEA Oy and Savant Simulators.

This publication is based on VTT's research work with Sandvik and Cargotec during the project. Some material has also been collected in the projects ManuVAR "Manual work support throughout system life cycle by exploiting virtual and augmented reality" in the European Commission's Seventh Framework Programme FP7/2007–2013 under grant agreement 211548 and COFEX "Cabin of the future – user experience" in the eEngineering programme funded by VTT.

Contents

1. Introduction

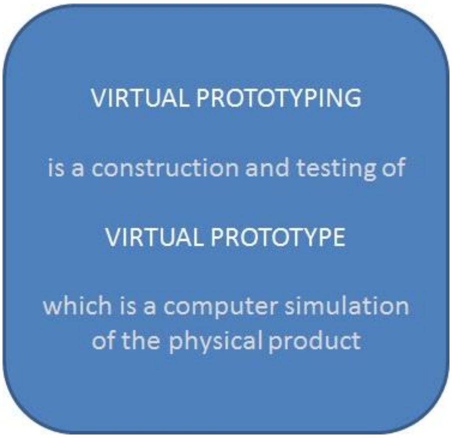
In recent years the use of virtual prototyping (VP) has increased in the product development process. The understanding of the advantages of VP, especially in human-machine interaction design, has initialised efforts made by companies. In addition, virtual prototyping technologies (software and hardware) are easily available and the prices have come down. Nevertheless, there is a need for a better understanding of what VP really is, how it is used, how it changes the production processes and how it differs from physical prototyping, for example. Companies do not necessary know how to use VP technologies effectively, and for that reason they don't gain the full potential from VP.

This publication presents the work that has been done by VTT in the research project called LEFA "New Generation Human-Centered Design Simulators for Life Cycle Efficient Mobile Machines". The work was funded by Tekes – the Finnish Funding Agency for Innovation and was carried out under FIMECC (Finnish Metals and Engineering Competence Cluster). In addition, some prior material was collected in the ManuVAR project, "Manual work support throughout system lifecycle by exploiting virtual and augmented reality", part of the European Commission's Seventh Framework Programme FP7/2007–2013 under grant agreement 211548, and the COFEX project, "Cabin of the future – user experience", part of the eEngineering programme funded by VTT.

The publication unites and concludes the research carried out about VP during the LEFA project. A small part of the material has been published during this project in conferences (see references) and a major part of the material is unpublished as such. Initially, the VP framework is described. Next the advantages and benefits that are acknowledged to have come from VP are presented. Thirdly, VP implementation into company use is illustrated; and finally, the application of VP during the design review is represented (see Figure 1).

Figure 1. Structure of the publication.

2. Virtual prototyping framework



This chapter presents the terminology that is used in our research when discussing virtual environments and virtual prototyping, and our proposal for the virtual prototyping framework. The research in the area of the reality-virtuality continuum lacks sufficient standardisation. For that reason there are many different specifications and definitions regarding virtual prototyping. The definition used in this paper is based on Wang's (2002) definition: "A virtual prototype, or digital mock-up, is a computer simulation of a physical product that can be presented, analysed and tested by concerned product life cycle aspects such as design/engineering, manufacturing, service, and recycling as if a real physical model. The construction and testing of a virtual prototype is called virtual prototyping." Our research into VP is focused on the area of human-machine interaction design. Therefore, this publication does not consider VP without human interaction, e.g. the simulation of multi-body system dynamics.

We propose a framework for virtual prototyping in human-machine interaction design to be able to systematically construct and test virtual prototypes. The VP framework (Figure 2) is based on theories, literature review and our previous research work. The main theory applied was Engeström's activity theory (1987; 2000; & Toiviainen 2011), based on the cultural-historical activity theory research by Vygotsky (1978) and Leont'ev (1978). Activity theory is most often used to describe actions in a socio-technical system through six related elements: object, subject, community, tools, division of labour and rules. In the framework, the subject is human, tools (or mediated artefacts) are the interface (virtual environment and virtual reality), and the object is the system model (Figure 2). In addition, theories such as domain theory (Andreasen, 1992), theory of technical systems (Hubka & Eder, 1988), and the VE definition by Kalawsky (1993) were used as background knowledge. Moreover, other attempts to define and structure the use of virtual prototypes in human-centred design have been made (Wang, 2002;

Ferrise et al., 2012; Mahdjoub et al., 2013; Ordaz-Hernandez et al., 2007). These approaches have some differences but what is common in these papers is that there is a need to have interaction/interface modules defined when using VP. Wang (2002) refers to this as “a human-product interaction model”.

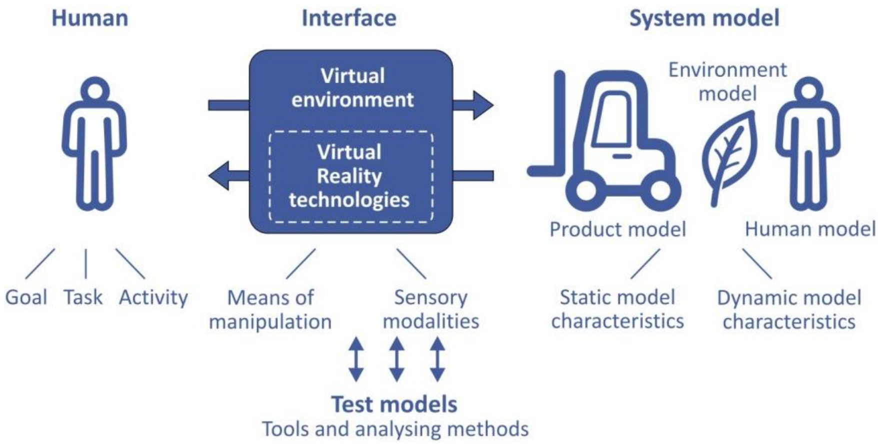


Figure 2. The framework for virtual prototyping in human-machine interaction is a combination of human, interface and system model elements. The human interacts with the system model through the interface. In addition, the test model element evaluates the design.

The structure of the virtual prototyping framework is based on the human, interface and system model elements (Figure 2). Humans have needs, goals, tasks and activities when interacting with the machine. In real life, humans have direct interaction with an object or a product. In VP, the human has indirect interaction with the system model through the mediated artefacts or tools, which are referred to here as the interface. In the interface element, the virtual environment (VE) uses virtual reality (VR) technologies to provide human with the means of manipulation and sensory modalities (Kalawsky, 1993). 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. steer the steering wheel) and get sensory feedback (e.g. visual or audio). The system model does not illustrate only the model of the product but it also includes other related models such as the environment and digital human models (avatars). Models have static characteristics (e.g. walls, colours) and dynamic characteristics (e.g. moving parts). There are relationships between the system model’s static and dynamic characteristics with the interface’s means of manipulation and sensory modalities, e.g. a human can pick up the part and move it in the VE by using a dataglove. In addition, test-related models (e.g. recording time, measuring distances) are needed in VP for the evaluation of the design.

3. Benefits of virtual prototyping

How are products best designed that users accept well and are willing to use? How do we make products that are better than those of our competitors? Virtual prototyping is one approach to improving design engineering and products. According to Ma et al. (2011) and Bordegoni et al. (2009), VP is particularly useful in the assessment of interaction systems used by users. The main benefits of VP are the reduced time-to-market, reduced costs, knowledge sharing and user participation (Aromaa et al., 2012; Aromaa et al., 2013a). The advantages and benefits of VP from three different beneficiary points of view – company/business, managers/designers and users/operators – are listed in Table 1.

Table 1. Advantages and benefits of virtual prototyping categorised by beneficiaries.

Beneficiaries	Advantages and benefits of the virtual prototyping
Company/Business	• Reduced costs • Reduced time-to-market • Reduced number of physical prototypes • Increased productivity • Better quality and customer satisfaction • Improved competitiveness • Efficient product process
Managers/Designers	• Better PLM/PDM management • Information and knowledge sharing • Understanding of complex product data • Enhancement of designers' experience • Design decision-making and learning • Easy design fault recognition • Early testing and analysis • Easy to consider features in different life cycle phases • Possible to conduct futuristic concept tests • Easy to evaluate safety critical tasks
Users/Operators	• User participation • Better user requirements definition • Realistic experience by visualisation and immersion • Natural interaction • Better user acceptance • Improved operator safety and comfort • Improved usability and ergonomics

Companies can benefit from virtual prototyping in terms of reduced costs, time-to-market and number of physical prototypes. Fewer physical prototypes mean less time and money spent on ordering and buying parts for the prototypes. In addition, VP can also increase productivity, quality and customer satisfaction, and therefore improve competitiveness.

Managers, designers and other stakeholders in the company can benefit from VP in the form of more efficient processes and better PLM/PDM management. By using illustrative VP, it makes it easier to share information and knowledge, and therefore also improve the understanding of complex product data. In addition, it can enhance the designer's experience of product design, and improve decision-making and early design fault recognition. The use of VP makes it easy to consider different life cycle phases in the early product design phase (e.g. it is possible to evaluate, with the same virtual prototype, the assembly worker's task, the operator's task and the maintenance worker's task). Moreover, virtual prototyping is a safe environment to test critical tasks or to illustrate futuristic concept ideas that do not exist yet.

Users/operators are one group that benefits from the use of VP. It allows users to participate and validate their product design as early as in the initial phases and it can help in the user requirements gathering phase. Because of the visual and immersive nature of VP, it is easier for the user to interact with and test prototypes. Due to this user participation during the design process, it is possible to achieve better products (e.g. usability, ergonomics, safety, comfort) and user acceptance.

3.1 Case example: Time savings by using virtual prototyping

In this case, VP was used for the testing and analysis assembly task (Figure 3). The test session revealed that an assembly worker did not have enough space to assemble an engine. In the initial plan, the first step in the assembly order was to put the tank into its place as early as possible. This would cause the worker to perform the assembly in a limited space between the tank and the engine. By changing the assembly order and adding a simple supportive structure, it was possible to give the assembly worker more working space (Aromaa et al., 2012).

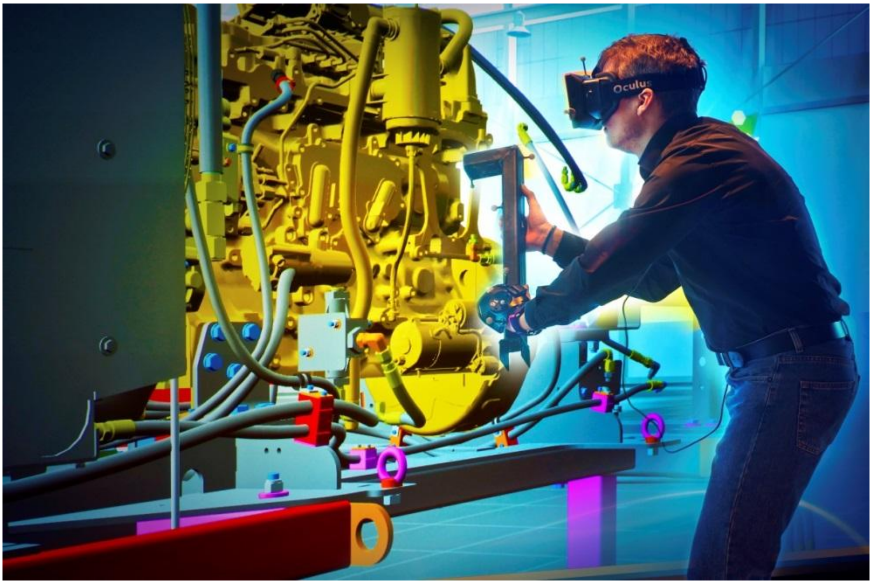


Figure 3. Using virtual prototyping for testing and analysing an assembly task.

Figure 4 illustrates this case example, where the use of virtual simulators rather than traditional engineering shifts the actual, physical system towards an earlier commercial product launch. It enables earlier and better decision-making based on earlier evaluation and validation of user and other stakeholder requirements, and verification of combined multidisciplinary design solutions with fewer engineering changes during product development and, therefore, faster time-to-market. Experiences from our partners show that the impacts are real.

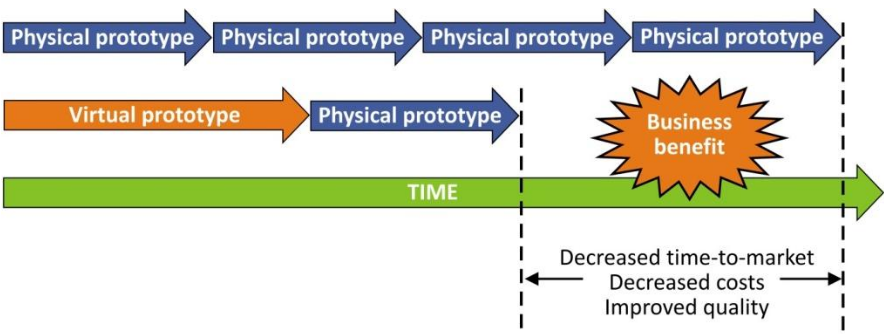


Figure 4. The amount of physical prototypes can be decreased by using virtual prototyping.

3.2 Case example: Human factors and ergonomic improvements by using virtual prototyping

To carry out a human factors and ergonomics (HFE) assessment, a VP design review meeting was held. The purpose of the study was to review a cab design from the following perspectives: operator's field of view, safety bars outside the front window, and controls in the driving position. During the design review, the model of the cab was provided in the VE. People from areas such as design, maintenance, safety and usability were represented. One person acted as an operator while others could observe the operator and the cab model in the screens. Some visibility, layout and space issues were detected, and one of the safety bar solutions was selected. (Aromaa et al., 2014.)

3.3 Case example: Enhancing the designer experience by using virtual prototyping

In this case, the goal was to compare the user's field of view and task visibility in crane cab design. Different design solutions were tested, such as different cab locations and the use of different camera views. A designer with driving experience sat on a chair on top of the motion platform with shutter glasses on and performed the task. His levels of visibility were exactly the same as what the user would have. Other participating stakeholders were able to see the broader angle of events on the screens and they could also observe the designer performing the task. The company made their decisions about the design based on discussions and findings. (Aromaa & Helin, 2011.)

4. Virtual prototyping implementation to company use

The potential of virtual prototyping in product design has still not been fully adopted in practice in industry, especially in the context of socio-technical system design. Based on a literature review (Leino & Riitahuhta, 2012) the main gaps relate to a lack of practical and adapted implementations of human-centred design, the integration of virtual engineering into product processes, bi-directional data and information flows between virtual engineering applications and data management systems (product data management [PDM]/product life cycle management [PLM]), and a lack of sufficient methods, tools and infrastructure for managing company content and knowledge (Aromaa et al., 2013b).

During the LEFA project, many challenges occurred in the implementation of VP. Users' attitudes towards VR technology can be negative because they have fears and resistance towards new technologies, and the benefits are not always visible to them. Therefore, they do not accept the technology. In addition, there might be a lack of resources in implementing the VP. Challenges can also derive from the technology itself, such as the fact that model updates are not easy to do, the fidelity of VP, and the use of new interaction technologies (e.g. head-mounted display, haptics). It might be that a company does not have a sufficiently systematic approach to apply concept design and it does not have a clear plan on how to implement VP from the very early stages (Aromaa et al., 2013b).

A maturity model was constructed in the LEFA project to improve VP implementation in companies (Aromaa et al., 2013b). The categories described in the maturity model (Table 2) are based on the company cases that resulted from the project, our previous experience, findings from the literature, approaches/theories such as Porter's value chain model (1985) and Hubka and Eder's design theory (1988), and relevant guidelines from systems engineering (ISO/IEC 15288, 2008). Moreover, Ameri's and Dutta's (2005) definition of PLM as a business solution that integrates organisations, processes, methods, models, IT tools and product-related information was used. The maturity model includes eight VP implementation categories and five maturity levels, from which the optimal level is illustrated in Table 2.

Table 2. Virtual prototyping implementation categories.

Virtual prototyping implementation categories (Aromaa et al., 2013b)	Optimal maturity level
Management understands the business impacts and opportunities	• Benefits and business impacts from virtual prototyping are fully known • Value of virtual prototyping for business is recognised
Definition of product process, including life cycle	• Processes are defined in detail and implemented in company use • Methods and tools for processes are defined • Processes are refined and iterated to the level of best practice
Description of virtual prototyping in the product process	• The use of virtual prototyping as part of the processes is managed • The methods and tools of virtual prototyping are embedded in daily practices
Level of virtual prototyping technology used	• Flexible virtual prototyping system that supports several design purposes and design needs
Data flow and quality	• Implemented efficient bi-directional model pipeline • Includes information modelling and integration with PDM/PLM
Support from enterprise infrastructure	• Dynamic infrastructure perfect for virtual prototyping • Dedicated facilities for virtual prototyping
Human resources for virtual prototyping technology management	• Nominated persons are responsible for the system's use • The whole company knows the system at a general level and how it can be used in their work
Attitudes and motivations in enterprise culture and organisation	• The whole company sees the potential and benefits of VP use • Active organisation culture of knowledge creation around VP • Company promotes use externally • The value network model is defined

The first category in the maturity model contains the company and management understanding of the business impact and opportunities that the use of VP can create. Companies need to have product processes described and implemented, and VP described as a part of those processes. The level and fidelity of the technology should be at such a level that it supports the VP purposes. Managing data flows and quality is also important: efficient bi-directional model pipeline, information modelling and integration with PDM/PLM. Proper infrastructure and dedicated facilities enable the use of VP. Human resources for managing the use of VP and the use of technologies is also required. In addition, the organisation's culture should support the VP approach (e.g. attitudes and motivations towards the VP) (Aromaa et al., 2013b).

4.1 Case example: A company's maturity level

Figure 5 presents an example of an assessed maturity level of a company that uses the VP maturity model categories listed in Table 2. Maturity was assessed in the machine manufacturer company during the workshop. Categories are evaluated using a five-step scale, where five is the optimal level and one is the lowest level of maturity.

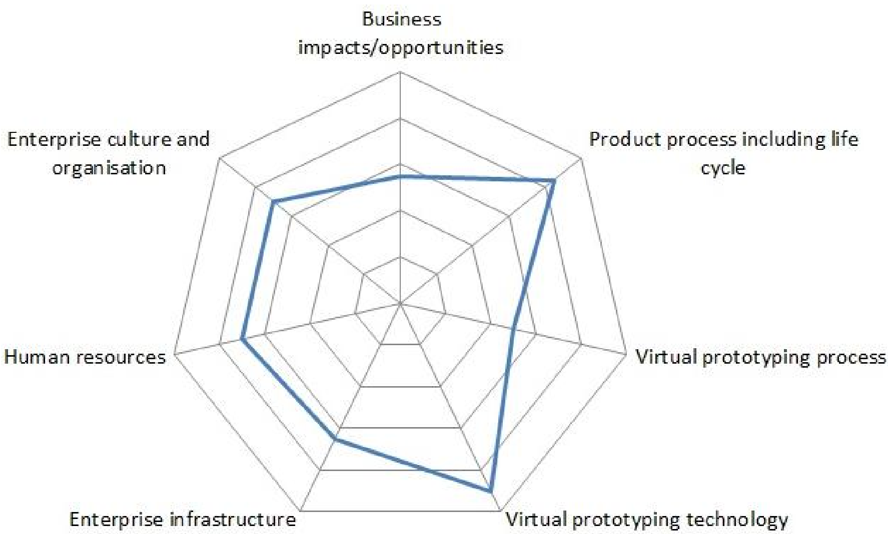


Figure 5. Illustrative figure depicting the virtual prototyping maturity level of the company.

The company had a good level of maturity for implementing VP at the product process level because it was adopted in the PLM implementation. It had also invested in VP technology and therefore it was also at a good level with this. The maturity of human resources, enterprise infrastructure and enterprise culture and organisation were at a medium level. Understanding of the business impacts and opportunities and VP processes were at a lower level. After the maturity assessment, the company was able make a plan as to how to develop VP in the future and decide on the checkpoints at which to assess the maturity again. In Figure 5 there are only seven categories due to the fact that the data flow and quality category was added to the maturity model after the case (cf. Table 2).

5. Virtual prototyping in design review

Design reviews facilitate the assessment of the status of the design against the input requirements; provide recommendations for improving the product or process, and guide towards appropriate actions. It is primarily intended to provide verification of the work of the design development team and thus design reviews should be considered as a confirmation and refining procedure and not a creative one. (IEC 61160, 2005.)

The objectives of a design review include (IEC 61160, 2005):

- Assessing whether the proposed solution meets the design input requirements
- Assessing whether the proposed solution is the most robust, efficient and effective solution to achieve the product requirements
- Providing recommendations as required for achieving the design input requirements
- Assessing the status of the design in terms of the completeness of the drawings and specifications
- Assessing the evidence to support the verification of the design performance
- Proposing improvements.

According to Seth et al. (2011), in human-machine interaction design expert assembly planners 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. There is often a lack of demonstrative and interactive interface between the reviewers and the design model, in order to be able to test the human-machine interaction in a natural way. Huet et al. (2007) and Verlinden et al. (2009) say that the organisation of the procedures for gathering, recording and sharing knowledge are usually not well organised or arranged because the importance of the reviews for the quality, usability, manufacturing and costs of the final product is not clearly seen.

As stated earlier, the preparation of the VP design review session (Figure 6) is different to the use of the physical prototype: there is a need for the preparation and development of the interface element (Figure 2). Therefore, the VP design review preparation procedure to support this process was developed during this research project. The approach was based on the research that was performed before and theoretical backgrounds such as domain theory (Andreasen, 1992), theory of technical systems (Hubka & Eder, 1988), activity theory (Vygotsky, 1978) and VE definition by Kalawsky (1993). In addition, other literature and material such as “Review of complex system lifecycle design” (Granholm et al., 2013) and systems engineering V-model were used.

Figure 6. Virtual prototyping design review session with design team and other stakeholders.

The preparation procedure for a virtual prototyping design review includes the stages shown in Figure 7. First there is a need to have an understanding of the product development project phase and maturity of the design (e.g. concept phase vs. detailed design phase). Next it is important to have a goal defined for the design review. System model content includes information about the models such as the product model and the environment model, and the activities that these should perform. Model characteristics refer to a model’s dynamic and static characteristics. Interface characteristics are sensory modalities and means of manipulation within VE. Test-related models include methods and tools to evaluate the design. Several actors are needed to prepare and attend the VP design review, so it is important that there is a common share of understanding and information all the way through this process.

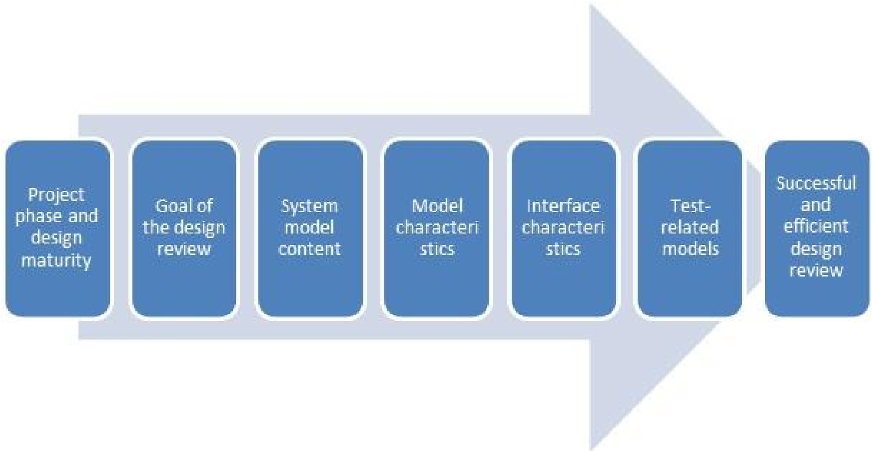


Figure 7. Process for the virtual prototyping design review preparation.

5.1 Case example: Challenges in virtual prototyping design review preparation

This section describes one example of the VP design review that was successful at a general level. Nevertheless, it lacked good communication in terms of sharing the common understanding during the preparation phase. The case example is from the machine cab design, where the visibility and control layouts were evaluated. A designer provided the 3D CAD model of the machine cab to the VR expert, who processed it and prepared the model for the design review. In the design review, eleven people from different responsibility areas such as design, maintenance, safety and usability were in attendance. In general, the design review provided many development suggestions and supported decision-making, but with more organised and effective practices, better results could have been gained.

Table 3 describes the shortfalls and consequences resulting from the poor preparation in this case. These are categorised based on the steps (Figure 7). The main reason for the inefficient preparation was the lack of sufficient communication. There was communication during the case but not enough to achieve a common understanding about the goals and models. The main consequences were waste of time and the lack of high-grade design decisions based on the best possible facts.

Table 3. Case example of challenges occurred during the virtual prototyping design review preparation. Challenges are categorised based on the virtual prototyping design review preparation procedure.

Preparation steps	Lack in preparation		Consequence
Project phase and design maturity	Current project phase was not discussed in detail	Not understanding the maturity of the model e.g. which things are still changeable in the model	Waste of time due to unproductive discussions
Goal of the design review	Understanding of the goal at a detailed level was not achieved	Not all the aspects that affect visibility were defined in detail e.g. the seating height	No facts for the visibility decisions
System model content	The context of the use was not fully understood	Not understanding the importance of visibility of the operator's whole body in the VE, only legs or hands were provided	Operator was not able to see his body well enough in the VE when evaluating legroom and reachability. No facts for the decision on the amount of legroom
Model characteristics	Model's dynamic and static characteristics were not discussed in detail. There were not enough discussions between different people	There were no predefined places for some model parts in VE e.g. for the two different seat locations	Waste of time due to changing chair position manually No decision based on facts, because the chair was not necessarily in the right position
	Some visual feedback was missing from the system model	Part of the machine model was missing	Visibility was not able to be evaluated in that direction where part of machine was missing
Interface characteristics	No modalities applied other than visuals, e.g. haptics was not included	Not able to sense where the cab walls and controls are without haptics	It was not possible to evaluate available space accurately
Test-related models	Special test-related model was not prepared	Not understanding the importance of the measuring distances when evaluating legroom or controls layout	It was not possible to measure distances in VE easily and quickly
Successful and efficient design review	Within these goals the review was successful only insofar as giving some rough estimates on how things currently are with product design.		

The project phase and design maturities of different design items are important for knowledge sharing during the design review. In addition, this step reveals decisions that have already been made, e.g. the size of the touchscreen that cannot be changed anymore. In this case the discussion on the screen size was useless and a waste of time because the screen had already been selected. The screen was blocking the visibility but the only solution was to move and rotate it to improve the field of view.

The definition of the virtual prototyping design review goal allows all participants to get into the right state of mind when they prepare themselves and attend the meeting. Everyone knows why they are attending and what is expected of them. In addition, this affects the preparation of the model and the virtual environment for the design review. If the goal is a little unclear it directly affects the system model content definition, such as if the user wants to test the legroom and reachability, a human model needs to be provided or at least related body parts are needed. In this case it was not possible to evaluate the legroom properly.

It is important to prepare a model's dynamic and static characteristics before the design review. In addition, the level of system model details needs to be known to be able to fulfil the goals of the design review. In this case there were not enough discussions with the VR expert who was preparing the system model for the VE. One specific issue was that the operator needed to sit in two different locations in the cab during the operations. Nevertheless, there were no predefined places for the two seat locations and time was wasted due to changing the seat position manually during the design review. In addition, it was difficult to ensure that the seat was in the correct position.

In this case there were not many requirements for interaction with the model. The goal was more to visually evaluate the machine model, but the lack of sensory feedback did affect the evaluation of the cab space and control layout. Without the haptics, the user was not able to accurately evaluate the available space.

Because the review was carried out based on the visual experience test, related models were not build. Even so, there could have been some test models for the visibility evaluation and for the measuring distances, e.g. measuring tape for the layout of the controls and for the legroom when changing the control panel location.

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Title	**Virtual prototyping in human-machine interaction design**
Author(s)	Susanna Aromaa, Simo-Pekka Leino & Juhani Viitaniemi
Abstract	In recent years, the use of virtual prototyping (VP) has increased in industry. Nevertheless, the potential of VP in product development has still not been fully achieved in practice. Companies do not necessary know how to use VP technologies and for that reason they are not able to achieve all the benefits. This publication presents the work that has been done by VTT, mainly in the research project called LEFA "New Generation Human-Centered Design Simulators for Life Cycle Efficient Mobile Machines", addressing VP in human-machine interaction design. The purpose is to describe what VP means, what benefits can be achieved, and how companies can use VP in practice. This publication improves the understanding of VP and can be used as a guideline by companies.
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Nimeke	**Virtuaaliprototypointi ihminen-kone –vuorovaikutuksen suunnittelussa** Alaotsikko
Tekijä(t)	Susanna Aromaa, Simo-Pekka Leino & Juhani Viitaniemi
Tiivistelmä	Virtuaaliprototypoinnin (VP) käyttö on lisääntynyt viime vuosina teollisuudessa. Siitä huolimatta kaikkea hyötyä VP:n käytöstä ei ole pystytty saavuttamaan. Tässä julkaisussa esitellään VTT:n projektissa LEFA "New Generation Human-Centered Design Simulators for Life Cycle Efficient Mobile Machines" tekemää tutkimustyötä ja johtopäätöksiä. Tutkimustyössä on keskitytty erityisesti VP:n käyttöön ihminen–kone-vuorovaikutuksessa. Tarkoituksena on kuvata, mitä VP tarkoittaa, mitä potentiaalisia hyötyjä VP:stä voidaan saavuttaa ja kuinka sitä voidaan hyödyntää käytännössä. Julkaisu lisää ymmärrystä VP:n käytöstä, ja yritykset voivat hyödyntää sitä ohjeena.
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