THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Virtual Reality Technology for Factory Layout Planning

LIANG GONG

Department of Industrial and Materials Science

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2017

Virtual Reality Technology for Factory Layout Planning
LIANG GONG

ISSN 1652-9243
Report no IMS-2018-19

Department of Product and Production Development
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover:
The cover illustrates a user using the virtual reality tool to evaluate a planned factory layout.

Printed by
Chalmers Reproservice
Gothenburg, Sweden 2018

ABSTRACT

Factory layout planning (FLP) has been a long-standing area that largely influences the overall productivity of the manufacturing practice. Today's manufacturing industry faces great challenges owing to an increasing awareness of environmental concerns and the trend-shift from mass production to mass customization. Companies are striving to continuously and effectively improve their existing production systems, adapt to demand and remain competitive in the global market. Such an adaption process usually involves a redesign of the production layout. Factory layout change are becoming more frequent and have much higher requirements for quality and efficiency.

Traditional ways of planning the layout change based on expert knowledge and onsite workshops cannot promise optimal solutions and bring unwanted stoppages to production, and computer aided design (CAD) and simulation have become widely used to support the process. The simulation approach focuses mostly on the quantitative measures (such as travel distance, time, frequency and throughput). It has shown to be efficient for general layout planning, but less satisfactory for detailed layout planning when qualitative factors such as safety, ergonomics and operator preference are becoming more and more important.

Virtual reality (VR) technologies have become ever mature in recent years and are known for their ability to provide users with experience closely akin to the physical world through computer-generated representation. The richness and flexibility of the computer-generated environment can be of overall benefit to the future layout planning process.

This thesis set out to investigate how different stakeholders, such as operator, maintenance engineer, production engineer, actively can support the decision-making in factory layout planning that utilizes virtual reality technologies, and it aims to improve current FLP practice through a systematic procedure that enables the active involvement of different stakeholders during the layout redesign and evaluation process.

Therefore, a literature review about previous virtual reality applications was conducted to understand the benefit and limitation and based on which, three empirical studies were followed iteratively to explore and evaluate different VR integration approaches. A general guidelines on how to integrate and use virtual reality technology for factory layout planning was developed and discussed.

Keywords: Virtual Reality, Factory Layout Planning, 3D Laser Scanning, Virtual Factory Modelling

ACKNOWLEDGEMENTS

The research work was full of joy and challenges and I would not have finished this thesis without the support from my colleagues and friends. I would like take this opportunity to express my sincere gratitude to all of them.

First of all, I would like to thank Chalmers University of Technology for providing such an amazing environment to work at. I want to thank my examiner, Professor Johan Stahre for all the support during this journey. I would also like to thank my supervisors, Professor Björn Johansson and Associate Professor Åsa Fast-Berglund for supporting my work and for all the valuable comments and advices along the way. Thanks to Associate Professor Anders Skoogh for being my co-supervisor in the first year.

Thanks to all the colleagues at the Department of Industrial and Materials Science for the lovely and inspiring working atmosphere. Jonatan Berglund, thank you for all the help for work and life in Sweden. Thanks to all the collaborators in different research projects, thesis students and partner companies for making this thesis possible.

Finally, I want to thank my family for the unconditional support. I would like to thank my parents for always being supportive to my choices. From the bottom of my heart, thank you my beautiful wife Canwei (张粲葳) for all your sacrifice and for always believing in me.

我的宝，谢谢你所付出的一切，我爱你！

Liang Gong 龚亮

Gothenburg

November, 2018

APPENDED PUBLICATIONS

Publication A: Gong L, Berglund J, Wang Z, et al (2016) Improving Manufacturing Process Change by 3D Visualization Support: A Pilot Study on Truck Production. Procedia CIRP 57:298–302. doi: http://dx.doi.org/10.1016/j.procir.2016.11.052

Contribution: Liang Gong initiated the paper and contributed with the implementation of test case and writing the paper. Jonatan Berglund assisted with data collection and data analysis. Zhiping Wang facilitated the case study at Volvo and reviewed the paper. Anders Skoogh and Björn Johansson provided with comments and advice.

Publication B: Gong L, Berglund J, Saluäär D, Johansson B (2017) A Novel VR Tool for Collaborative Planning of Manufacturing Process Change using Point Cloud Data. Procedia CIRP 63:336–341. doi: https://doi.org/10.1016/j.procir.2017.03.089

Contribution: Liang Gong designed and conducted the study with assist from Jonatan Berglund. Liang also contributed with data collection, data analysis and writing the paper. Dennis facilitated the case study at Volvo and reviewed the paper. Björn Johansson provided with comments and advice.

Publication C: Gong L, Berglund J, Fast-Berglund, Å, Johansson B, et al. (2018) Development of virtual reality support to factory layout planning. International Journal on Interactive Design and Manufacturing (Submitted)

Contribution: Liang Gong contributed with the implementations of cases and writing the paper. Jonatan Berglund assisted with data collection. Åsa Fash-Berglund helped with data analysis and provided comments and advice in writing together with Björn Johansson.

ADDITIONAL PUBLICATIONS

Publication 1: Berglund J, Gong L, Sundström H, Johansson B (2017) Virtual Reality and 3D Imaging to Support Collaborative Decision Making for Adaptation of Long-Life Assets. In: Grösser SN, Reyes-Lecuona A, Granholm G (eds) Dyn. Long-Life Assets From Technol. Adapt. to Upgrad. Bus. Model. Springer International Publishing, Cham, pp 115–132

Contribution: Liang Gong contributed with implementing the VR system and collecting the data and feedback as well as reviewing the paper.

Publication 2: Berglund J, Gong L, Sundström H, Johansson B (2017) Adaptation of High-Variant Automotive Production System Using a Collaborative Approach. In: Grösser SN, Reyes-Lecuona A, Granholm G (eds) Dyn. Long-Life Assets From Technol. Adapt. to Upgrad. Bus. Model. Springer International Publishing, Cham, pp 255–275

Contribution: Liang Gong contributed with implementing the VR system and collecting the data and feedback as well as reviewing the paper.

Publication 3: 1. Gong L, Li D, Mattsson S, et al (2017) The comparison study of different operator support tools for assembly task in the era of global production. Procedia Manuf 11:1271–1278. doi: https://doi.org/10.1016/j.promfg.2017.07.254

Contribution: Liang Gong further developed the study based on previous cases made by Sandra and Dan. Liang also contributed by developing and conduct the VR test as well as writing the paper.

TABLE OF CONTENTS

1 INTRODUCTION 1
1.1 Factory layout planning 1
1.2 Emerging virtual reality (VR) technology and opportunities for factory layout planning 1
1.3 Problem statement 2
1.4 Purpose, Aim and Research Questions 3
1.5 Delimitation 3
1.6 Thesis structure 4
2 FRAME OF REFERENCE 5
2.1 Factory layout planning 5
2.1.1 Conventional factory layout planning methods 5
2.1.2 Factory layout planning with virtual reality 6
2.2 Virtual reality technologies. 7
2.2.1 Virtual reality definitions 8
2.2.2 Immersion and presence in virtual reality 9
2.2.3 Virtual reality classifications 9
2.3 Point cloud representation of environment 10
3 RESEARCH APPROACH 13
3.1 Philosophical worldview 13
3.2 A multiphase mixed methods research design 14
3.3 Research methods 15
3.3.1 Data collection methods 15
3.3.2 Data analysis methods. 16
3.3.3 Summary of research methods 17
3.4 Research quality 17
4 SUMMARY of APPENDED PAPERS 19
4.1 Paper A 19
4.1.1 Results of the paper 19
4.1.2 Contribution to research questions 20
4.2 Paper B 20
4.2.1 Results of the paper 20
4.2.2 Contribution to research questions 22
4.3 Paper C 22
4.3.1 Results of the paper 22
4.3.2 Contribution to research questions 23
5 RESULTS 25
5.1 Analysis of literature review 25

5.2 Analysis of results in appended papers 28
5.2.1 Paper A 28
5.2.2 Paper B 28
5.2.3 Paper C 30
6 DISCUSSION 33
6.1 Discussion of the results 33
6.2 Discussion of methodology 35
6.3 Academic and industrial contribution 35
6.4 Future research 36
7 CONCLUSION 37
8 REFERENCES 39
9 APPENDIX – Table of reviewed articles 1

PAPER A
PAPER B
PAPER C

LIST OF ABBREVIATIONS

3D – Three Dimension
CAD – Computer Aided Design
CAVE - Cave Automatic Virtual Environment
CIP – Continuous Improvement Process
DoF – Degrees of Freedom
FLP – Factory Layout Planning
FOV – Field of View
FPS – Frame per Second
HCI – Human Computer Interaction
HMD - Head-Mounted Display
IT – Information Technology
LIDAR – Light Detection and Ranging
PC – Personal Computer
SLP – Systematic Layout Planning
VirCA - Virtual Collaboration Arena platform
VLP – Virtual Layout Planning
VR – Virtual Reality

LIST OF FIGURES

Figure 1. Number of publications with keyword “virtual reality” over the years from Google Scholar. 8
Figure 2. The mechanism of a 3D laser scanner. 11
Figure 3. The interconnection of worldview, design and research methods (Creswell, 2013). 13
Figure 4. The multiphase mixed methods research design. 14
Figure 5. Iterations of systematic approach of empirical research, inspired by Flynn et al. (1990). 15
Figure 6. The graphic interface to create alternative layouts. 19
Figure 7. First person view of alternative layout A. 20
Figure 8. Conceptual model of the collaborative VR tool 21
Figure 9. One stakeholder evaluating layout via immersive VR. 21
Figure 10. Overview of number of publications of VR in production system from 1993 to 2017. 25
Figure 11. Publications categorized with different types of VR technologies 26
Figure 12. Correlation between application areas and VR types. 27
Figure 13. Test subjects’ rating feedback on the VR tool. 29
Figure 14. Result of promising application areas. 29
Figure 15. Guidance for employing VR in FLP. 31

1

INTRODUCTION

This chapter describes the background to the research within this thesis, and the structure of the thesis.

1.1 FACTORY LAYOUT PLANNING

Factory layout planning (FLP) has been a long-standing area that largely influences the overall productivity of the manufacturing practice. Dating back to the period prior to the Industrial Revolution, blacksmiths started arranging their workspace according to process requirements and the movement of their work. They allocated various resources within their production environment to best address the requirements and constraints which the encountered. FLP is considered one of the most important aspects in the success of a manufacturing company, as it may affect overall production in terms of throughput, volumes, quality, cost, employee satisfaction and so on. It has been reported that a well-designed manufacturing layout can reduce operational costs by 50 percent (Tompkins et al. 2003). With the growing complexity of products and production process, various research projects and practices have been devoted to coping with this increasingly challenging task. The result has been such schemes as project layout, functional layout, production line layout and systematic layout planning (Korves and Loftus 1999).

Today's manufacturing industry faces great challenges owing to an increasing awareness of environmental concerns (Greis 1995) and the trend-shift from mass production to mass customisation (El Maraghy 2006). Companies are striving to continuously and effectively improve their existing production systems, adapt to demand and remain competitive in this global market. Such an adaption process usually involves a redesign of the production layout. FLP tasks are becoming more frequent with much higher requirements for quality and efficiency. In this context, new technology, methods and tools are needed to support and smooth the adaptation process.

1.2 EMERGING VIRTUAL REALITY (VR) TECHNOLOGY AND OPPORTUNITIES FOR FACTORY LAYOUT PLANNING

In 1965, the initial idea of VR was proposed as “a system that can display information to all senses of the user with an equal or bigger resolution than the one that can be achieved in a natural way so that the user cannot say that the artificial world is not real." (Sutherland 1965). This idea has attracted a great deal of attention and enthusiasm ever since. However, due to the limitations of hardware and software in the 1960s, these changes could not be realised. Only in the last decade with more advanced information technology, cheaper, more powerful hardware and more effective algorithms, has VR matured enough to play its role in this interesting and challenging era.

The representation and direct manipulative capabilities of virtual manufacturing technology seem particularly appropriate for visualising and assessing complicated physical production facility constraints, whilst also determining optimal process flows. When designing and analysing production systems, there should be concurrent consideration of the economic and operational aspects.

VR technologies are known for their ability to provide users with an experience closely akin to the physical world through computer-generated representation (Smith and Heim 1999). The richness and flexibility of the computer-generated environment can be of overall benefit in FLP work. Virtual layout planning (VLP) has drawn much attention because of the richness and flexibility it brings to the computerised virtual environment. It is thought that the visualisation and interaction provided in the virtual model will help bring stakeholders closer to the decision-making process and thus raise the bar for qualitative and quantitative perspectives (Yaman 2001). There are reportedly three main advantages of VLP (Smith and Heim 1999) (Heragu 2016):

1. The ability to play "what if" and test alternative scenarios with relative ease.

2. Moving various stakeholders affected by the layout design closer to the layout decision-making process.

3. Improving the decision making-process from quantitative and qualitative perspectives, bearing in mind the richness and flexibility that a virtual model can provide.

1.3 PROBLEM STATEMENT

Manufacturing companies need to constantly improve and upgrade their production to cope with new challenges in today's global completion. The improvement process inevitably involves changes to the factory layout. However, any changes in the real factory environment will affect all stakeholders and the performance of the production system as a whole. Therefore, a systematic process of planning and evaluation before the layout change is of great importance to aid the understanding for these stakeholders within the production system.

Traditional ways of planning the layout change based on expert knowledge and onsite workshops cannot promise optimal solutions and bring unwanted stoppages to production, which make them not sufficient to cope with the ever growing complexity in today's factory environment (Lindberg 1992; Jong, Li, and Syu 2012). Computer aided design (CAD) and simulation have become widely used to support factory layout planning (FLP) process. The simulation approach focuses mostly on the quantitative measures (such as travel distance, time, frequency and throughput), by applying mathematical models and algorithms to select the optimal solution (Sly 1996; Grajo 1996). It has shown to be efficient for general layout planning, but less satisfactory for detailed layout planning when qualitative factors such as safety, ergonomics and operator preference are becoming more and more important. The CAD approach works with the general assumption that the virtual model developed in the computer can fully represent the actual factory environment. However, due to the complexity of the factory environment, it has to deal with the dilemma of modelling time and model quality. Thus, certain simplifications of the models are not uncommon which can lead to potential design flaws. At the same time, both approaches require specific technology expertise, which hinders the involvement of various affected stakeholders to contribute in the new layout design process. Therefore, it is no surprise to find out that the cost of layout design errors and production disruptions often outweighed the intended improvement to the production systems(Aurich, et al. 2006).

The limitations mentioned above make the existing approaches less desirable. As Smith and Heim (1999) pointed out that FLP is a multi-criteria problem, which must satisfy both quantitative and qualitative constraints, there is therefore a need to further explore and develop new ways of supporting the FLP in this transformation to industry 4.0 era.

1.4 PURPOSE, AIM AND RESEARCH QUESTIONS

The purpose of this thesis is to investigate how different stakeholders, such as operator, maintenance engineer, production engineer, actively can support the decision-making in factory layout planning (FLP) tasks utilizing VR technologies.

This thesis aims to improve current FLP practice through a systematic procedure that enables the active involvement of different stakeholders during the layout redesign and evaluation process. The intended improvements include the development of realistic virtual factory models utilizing VR, which facilitates ease in involvement of all the affected stakeholders to contribute to the layout redesign process.

To accomplish the aim, two questions are formulated in order to 1) understand the benefits and challenges for stakeholders to use VR technology in production systems through previous studies and 2) Conduct empirical studies in order to develop a systematic process to improve existing FLP practices by integrating VR technology.

RQ1: How has virtual reality (VR) technology been used in production system development?

A systematic review of previous publications is an important first step, if we are to understand state-of-the-art VR research and practice in the area of production. This requires: 1) a working definition of VR in this thesis, 2) a list of characteristics and features, which the latest VR hardware and software can provide and 3) a classification of VR's area of application within production engineering. The overall trend and promising areas for VR technology in manufacturing should also be identified.

RQ2: How can virtual reality (VR) technology be systematically used to support decision-making during factory layout planning (FLP)?

In response to rapidly changing demands, manufacturing companies need to conduct more frequent FLP tasks and thus adapt or improve existing production procedures. It is thought that the promised advantages of VR technology will benefit FLP activities. However, this requires the development of systematic methods of integrating VR into current FLP practice. Empirical case studies, which explore and evaluate different VR integration approaches, will be conducted and general guidelines on using VR in FLP tasks need to be developed.

1.5 DELIMITATION

The research in this thesis has been conducted with the emphasis on using VR technology in FLP processes, to improve the quality of decision-making. The delimitations of the research are as follows:

- This is a study of adopting existing VR technology, rather than developing it.

  This thesis studied ways to use state-of-the-art VR technology in FLP by identifying the benefits and challenges it brings and trialling different integration approaches. The development of VR technology is beyond the scope of this thesis.

- The usability-related issues of the demo applications are beyond the scope of this research.

  In the three empirical studies, demo applications were developed to demonstrate the proposed approaches to adopting VR in FLP. However, usability issues, such as 3D user interface design, user interaction and so on were not taken into account. The demo applications were used to evaluate proposed work procedures, rather than the usability of the software application.

1.6 THESIS STRUCTURE

This thesis comprises seven chapters, with the content of each chapter summarised in Table 1.

Table 1: Content summary of thesis chapters

Chapter	Content
1. Introduction	This chapter provides the background to the research by outlining the problem. Descriptions of the purpose, aim and research questions follow.
2. Frame of reference	This chapter describes the theoretical foundations of this research, including the introduction of virtual reality technology and the factory layout planning methods.
3. Research approach	This chapter describes the procedures used throughout the research and the rationale for the chosen methodology, including philosophical worldview, multiphase mixed methods design and research methods.
4. Summary of appended papers	This chapter summarises each of the appended papers, with case descriptions and implementations. It also explains the contribution of each paper to the research questions.
5. Results	This chapter synthesises the answers to the two research questions.
6. Discussion	This chapter discusses the research questions in a broader context, in terms of results and methodology. There is also a presentation of the scientific and industrial contributions of this thesis and proposed future research.
7. Conclusion	This chapter concludes the thesis by describing the answers to the two research questions.

2

FRAME OF REFERENCE

This chapter describes the studies in relation to the research focus area.

2.1 FACTORY LAYOUT PLANNING

FLP is not a new problem in manufacturing engineering; due to its multi-criteria nature, it is a complex decision-making process. Every change made to the production system will affect various stakeholders throughout the whole manufacturing process.

2.1.1 Conventional factory layout planning methods

Muther (1974) was one of the first to apply a systematic methodology to the planning process and his systematic layout planning (SLP) approach is still a valid procedure. Muther considers the planning process as a loop, which must be executed twice; once for the overall layout and a second time to detail the layout plans. Ishikawa (1985) and Deming (1986) suggested workshops conducted by relevant workers as a systematic way to achieve improvement in manufacturing systems. Each workshop lasts one to five days while production is temporarily stopped. The workshops are conducted by workers in the manufacturing area, which needs improvement, plus engineers from other functions. The joint participation of all stakeholders involved ensures proper outcomes from the workshops. Such outcomes might include the reduction of setup times or improved layouts (Imai 1986). Aurich et al. (2006) further developed this workshop approach and proposed the workshop-based Continuous Improvement Process (CIP). The workshops should be held at set intervals to ensure continuous improvement.

Despite the long-term benefits of manufacturing process change, it can also bring serious short-term disruptions. The costs may outweigh the potential benefits if the process change is not designed and implemented properly. Short-term disruptions such as reduced productivity, excessive equipment downtime and problems scheduling materials, quality and maintenance are common by-products of process change (Lindberg 1992). Hayes and Clark (1985) pointed out that the short-term loss in productivity from implementing new manufacturing equipment is often more costly than the actual equipment purchase. Goodman and Griffith (1991) state that managers tend to select and plan process change from the narrow viewpoint of the long-term benefits being sought. Carrillo and Gaimon (2000) subsequently identified four common challenges in manufacturing process change: 1) disruptions during process change typically reduce short-term capacity, but may increase effective capacity in the long run; 2) shrinking product lifecycles complicate the implementation of process change; 3) while knowledge may enhance the ultimate benefits derived from process change, the correct timing and means of knowledge creation are difficult to discern; 4) a series of trade-offs must be evaluated when choosing a particular process change to implement. A coherence procedure which can facilitate the active participation and contribution of all stakeholders is therefore essential (Saha et al. 2000).

Of the previous attempts to resolve FLP problems, two major directions are the algorithmic and procedural approaches. Algorithmic approaches use mathematical modelling techniques to formulate the FLP as optimisation problems. They use heuristic algorithms to simplify design constrains and objectives and thus reach feasible solutions (Jiang et al. 2014). Quantitative measures such as flow distance of material and operators are the sole focus of this method. Procedural approaches, on the other hand, can bring both quantitative and qualitative measures into the design process (Yang and Kuo 2003). It aims to divide the design process into several steps which are solved sequentially (Mahdavi et al. 2008). However, its implementation is heavily dependent on generating quality design alternatives, which are largely based on experts' experience (Shahin 2011). The advantages and limitations of these conventional FLP methods are listed and summarised in Table 2.

Table 2. Advantages and limitations of conventional FLP methods.

Advantages (Welgama and Gibson 1995)	**Limitations** (Yaman 2001)
material handling costs can be minimised	solutions are locally optimised
overall production time can be optimised	quality relates directly to local facilities
effective facilitation of the manufacturing process	competitiveness between disciplines is limited and sometimes not possible
flexibility of rearrangement and operation	specific area of concentration is limited
minimising investment in equipment	there are performance limitations
effective utilisation of space	flexibility of production is limited
provision of a safe workplace designed for convenience	costs of prototype and agile manufacturing are high

2.1.2 Factory layout planning with virtual reality

Zetu et al. (1998) proposed an approach for automatically extracting three-dimensional models of physical objects. These would be used for VR tools (in detailed layout decision-making support). Korves and Loftus (1999) developed a framework for integrating VR into factory layout planning (FLP) and further exemplified it with an industrial case study comparing the use of immersive VR with a monitor-based system for detecting layout design flaws (Korves and Loftus 2000). The study showed that immersive VR can provide better support for early detection of serious layout design flaws such as tool arrangement, visibility, and tool location. Smith and Heim (1999) pointed out that FLP may benefit most from VR systems when the footprint or rectangular area required by the work cell or machinery offers insufficient information for the decision-maker. The interactive three-dimensional display provided by VR systems are better able to convey the information needed by factory layout designers. Duffy et al. (2003) designed an internet-based VR system to test the influence of modifications in the virtual environment (lighting, sound and so on) on hazard perception during the FLP process. In a similar study, Ng et al. (2012) demonstrated the potential of applying VR to improve FLP in terms of the hazard and risk perception, safe waiting time and maximum reach of robot arms. The study also discusses preliminary guidelines for using VR in FLP. Okulicz (2004) developed a VR-based manufacturing and layout planning system, focusing on evaluating the ergonomics and accumulated loads for operators. Aurich et al. (2009) further developed their continuous improvement process (CIP) workshop for FLP by integrating VR technology and proposing a VR-based CIP workshop. They demonstrated that the CIP workshops within a virtual manufacturing environment can successfully transfer their results back to the physical environment. Choi et al. (2010) introduced a rule-based system, which creates a virtual prototype using product, process, plant and resource data for virtual plant review. They proposed a new virtual plant review procedure. In the same year, an approach to immersive multi-projection visualisation of manufacturing processes was reported (Filho et al. 2010). This allows scenarios with dynamic components, plus collaborative VR visualisation between geographically distributed users. This approach uses multi-CAVE devices and has been proved efficient in regard to complex scenarios, scalability, collaboration and low implementation costs. Galambos et al. (2012) later introduced a similar approach, using the Virtual Collaboration Arena platform (VirCA) for distance collaboration. This allows users to work in a joint virtual space during FLP. Lee et al. (2011) studied several methods of integrating real objects (such as real images) with virtual ones and derived a general framework for developing virtual FLP systems. Menck et al. (2013) highlighted the FLP process phases, which need VR support and emphasised that VR should be used for collaboration and communication purposes, not just visualisation. Kunz et al. (2016) presented a new VR-based tool for factory planning and evaluation, which allows designers, planning experts and workforces to walk naturally and freely within a virtual factory. Phoon et al. (2017) proposed an interactive solution approach using VR technology for loop layout planning. This reduces the gap between numerical results and the real situation through an enhanced human-machine interface.

Despite all the benefits promised by VR in the above studies, the process of virtualising the manufacturing environment still needs expert knowledge and time to build the virtual model. These factors prevent its wider implementation in industry. The main challenge, identified from previous virtual layout planning approaches, is the time-consuming process of virtual modelling. This is especially true when redesigning existing factories, where the detailed environment is usually too complex to model accurately in CAD software.

2.2 VIRTUAL REALITY TECHNOLOGIES.

Virtual reality (VR) is a popular information technology (IT) area. VR provides an indirect experience by creating a virtual space, which interacts with human sensory systems and overcomes the spatial and physical constraints of the real world (ETRI, 2001). The concept of VR has evolved gradually since the 1960s to its current state, with numerous applications across many business fields, including manufacturing.

Morton Heilig developed a motorcycle ride simulator called Sensorama in 1962 (Heilig 1962). It used light, sound, motion and smell to display stereoscopic 3D images and immerse the participant in a motorcycle ride through Brooklyn and other locations. This simulator system would later evolve into the flight simulators commonly used in US military training. Today, it is often considered the parent of modern-day VR (Lu, Shpitalni, and Gadh 1999). Several significant studies subsequently contributed to the development of current VR technologies.

Ivan Sutherland published “The Ultimate Display”, which described “a system that can display information to all senses of the user with an equal or bigger resolution than the one that can be achieved in a natural way so that the user cannot say that the artificial world is not real.” (Sutherland 1965). Three years later, he successfully implemented the first VR system with an head-mounted display (HMD) which gave the user a stereoscopic 3D view, slaved to a sensing device to track the user’s head movement (Sutherland 1968). Although this early research provided the foundation of current VR technology, it did not result in practical applications at the time. The limited computing power and high cost of hardware prevented any significant further research or real-world utilisation.

Towards the beginning of the 1990s, the ever-advancing computer technologies and lower cost have made VR feasible for practical uses. This attracted widespread attention in research and practice. Figure 1 illustrates the annual number of publications with the keyword “virtual reality” in the Google Scholar database. VR-related research has evidently surged since the 1990s and is still growing. In 1993 alone, there were almost as many publications (2,610) as there were in the entire period prior to 1990 (2,630). With the increasing popularity of VR came the various definitions, characteristics and classifications of it. For the rest of the thesis to proceed on common ground, those terms should be clarified (see following section).

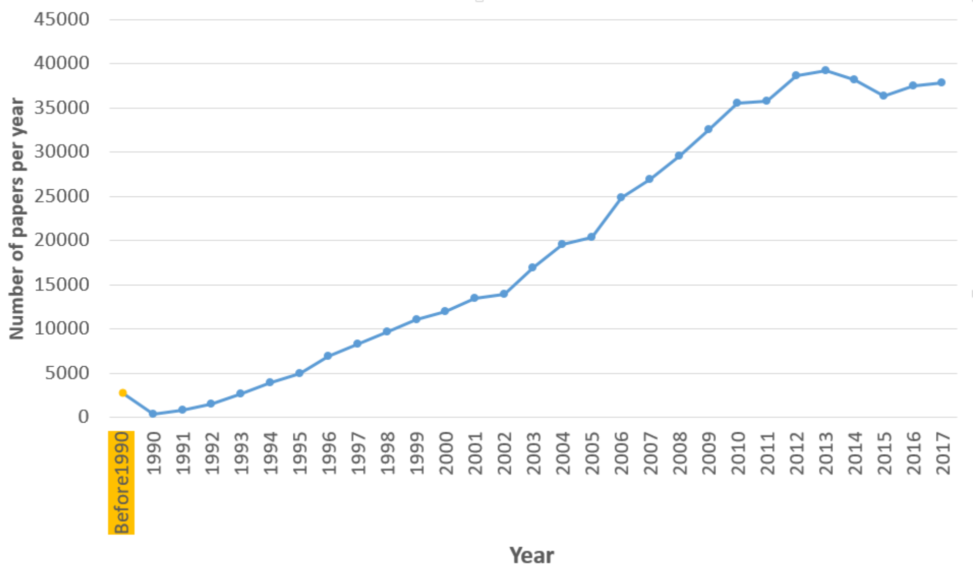

Figure 1. Number of publications with keyword “virtual reality” over the years from Google Scholar[1].

2.2.1 Virtual reality definitions

As defined by the Oxford Dictionary, VR is the computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors (“ Virtual Reality” 2017). Based on previous studies, a selection of definitions is listed below:

“A system which provides real-time viewer-centered head tracking perspective with a large

[1] https://scholar.google.se/

angle of view, interactive control, and binocular display."(Cruz-Neira *et al.* 1993)

"VR is a three-dimensional, computer generated, simulated environment that is rendered in real time according to the behavior of the user."(Loeffler and Anderson 1994)

"The use of real-time digital computers and other special hardware and software to generate a simulation of an alternate world or environment, which is believable as real or true by the users." (Lu et al. 1999)

The above definitions of VR are essentially identical, even though the descriptions vary. However, several key components of VR can be identified: computer-generated 3D environment, multi-sensory, real-time interactive and viewer-centred. It is these features, which ensure the system, can simulate close to real-world experience in the virtual environment. Therefore, in this thesis, VR is defined as a computer-generated 3D environment, which provides real-time visualisation and interaction based on users' movements. In other words, VR is a system that simulates an environment in which the human brain and sensory functions are so tightly linked with the computer-mediated environment that the user can explore it seamlessly, as if she/he were in the real world.

2.2.2 Immersion and presence in virtual reality

Immersion and presence are often recognised as the two key characteristics used to differentiate VR systems. Immersion refers to the VR user's sensation that the virtual environment is real. In other words, if a user cannot tell which reality is "real" and which is "virtual", then the computer generated environment is totally immersive (Thalmann and Thalmann 1999). A higher degree of immersion is considered desirable for VR applications, so that a seamless experience can be created and evaluated. The degree of immersion is mainly affected by feedback lag time and field of view (FOV), but can be enhanced by spatial audio, tactile feedback and force feedback (Lu, Shpitalni, and Gadh 1999). While immersion can be an objective measure, presence is often a subjective sensation of the user being part of the virtual environment (Liebert 2001); a VR user's self-representation and association within the virtual environment. Virtual representation of the user (such as hands or body) and real-time responses to user movements are important factors in creating the degree of presence. Clearly, both immersion and presence are important in VR applications.

2.2.3 Virtual reality classifications

VR can be classified in many different ways. According to the ETRI report, VR technologies are classified into four categories: 1) expression technology, 2) interaction technology, 3) authoring technology and 4) collaboration technology (ETRI, 2001).

- Expression technology. This category of VR technology includes technology related to human sensory systems, including visual, auditory, haptic, olfactory, and taste.
- Interaction technology. This refers to technology used to interface humans and computers by using motion, symbols and bio-signals.
- Authoring technology. This refers to technology, which generates VR content and its supporting database.
- Collaboration technology. This refers to networking of multiple participants (in the form of avatars) in a VR environment.

Ong and Nee categorised VR systems as hardware-based or computer-based. A hardware-based VR system depends on special VR hardware such as a head-mounted display (HMD), VR glove, etc. A PC-based VR system uses software on personal computers (PCs) and uses standard PC peripherals as input and output tools (Ong and Nee 2004).

The preferred classification of this thesis is based on the levels of immersion, while the levels of presence can vary within each category depending on individual implementations. Thus, VR systems can be classified as:

- Non-immersive (Desktop system).
- Semi-immersive (Wide-screen projection system).
- Immersive:
    - Cave automatic virtual environment (CAVE) system.
    - Immersive VR system using HMDs.

Desktop VR most closely resembles the typical human–computer interaction (HCI). It uses the monitor as its viewing device and a mouse, keyboard or haptic devices such as data gloves for interaction. With a suitable VR software package and a computer capable of displaying the virtual model in real time, this arrangement provides the lowest sense of immersion and often serves as an entry-level VR system.

Widescreen projection (also known as a semi-immersive VR system) is used to increase the FOV (of 20–30° with a monitor) to over 100° or indeed the entire viewing area, if multiple projection screens are used. The increased FOV provides users with a higher degree of immersion.

A setup with multiple projections (usually three walls and a floor) is called a CAVE and is by far the most expensive VR platform. Shutter glasses, which provide stereo vision, complete this very effective, immersive VR system. A 3D mouse or trackable input devices are usually also used to enhance the sense of immersion and presence.

VR using an HMD offers a much more affordable immersive system. Two displays are mounted in a helmet, providing the user with a stereoscopic image of the model. The HMD is position-tracked in real time and the images updated according to the user’s position and orientation. A keyboard and mouse cannot be used because they are invisible to the user. A 6 degrees of freedom (6DoF) interactive device is used instead. Immersive VR with a position-tracked HMD and input devices has the following advantages:

1. Using motion parallax and a stereo view, it provides a sense of scale capable of fully immersing users in the virtual environment.
2. Ease of interaction with complex components, using three-dimensional input devices.
3. Improved understanding is gained through direct interaction, potentially heightening the sense of presence.

2.3 POINT CLOUD REPRESENTATION OF ENVIRONMENT

3D laser scanning, often also termed Light Detection and Ranging (LIDAR), is an active, non-contact, range measuring technology (Beraldin et al. 2007). The media is a laser beam, which is either overlaid with a modulated wave pattern for phase based distance measurements or pulsed intermittingly for time of flight based distance measurement. To capture spatial information the 3D laser scanner is positioned inside the area of interest and will emit the laser while capturing the returned reflection to measure the distance to the reflecting surface. The device articulates the laser beam 360 degrees around the area using a rotating mirror which is spun methodically to face all directions around the device with a given increment, as illustrated in Figure 2. Each measurement taken, typically tens of millions per scanner position, is stored as a coordinate in space referenced to the center of the LIDAR. Many modern LIDAR devices also incorporate an RGB sensor to enable capture of the color of the measured coordinates.

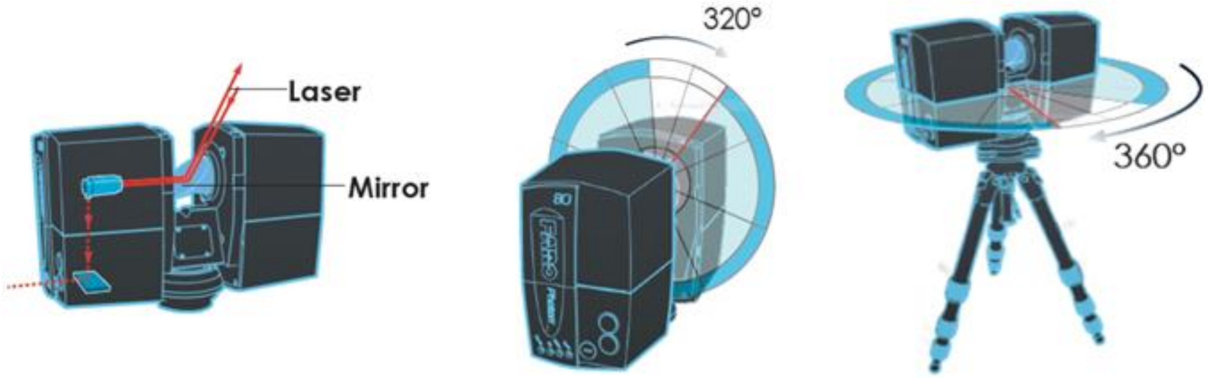

Figure 2. The mechanism of a 3D laser scanner.

In areas that are densely populated with machines and equipment, such as a production system, the line of sight of the LIDAR will be limited and the data capture needs to be repeated on several positions throughout the area in order to capture all the objects and surfaces. This results in multiple data sets, which needs to be registered together into a common and coherent coordinate system. The resulting combined data set is popularly called a point cloud, owning to the nature of the data; millions of measurements organised in space. When rendered on a computer screen the point cloud represents a photorealistic 3D environment in scale 1:1 with the captured area (Lindskog 2014).

This technology has many applications now, but the earliest to break through were construction surveying and archaeology. The main benefits are the ability to rapidly digitalize spatial data, a) for documentation or b) for sharing remotely with others. Documentation can be used to verify adherence to building plans or to track changes over time due to load application or changes in external conditions. A good example of an archaeology application is the Smithsonian X 3D, a web platform which anyone can visit and interactively explore artefacts from the Smithsonian Institution collection in 3D (Metallo and Rossi 2011).

There are currently more and more application examples in the industrial production area. Some applications are machine vision, virtual commissioning, visualisation, validation/verification of installation, or use in production flow simulation (Bi and Wang 2010; Berglund et al. 2014; Lindskog 2014; Shellshear et al. 2015).

3

RESEARCH APPROACH

This chapter describes how the research is structured by explaining the philosophical assumptions, giving the rationale behind mixed methods research and summarising the research design and methods used.

A research approach is a plan or proposal to conduct research and is based on three interconnected components: philosophy, research design and research methods. This is shown in Figure 3 (Creswell, 2013). When planning research, it is important to think through the philosophical worldview behind the study, the research design relevant to this worldview, and the specific methods, which translate the approach into practice. The following sections of this chapter will therefore explain these three components, as used in this thesis.

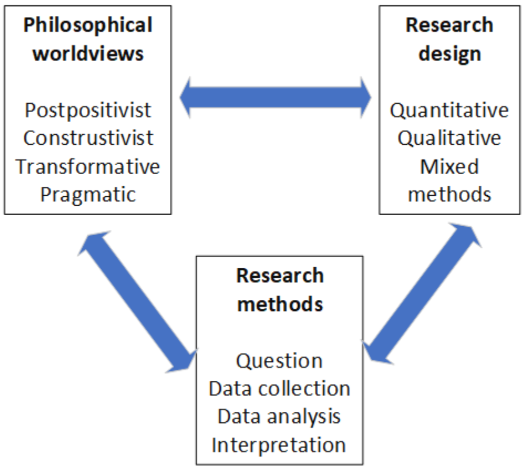

Figure 3. The interconnection of worldview, design and research methods (Creswell, 2013).

3.1 PHILOSOPHICAL WORLDVIEW

The philosophical element embodies the researcher's worldview, understood as "a basic set of beliefs that guide action" (Guba, 1990). It provides a general philosophical orientation for research work. According to Creswell and Clark (2011), there are essentially four possible worldviews which can inform research: postpositivist, constructivist, participatory and pragmatist. They differ as to the nature of reality (ontology), how we gain knowledge of what we know (epistemology), the role values play in research (axiology), the process of research (methodology) and the language of research (rhetoric) (Creswell, 2009c; Lincoln & Guba, 2000). Different research problems call for different worldviews.

This research deals with problems in production systems. Production systems are known for their complex environments, in which various entities (such as humans, machines, materials and systems) are interconnected and interact with each other. The main focus of this research is also on using VR technology in production systems; an exploratory process. Considering the nature of the research problem and the different characteristics of worldviews, pragmatism has therefore been chosen.

Pragmatism is a set of ideas articulated by many scholars, including Cherryholmes (1992) and Murphy (1990). It draws on many ideas, including using “what works”, using diverse approaches and valuing both objective and subjective knowledge. A pragmatic approach may combine deductive and inductive thinking, as the researcher may mix qualitative and quantitative data. Pragmatism focuses on the consequences of research, on the primary importance of the question asked rather than the methods and on the use of multiple methods of data collection to inform the problems being examined in the study. Thus, pragmatism is pluralistic and oriented towards practice and “what works” (Creswell and Clark 2011). On the broadest level, it was this worldview, which informed the author’s choice of research design and methods.

3.2 A MULTIPHASE MIXED METHODS RESEARCH DESIGN

A research design “represents the structure that guides the execution of a research method and the analysis of subsequent data” (Bryman and Bell, 2011). In general, quantitative research design involves the collection and analysis of numbers and broadly aims to achieve breadth, whilst qualitative research design emphasises the collection and analysis of words and broadly aims to achieve depth (Johnson et al., 2017). These represent different ends on a continuum (Newman & Benz, 1998). In the middle of this continuum lies the mixed methods design. This uses a combination of quantitative and qualitative methods to gain a deeper understanding of a phenomenon (Östlund et al., 2011; Zohrabi, 2013).

The main research problem in this thesis is to explore whether VR technology can benefit the FLP process and, if so, how to use VR technology effectively and systematically for FLP. This line of enquiry requires an iterative process of theory building and testing, with incremental research questions addressed by connecting quantitative and qualitative methods. The multiphase mixed methods design has therefore been chosen for this thesis. Accordingly, Figure 4 illustrates the mixed methods research design in relation to the appended papers and the contribution to RQs.

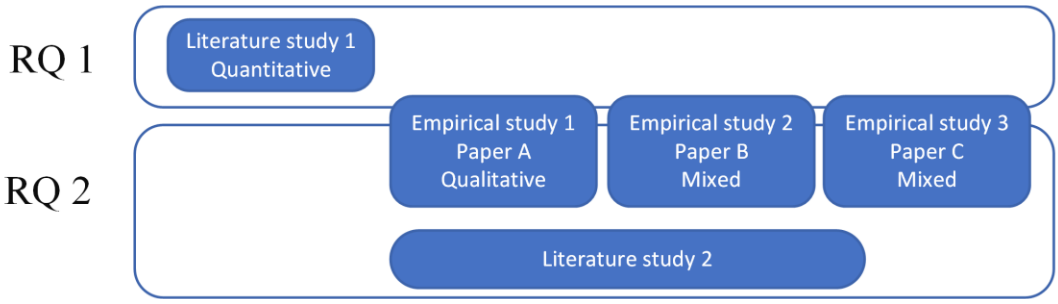

Figure 4. The multiphase mixed methods research design.

The work started with a literature study of peer-reviewed journal articles, which have implemented VR technology in production systems between 1993 and 2017. A quantitative analysis of the literature was used to answer RQ 1. Based on the results of RQ 1, FLP is identified as one of the promising application areas, which may benefit more from adopting VR technology. This led to the investigations relating to RQ 2.

Thereafter, three empirical studies were carried out in sequence, each contributing to the answer to RQ 2. Each empirical study is one execution of the systematic empirical research approach inspired by Flynn et al. (1990), as shown in Figure 5. The incremental results were used to refine the next iteration and ultimately provide the guidelines to answer RQ 2.

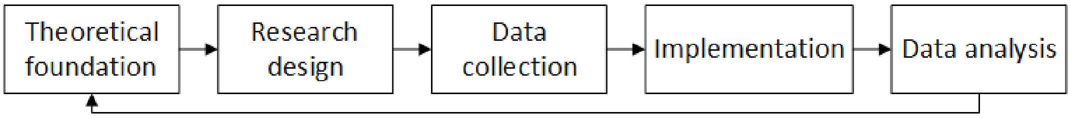

Figure 5. Iterations of systematic approach of empirical research, inspired by Flynn et al. (1990).

In Study 1 (based on the knowledge and theory obtained from the literature study), the idea of incorporating point cloud data into modelling a desktop VR environment for FLP was implemented using a demo application. Thereafter the stakeholders tested the demo application. Qualitative feedback was then collected using semi-structured interviews. The results were analysed and published in appended Paper A; they also support the iteration of the second empirical study.

In study 2, the knowledge and theory are refined and further developed based on the results of Study 1. A second demo application was developed and evaluated. Quantitative and qualitative measures were taken into account, using a scale rating and open-ended questionnaires. This study is reported in the appended Paper B.

Supplemented by Study 3 (which further explored immersive VR for FLP using mixed methods), general guidelines for the effective and systematic use of VR technology in FLP were extracted and evaluated. Appended Paper C gives full details of this work.

3.3 RESEARCH METHODS

Research methods are all those methods or techniques that are used for conduction of research (Kothari 2004). The mixed methods research approach chosen in this thesis, consists of combining data collection methods and selecting the most appropriate in each case. The pragmatic worldview enables the combining and converging data from the different data collection methods to strength the results. A variety of data collection and data analysis methods are presented in the following sections with description of how these methods were applied in this research.

3.3.1 Data collection methods

Literature review:

There have been two literature studies conducted in this research process, which focused on VR applications in production systems and different FLP approaches respectively. Initially, a five-stage systematic literature review (Rutter and Francis, 2010) which includes define, search, select, analyze and present was conducted for VR technology usage in production. There are in total 269 peer-reviewed journal articles from the year 1993 to 2017 have been identified and included. The articles were analyzed and categorized in terms of the types of VR technologies and the types of applications area in production, as well as the year of publication. The second literature study has identified major approaches of planning factory layout change and their advantages and limitations. As Creswell and Clark (2011) pointed out that literature review can accomplish several purposes. The results have allowed the author to identify initial research gaps and barriers, which narrowed down the research scope to the two feasible research questions. In addition, the literature reviews have been used as benchmarks for comparing the results with the findings of other researchers.

Interviews and questionnaire:

Interviews can be designed in various forms, depending on the purpose. It can be divided into three distinct types: structured, semi-structured and unstructured (Bryman and Bell, 2015). Structured interviews follow a fixed sequence and use the same questions in each interview session (Williamson, 2002b). Semi-structured interviews have a predefined list of questions, but allow for the interviewer to ask follow-up questions (Dicicco-Bloom and Crabtree, 2006; Williamson, 2002b). Unstructured interviews do not follow any predefined structure or questions (Dicicco-Bloom and Crabtree, 2006; Williamson, 2002b). The questions are generated from the previous answer. Questionnaires are good for collecting information from multiple respondents without the researcher being present, but there is a risk of low response rates (Kothari, 2004). Questionnaires often use close-ended questions to allow quantification and ensure questions are intelligible (Bryman & Bell, 2011).

In this thesis, semi-structured interviews and close-ended scale rating questionnaires have been used in each empirical study iteration. After the participant have been tested the demo applications, a semi-structured interview and scale rating were followed to get feedback and triangulate the results. The demo application worked as a stimulus which helped focus on the specific product or idea of interests for the research (Dagman et al., 2010). This approach made the respondent feel more comfortable due to its conversational nature. The research proved to obtain richer information because of this format.

Observations:

Participant observation is a data collection method for qualitative research. It is used when the researcher is aiming to collect objective data on events or situations (Kawulich, 2005; Mack et al., 2005). This method allows the researcher to gain insight into context, relationships and behaviors (Mack et al., 2005). It allows a researcher to add dimensions to, and increase understanding of, the context or phenomenon being studied. More specifically, observations can be invaluable aids in understanding the actual use of technology (Yin, 2014).

The studies in this thesis involved observations of how the participants have engaged with the demo applications while testing. This method was chosen to compliment the understanding gained during interviews. It also allowed the researcher to compare with participants' feedback and validate the results.

3.3.2 Data analysis methods.

Statistical analysis:

There exist many statistical analysis methods which can be carried out for quantitative studies, such as statistical significance testing or inferential statistical tests and such things as the confidence interval and effect size can be reported (Creswell, 2013). There are also less advanced statistics such as descriptive statistics; means and ranges (Creswell, 2013).

In this thesis, descriptive statistical methods were selected to gain insight into the VR technology used in production. At the same time, the statistical significance testing and inferential tests were also conducted for the collected scale rating results to compare with qualitative data and further enhance the validity of this research.

Content analysis:

It concerns analyzing the content of written or oral material, often transcribed from interview and it is considered as the major qualitative method of studying the general message (Kothari, 2004). The methods used for collecting qualitative data usually result in extensive amounts of raw data to analyze (Bryman and Bell, 2011; Pope et al., 2000). Qualitative data analysis is about making sense of the raw data. This means taking it apart as well as putting it together again (Creswell, 2014). The collected data should be analyzed to draw valid inferences that can be used in further research (Blessing and Chakrabarti, 2009).

To analyze the qualitative data collected in this research, semi-structured interview was transcribed together with notes from observations. The data was analyzed to generate re-occurring themes and categories. The converging of the qualitative and the quantitative results contribute to the validity and the conclusion of this thesis.

3.3.3 Summary of research methods

The summary of all the studies conducted in this thesis and research methods used as well as the contribution to the RQs are presented in Table 3 below.

Table 3. Summary of research methods used within each study and the desired knowledge.

Study	RQ1	RQ2	Desired knowledge	Data collection methods
Literature study 1	X	x	VR technology used in production system.	Literature review
Literature study 2		X	Different approaches of planning factory layout change.	Literature review
Empirical study 1	x	X	How to speed up virtual factory modelling process while keep virtual model realistic.	Semi-structured interview
Empirical study 2	x	X	How to better present virtual model to engage more stakeholders contribute in the layout design process.	Questionnaire Semi-structured interview Direct observation
Empirical study 3	x	X	Development of the systematic process to guide future practice.	Questionnaire Semi-structured interview Direct observation

X strong contribution; x low contribution

3.4 RESEARCH QUALITY

Validity and reliability are the two key criteria, which ensure the quality of scientific research (Yin, 1994; Bryman and Bell, 2011).

Validity is the concept of result validation and it is the quality of the relationship between the reality and the research outcome (Maxwell, 2012). It answers the question “Did the research do the right things?” It is commonly categorized as the construct, internal, external and contextual validity (Yin, 1994; Ihantola and Kihn, 2010). To ensure validity in this research, multiple cases of different companies were used in the empirical studies, which increased the external validity. At the same time, both qualitative and quantitative data were collected to validate the result, so the internal validity is ensured.

Reliability is the concept of research verification and is often measured as the capability to repeat the methods used and achieve the same result in a repeat study (Flynn et al., 1900). It answers the question “Did the research do things right?” Qualitative studies have practical issues when it concerns the repeatability. There is debate on whether reliability is a suitable quality assessment criterion for qualitative data collection methods (Bryman and Bell, 2011). The importance of documenting the detailed procedures of the studies to ensure reliability is highlighted by Yin (1994). Creswell (2013) proposes strategies such as checking transcripts, crosschecking the codes, to ensure reliability within mixed method research. The detailed and structured documentation of the procedures of each study and the collected data in this research ensure the reliability (Williamson, 2002, Yin, 2009).

4

SUMMARY of APPENDED PAPERS

This chapter summarize the three appended papers with brief background and implementation along with orientations on how these papers contribute to the research questions.

4.1 PAPER A

Title: Improving manufacturing process change by 3D visualization support: A pilot study on truck production

This paper aims at exploring the potential of a desktop VR tool in supporting the FLP decision-making process. The VR tool is developed with point cloud data of the existing factory environment and CAD models of the equipment that are planning to be installed. Alternative layout solutions were presented through the desktop VR tool to and analyzed by stakeholders from different function groups.

4.1.1 Results of the paper

3D laser scanning was used to capture spatial data of the factory environment. The captured point cloud data was processed and formatted for later integration in creating the desktop VR tool. 3D CAD models were gathered and imported to the VR tool. A graphic interface is developed to create alternative layouts for further evaluation, as shown in Figure 6.

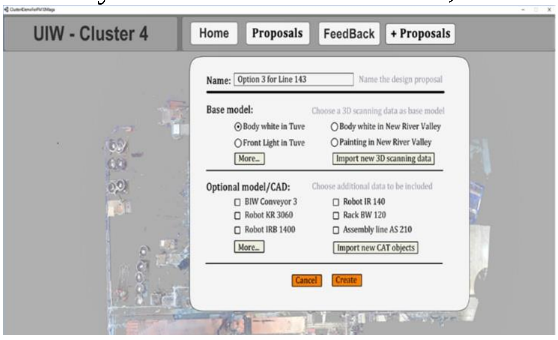

Figure 6. The graphic interface to create alternative layouts.

Semi-structured one-to-one interviews were conducted with five stakeholders from different functional groups in the company. Each interview was carried out at the stakeholder's office and lasted around 45 minutes. The interview consists of three parts. It begins with questions regarding the interviewee's role and responsibilities in the current manufacturing process change as well as their comments and reflections about the current practice. A demonstration of the collaborative tool and work process is followed, which presents the 3D visualization of the three layout designs for assessment, shown in Figure 7. At last, it is the discussion concerning how the desktop VR tool and work process could help improve the current work practice and what are the limitations.

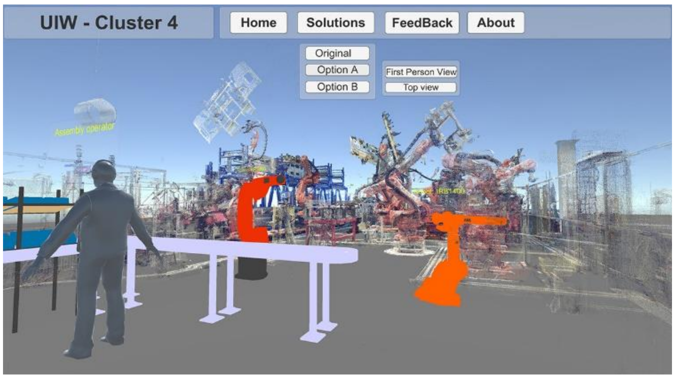

Figure 7. First person view of alternative layout A.

4.1.2 Contribution to research questions

Paper A contributes to both RQs raised in Chapter 1.4. The desktop VR approach to support FLP decision-making is one addition to the state-of-the-art VR applications in production area as to RQ1. The idea of incorporating point cloud data of existing environment into the modelling of virtual factory and presenting the virtual factory through desktop VR systems to evaluate alternative layout options, is the first step towards answering RQ2 on how VR can support FLP tasks. Paper A demonstrated the need and benefits of having realistic 3D contextual data in the process of decision-making on alternative layouts, it also pointed out direction for later studies to answer RQ2.

4.2 PAPER B

Title: A novel VR tool for collaborative planning of manufacturing process change using point cloud data

This paper is one step further from desktop VR to immersive VR support in the FLP decision-making process. It proposed a working procedure for the development of virtual factory consisted with point cloud data and 3D CAD models. The virtual factory then can be used to test out alternative layouts by all the stakeholders. The immersive HMD and trackable controllers are used to provide near-to-life visualization and interaction. The proposed approach was implemented and tested by the stakeholders. Feedback were gathered through questionnaire and interview and later analyzed.

4.2.1 Results of the paper

A truck manufacturing plant in United States was selected to demonstrate the immersive VR for the planning of manufacturing process change. The proposed working procedure (shown in Figure 8.) starts with the data preparation for the virtual factory. 3D laser scanner captures the point cloud data set of the real factory, which provide the most important 3D contextual data of the virtual model. Another data source is the CAD models of any machines that are intended to be implemented during the layout change. The data can be further enhanced with the connection to the existing ICT systems, so that the virtual model not only shows the realistic factory environment, but also has the possibility to augment additional machine specific information in the virtual model for the better support of the decision-making in new layout design.

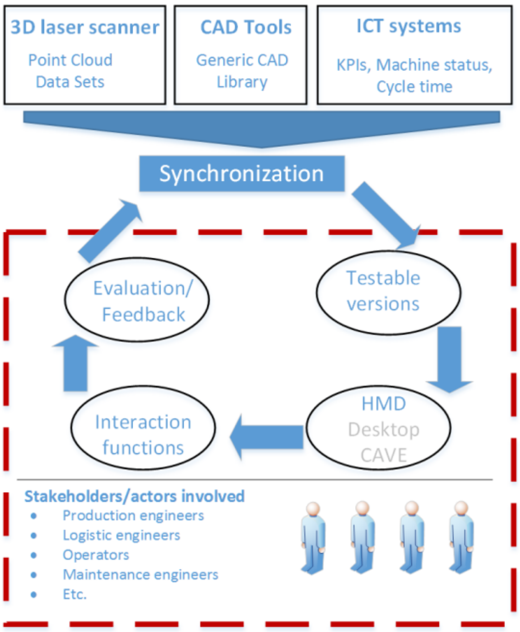

Figure 8. Conceptual model of the collaborative VR tool

Depending on the specific requirement of each layout planning scenario, the above data can be prepared and feed into the Unity development tool for synchronization, so that the virtual tool is ready for later layout creation and evaluation. After the virtual factory is prepared and deployed to the server, all the stakeholders can access the virtual factory anywhere in the world provided that an immersive VR HMD is available. In the virtual factory, each stakeholder is provided with the information they need to create new layouts or assess and leave comment to existing layouts based on their own expertise, as shown in Figure 9. Thus, different layout proposals and feedback are gathered in the system for the synchronization which will either reach the idea solution for implementation or repeat the same process until the idea solution is reached.

Figure 9. One stakeholder evaluating layout via immersive VR.

4.2.2 Contribution to research questions

Paper B adds one more exploratory study to the applications of VR in production systems as for RQ1. It contributes to RQ2 in two parts: a second type of VR system is tested and a working procedure is proposed for employing VR in FLP. This paper is a continuation of point cloud based VR approach for FLP decision-support. It moved one step further from desktop VR to immersive VR in visualizing and interacting with the virtual factory. The immersive VR which brings near-life experience to the stakeholders, has demonstrated its advantages of facilitating better contextual awareness when evaluating different layout options. An iterative working procedure was proposed, which is the first step towards the systematic employment of VR to support FLP decision-making.

4.3 PAPER C

Title: Development of virtual reality support to factory layout planning

This paper aims at developing a general guidance for employing point cloud based VR to support FLP decision-making. Through three industrial cases which incorporated point cloud data into modelling virtual factory for FLP, the general guidance is extracted and refined.

4.3.1 Results of the paper

Three case studies that adopted the point cloud based virtual factory modelling approach were conducted. They are all industrial cases where layout changes were needed in existing production sites either for improving productivity or adaption of new products. The cases vary in the areas of manufacturing and the scale of the layout change. Desktop VR was implemented in the first case and immersive VR system was chosen for the latter two cases as the technology has becoming ever mature with much lower price and improved performance. With the 110-degree FOV and 90 frame per seconds (FPS) image rendering, it enables nature visualization that users feel as if they were present in the real environment and intuitive interactions within the virtual model. The cases and implemented functions are summarized in the Table 4 and Table 5 respectively.

Table 4. Summary of three industrial cases.

	Industry	Scale of change	VR types	Features
Case I	Aerospace	Workstation	Desktop VR	Visualization
Case II	Trucks	Production cell	Immersive VR	Visualization, interaction
Case III	Snus, tobacco	Packing line	Immersive VR	Visualization, Interaction

Table 5. Implemented functions of each case.

Functions	Descriptions	Case I	Case II	Case III
Visualization	Desktop screen/projector or HMD	x	x	x
Navigation	Mouse & keyboard or trackable controllers	x	x	x
Pick & place	Collision detection, Controller button		x	
Save & Load layout	Serialization of object position and rotation		x	
Feedback	Collision detection and UI		x	
Accessibility	Collision detection, Controller button, Hands			x

4.3.2 Contribution to research questions

This paper contributes mostly to RQ2 on how VR can support FLP task. The working procedure for point cloud based VR approach proposed in Paper B was exemplified and refined with three industrial cases. It categorized different forms of data that can be used in the virtual factory modelling process as well as their characteristics and requirements. The merits and limitations of desktop and immersive VR systems are discussed in relation to how well they can support FLP. As the final step in answering RQ2, the extracted guidance provided a systematic methodology to employing the state-of-the-art VR technology in supporting FLP.

5

RESULTS

This chapter presents the answers to the two RQs of this thesis, two sub sections illustrate the answer to RQ1 and RQ2 respectively.

5.1 ANALYSIS OF LITERATURE REVIEW

How has virtual reality (VR) technology been used in production system development?

Prior to answer this question, Chapter 2 discussed the working definition of VR and classified the different types of VR technologies. The related literature review about VR applications in production systems was conducted and it contributes to the answer of RQ1.

The following section will summarize and analysis the reviewed articles to answer RQ1. Keyword combinations of VR and production systems were used to filter in the database of Scopus. At the end, 269 peer-reviewed journal articles from 1993 to 2017 were identified and included for the following analysis. The brief contents of the reviewed articles are listed in Appendix A. Figure 10 shows that research on VR applications in production systems is growing steadily.

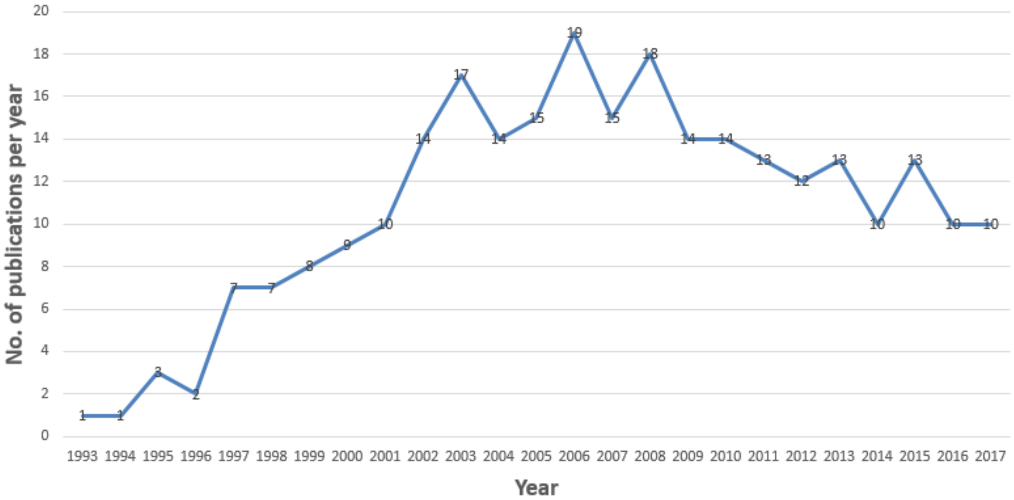

Figure 10. Overview of number of publications of VR in production system from 1993 to 2017.

Based on the classification of VR technologies, desktop VR which has the lowest requirements, accounts the most with 72% of the total reviewed articles as shown in Figure 11. The immersive VR technology is becoming ever mature over the years with lower cost and better performance, it is found in 15% of the selected articles which makes it the second largest VR system implemented. Semi-immersive and CAVE systems only accounts 3% and 10% respectively.

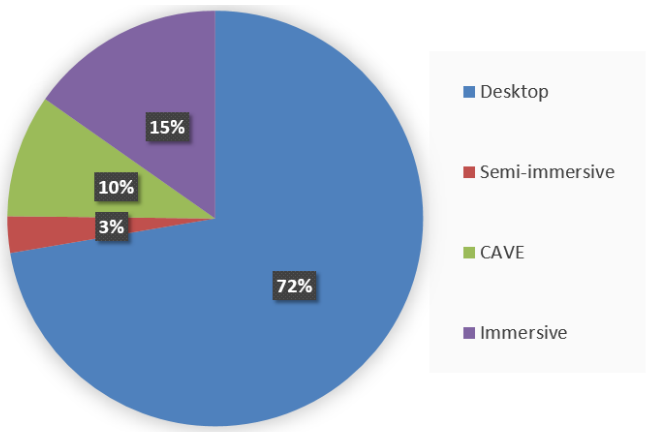

Figure 11. Publications categorized with different types of VR technologies

In terms of the different application areas in production systems, 11 areas were identified from the 269 articles and result is illustrated in Table 6. Among the 11 areas, VR technology has been adopted mostly in product development (29.01%), (dis)assembly (16.38%) and manufacturing process (10.58%). FLP is found only in 18 articles (6.14%). Those less represented areas likely hint that there is relatively little benefit given the available VR technologies at the time. It can also be interpreted as areas with more potentials for future research, especially, when the VR technologies is advancing rapidly in recent years.

Table 6. Publications categorized with different application areas in production systems.

Application Areas	**Numbers**	**Percentage**
Product Development	85	29.01%
Maintenance	9	3.07%
Robotics	24	8.19%
(Dis)Assembly	48	16.38%
Digital human	14	4.78%
Manufacturing Process	31	10.58%
FLP	18	6.14%
Virtual factory modelling	13	4.44%
Training	18	6.14%
Machining	22	7.51%
Simulation	11	3.75%

A correlation analysis between different VR systems and application areas is made to further understand previous research on VR applications in production systems as shown in Figure 12. It is obvious that most research effort has been dedicated to desktop VR for product development with 58 articles. Desktop VR for (dis)assembly comes as second with 31 articles.

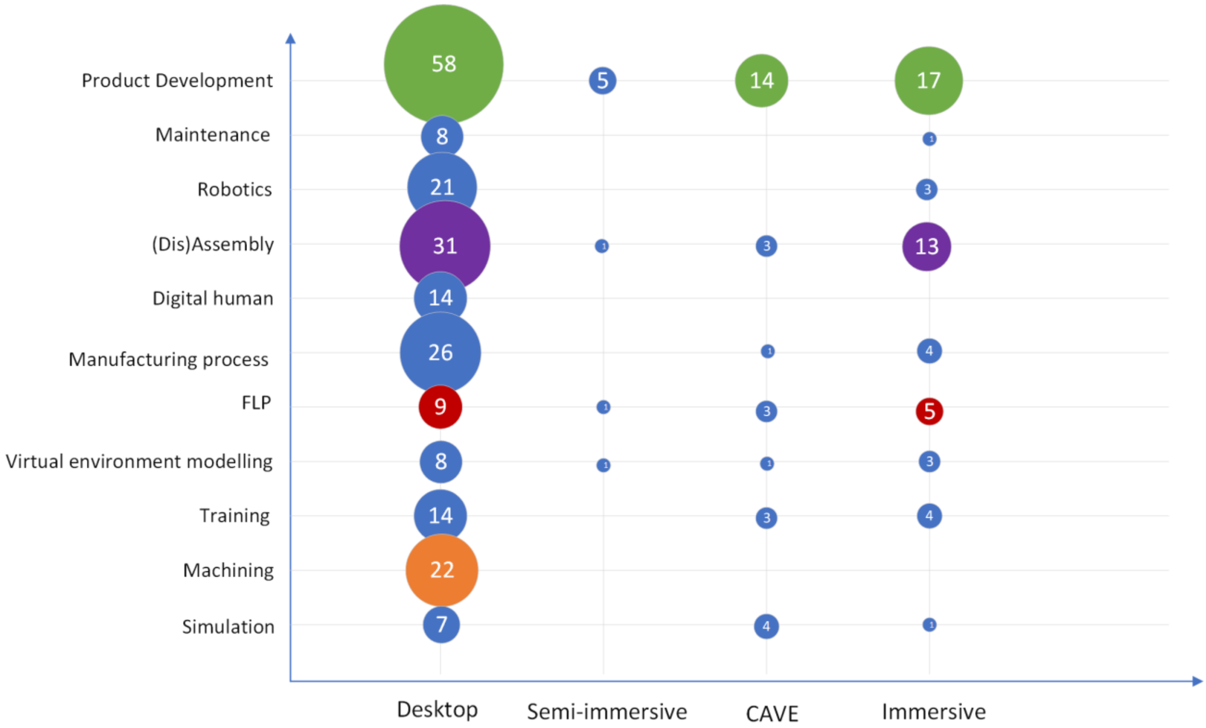

Figure 12. Correlation between application areas and VR types.

In Table 7, it shows the percentage of each VR system within a specific area. It is worth noting that all the articles concerning machining and digital human have adopted only desktop VR. Similarly, over 80% of VR systems for maintenance, robotics and manufacturing process are desktop VR. It is likely that the non-immersive VR system is sufficient enough in these areas. On the other hand, in the areas of FLP, (dis)assembly and virtual factory modelling there are the highest rate of employing immersive VR. It can be that the feeling of higher level of presence and immersion in the virtual environment provided in the immersive VR systems are more important to meet certain requirements that are unique in these areas. Nonetheless, even in the area of FLP, which has the highest rate (27.78%) of employing immersive VR systems, there are still great potentials to explore further to improve the existing practice through integration with the latest advancement of immersive VR systems.

Table 7. Percentage of each VR system within an application area.

Application areas	**Desktop**	**Semi-immersive**	**CAVE**	**Immersive**
Product Development	61,70%	5,32%	14,89%	18,09%
Maintenance	88,89%	0,00%	0,00%	11,11%
Robotics	87,50%	0,00%	0,00%	12,50%
(Dis)Assembly	64,58%	2,08%	6,25%	27,08%
Digital human	100,00%	0,00%	0,00%	0,00%
Manufacturing Process	83,87%	0,00%	3,23%	12,90%
FLP	50,00%	5,56%	16,67%	27,78%
Virtual factory modelling	61,54%	7,69%	7,69%	23,08%
Training	66,67%	0,00%	14,29%	19,05%
Machining	100,00%	0,00%	0,00%	0,00%
Simulation	58,33%	0,00%	33,33%	8,33%

5.2 ANALYSIS OF RESULTS IN APPENDED PAPERS

How virtual reality technology can be used to support factory layout planning (FLP)?

5.2.1 Paper A

A desktop VR system was developed to support the layout change in a truck plant. The system is made of point cloud data of the real factory environment and CAD models of planned new equipment. Stakeholders from industrial partner used mouse and keyboard to interact and assess different layout options. Follow-up interview was conducted to get feedback about the desktop VR support tool.

Based on the analysis of the interview transcriptions, all stakeholders agreed that it would be helpful to their work when the point cloud based 3D visualization of the production site is accessible from their desktop computers. They also believe that it would help prevent potential errors or conflicts early in the design phase if all the stakeholders could have evaluated the plan through the desktop VR system before actual implementation. Compared to text description or two dimension data that are widely accepted in current work practice, the desktop VR system gives much more context to stakeholders to understand the situation and make the right decisions. The realistic virtual factory which is accessible from any connected desktop computers, for companies with globally distributed office or factories, it would improve the work efficiency and contribute towards the sustainable manufacturing goal.

Nevertheless, each stakeholder also expressed their doubts and concerns: The layout and logistic engineers questioned how to keep the virtual factory model up to date. It is not uncommon that minor changes and movements would be made continuously in the factory and in the presented work process, it is difficult to reflect the latest changes of the plant. The lean production specialist pointed out the accuracy of the 3D visualization might be the problem and higher quality of 3D data is needed. This leads to further studies about finding better ways to present the virtual model, such as immersive VR. The virtual tool specialist would like the collaborative tool to include features, such as evaluation task allocation and even augment reality for operator task design and balance. In short, all the stakeholders think it is promising to have a 3D collaborative tool as an aid to current FLP practice.

The following challenges were identified and need to be met before it could be used as a day to day basis tool in the actual work. First, how to better present the virtual factory to the users, so that user can have the seamless experience of performing the same assessment virtually. Another challenge is the post-processing of point cloud data in terms of keeping virtual factory up-to-date and streamline the data integration process.

5.2.2 Paper B

An immersive VR system was implemented on a selected industrial case from an automotive partner, which was going through a major change in one of its plants. The system consists of point cloud data of the real factory environment and CAD models of planned new equipment. It supports immersive visualization rendered in HMD and interactions through trackable controllers. Stakeholders are free to navigate around and perform layout assessment tasks in the immersive virtual factory. Questionnaire with scale ratings and open-ended questions was conducted to gather feedback for later analysis.

The questionnaire asked the respondents to rate different aspects of the immersive VR system and the value of the proposed system to different stakeholders across the organization. Figure 13 illustrates the rating scores from the respondents. It is clear that the majority of the stakeholders were positive with the potential benefits of this VR approach and would like to share or recommend the system for a wide usage. Due to the fact that the tool is in prototype phase of the concept, so that the user experience related ratings were not as good as the potential benefits.

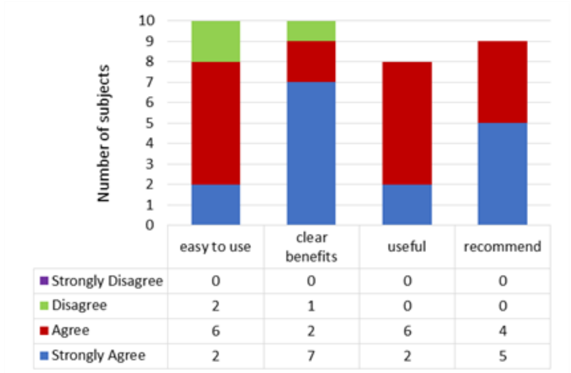

Figure 13. Test subjects' rating feedback on the VR tool.

When asked about in what areas within the manufacturing system that they saw uses for the collaborative VR tool. "In which areas of manufacturing do you think this system can be beneficial for the improvement of current work practice?" The listed categories are based on the work of Nee et al. [26]. The most promising application areas were chosen as layout planning, training and education, and simulation. Figure 14 lists the results from the questionnaire. The result also provides certain hints are the future research focus.

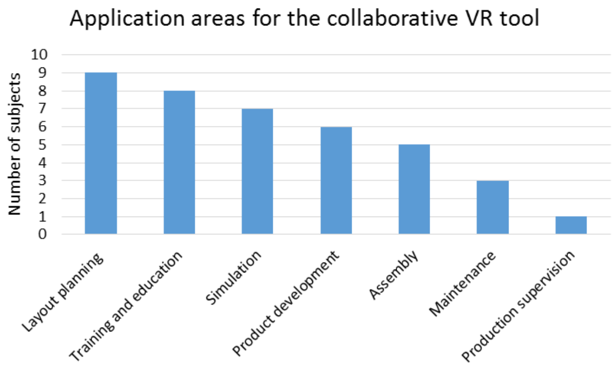

Figure 14. Result of promising application areas.

Open-ended questions were analyzed and some reoccurring themes were identified. With the positive benefits such as easy to use, visually representative of the real factory, accurate and near-life like experience. At the same time, some obstacles were detected as one test subject experienced dizziness while using the HMD, another one had problem of disorientation in the virtual environment. Additionally, two test subjects believed that the tool as such is different from what they used to, thus it takes time to learn and get familiar with.

Towards the end of the open-ended questions, the stakeholders were asked: "What challenges do you anticipate if your company is going to implement this VR systems?" The answers given can be categorized into three different challenges: data compatibility, organizational attitudes, and cost. Data of the various aspects of the production system resides in many internal systems and in different formats. Accessing all of them seamlessly is not an easy task.

5.2.3 Paper C

Statistical analysis

As part of the evaluation in case 2 and case 3, four statements were ranked using scale analysis, using a four-level Likert scale (strongly disagree, disagree, agree, and strongly agree), illustrated in table xx. A total of 49 persons were participating in the workshops. It is worth noting that there are 9 participants who did not fill in the questionnaire due to their time limit or other reasons. As a result, some critiques might be hidden behind the scene. For the correlation statistics 32 answers were valid. The reliability statistics (Cronbach alpha) was 0,875 (N=4) for this study.

The mean value was high for all statements, illustrated in Table 8, which indicates that this technology is seen as a mature technology that is easy to use. Hence, the attendees had hard time to see where it could be useful in their daily work. The majority of the test subjects in case I were positive with the potential benefits of this VR approach and would like to share or recommend the system for a wide usage. Due to the fact that the tool is in prototype phase of the concept, user experience related ratings were not as good as the potential benefits.

Table 8. Descriptive statistics of the survey results

Statements	Mean	Std. Deviation	N
Easy to use	3,45	,597	40
Clear benefit	3,55	,552	40
Useful to my job	3,16	,628	32
Recommend to others	3,58	,502	33

The correlation between the statements shows the same pattern as the mean value, illustrated in Table 9. The strongest and significant correlation is between easy to use and recommend (0,939), which means that the attendees thought that is was easy to use and understand the tools, but also that they would recommend the tools to others. Positive benefits was also the visually representative of the real factory, accurate and “near” life like experience. They could also see a clear benefit with the tools and the easiness of using the tool (0,863). There were moderate or weak correlation between ‘useful to my job’ and the other statements. This could depend on lack of business models, and maturity within the organizations on using these tools in the daily job. We believe that this will increase over the next few years due to the fast development and improvement of technology, but also increase of use within companies.

Table 9. Correlations between the different statements.

		easy to use	clear benefit	useful to my job	recommend
easy to use	Pearson Correlation	1	,863**	,509**	,939**
	Sig. (2-tailed)		,000	,003	,000
clear benefit	Pearson Correlation	,863**	1	,496**	,768**
	Sig. (2-tailed)	,000		,004	,000
	Pearson Correlation	,509**	,496**	1	,518**

useful to my job	Sig. (2-tailed)	,003	,004		,002
recommend	Pearson Correlation	,939**	,768**	,518**	1
	Sig. (2-tailed)	,000	,000	,002	

** Correlation is significant at the 0.01 level (2-tailed).

Guidelines for employing VR to support FLP

With the three cases described above, the hybrid approach that combines point cloud data with 3D CAD models to build virtual factory for layout planning were demonstrated and tested. The results showed that it is a promising path towards efficient and effective decision-support in (re)designing factory layout with the following advantages:

- Fast modelling process of the virtual factory;
- Realistic virtual representation and interaction that facilitate qualitative feedback;
- Easy modification of layout design,
- Collaborative environment that could involve all stakeholders.

To streamline the point cloud based virtual factory modelling approach for future implementation to FLP tasks, a general guidance is extracted and shown in Figure 15. Detailed description of each step in the guidance can be found in appended Paper C.

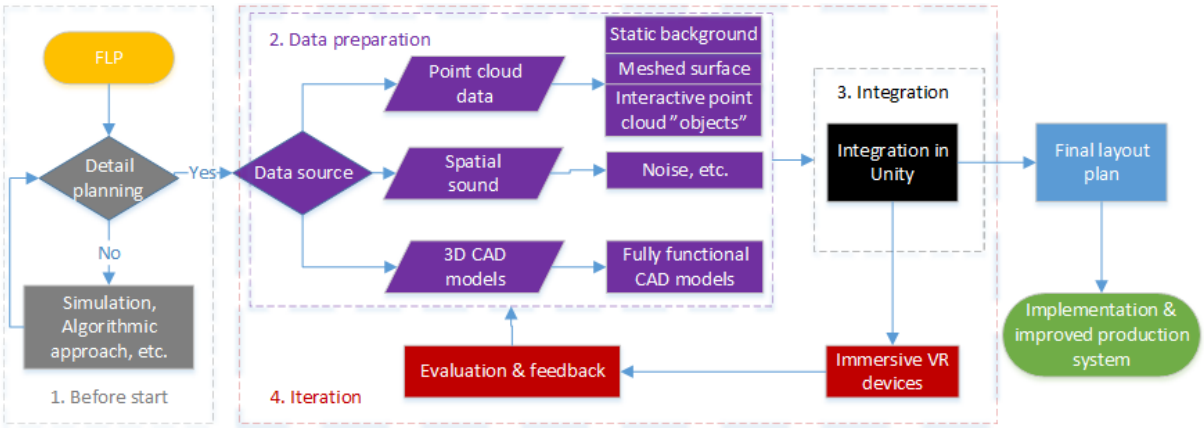

Figure 15. Guidance for employing VR in FLP.

6

DISCUSSION

This chapter discusses the research questions in a broader context in terms of results and methodology. In addition, the scientific and industrial contributions of this thesis and future research are presented.

The research in this thesis has followed the aim of improving current factory layout planning practice through the development of a systematic guidance process that incorporates VR technology. One literature study and three iterative empirical studies have been conducted to move towards the research aim.

6.1 DISCUSSION OF THE RESULTS

RQ1: How has virtual reality technology been employed in production systems?

This question is addressed through a comprehensive literature review of 268 journal articles that implemented VR technology in the production systems. The main findings came out of the study have been described in Chapter 5.1. It defined what virtual reality (VR) for this thesis is and classified different VR systems as three major groups in terms of the level of presence and immersion. At the same time, eleven application areas of productions were identified from the literature. The VR classification and application areas were used to categorize the previous VR attempts and it has provided an overall picture of how VR technology has been adopted in production systems. By digging down into the distribution of studies with specific VR technology and application area, it showed an unbalance research effort with desktop VR and product design area have been given the most attention. There is a lack of research in the area of employing VR for factory layout planning (FLP), even though advantages were reported in the limited studies that have implemented VR systems for FLP support. It is mostly due to the complex process of modelling realistic virtual models for the task and the high cost of VR systems at the time. However, it is worth noting that within the studies that using VR for FLP support, there is higher percentage of immersive VR systems implemented for FLP than desktop and semi-immersive VR systems combined. This hinted that FLP may benefit most from immersive VR systems as it usually involved working with large scale virtual models, and the immersive VR systems is better at generating transferable experience between virtual and real world compared with the other types of VR systems.

The literature study confirmed the idea of adopting VR technology into production systems is beneficial. It also showed that certain areas including but not limited to factory layout planning need more research effort. However, conference articles are not considered in this literature study. Given the fact that VR technology is gaining increasing attention in research and practice in recent years, there are also large number of conference papers covering this topic, so the results might not reflect exactly about the trend. But this is a rational choice considering the time limit and data source quality. The results presented such as VR systems classification, applications area in production systems, advantages and limitations of VR technologies are still considered valid.

RQ2: How can virtual reality (VR) technology be systematically used to support decision-making during factory layout planning (FLP)?

To answer this question, three iterative empirical studies have been conducted to develop a working procedure to support FLP with VR technology. As the main challenges identified from previous studies are twofold, which are the modelling of virtual factory and the involvement of different stakeholders. The empirical studies focused on developing a systematic procedure that can improve the virtual factory modelling in terms of reduced time and cost while keeping the model realistic. Therefore, Study 1 proposed and implemented a hybrid approach for virtual factory modelling that combines point cloud data obtained from 3D laser scanner and existing 3D CAD models of equipment. A desktop VR system was used to present and interact with the model for the FLP tasks. Study 2 and Study 3 took the same hybrid approach for modelling and refined it with improvements in data processing and integration. These two studies also addressed the challenge of stakeholder involvement by using VR devices as the medium for presenting and interacting with the virtual model. The close to real life experience comes along the VR technology is believed to enable more stakeholders actively contribute to the designing of new factory layout.

Among the various approaches of supporting FLP activities, most falls into the category of developing computer models to plan and evaluate the planned changes. What differs are how the virtual models are created. There are mainly two directions have been identified, which are either creating the computer model completely virtually using CAD software, or transforming existing facilities into virtual objects through devices such as camera or scanners. 2D/3D CAD software are widely used to model the factory layout, but it is reported that these models are difficult to achieve accurate representation of reality (Stoli and Rex, 2014) and human cognition is poor to comprehend (Iqbal and Hashmi, 2001). On the other hand, transforming physical facilities into virtual models using camera or 3D laser scanners are getting more attention in research and practice as the technology matures over time. Compare to the 3D laser scanner used in this research, photogrammetry has the advantage of lower cost for the hardware as normal camera is enough. However, the software cost is still high and more importantly, model accuracy is lower than 3D laser scanning. Therefore, 3D laser scanning was found most suitable in this research (Shellshear et al., 2015).

The importance of involving all the stakeholders in the FLP process have been emphasized in previous studies (Dahl et al., 2001) and the visualization of the virtual model is the central part of the layout design activities (Pehlivanis et al., 2004). The immersive virtual reality devices used in this research have provided an intuitive and close to reality interface for stakeholders from different background to easily contribute during the process. This will enhance the understanding of alternative layouts at the beginning of FLP task and in turn reduce the gap between the optimal layout and the actual one (Schenk et al., 2005).

Besides the advantages described above for the selected path in this research, there are also some challenges identified along the process. For examples, data compatibility is one area that needs further effort and studies to smooth the process of developing virtual models; user interaction design for VR interface also worth more attention in research as the mediums for users to interact with VR systems are different from the conventional mouse/keyboard style.

It is also worth noting that factory layout planning in this thesis is for existing factories. FLP can be for building completely new factories on empty plots or redesigning existing ones. The empirical cases used in this thesis are all concerned with upgrading existing factories to adapt to changing requirements. This actually matches with the reality where it is more often to have the continuous improvement process for existing facilities than creating something completely new from scratch. Thus, the results in this thesis is not suitable for FLP that intends to build completed new factories.

6.2 DISCUSSION OF METHODOLOGY

The author's pragmatic philosophical worldview led to the use of multiphase mixed methods as described in Chapter 3.2, and it also helped the author to see the production systems not as an absolute reality. It enables the author to use different research methods to answer the research questions. The impact of the pragmatic worldview to the outcome and quality of this thesis is discussed below.

Creswell and Cark (2007) pointed out that pragmatic researchers hold truth as what works at the time and some even argue that metaphysical concepts such as truth should be abandoned. This viewpoint focuses mostly on the usefulness of the research rather than the rigor of research, which is achieved through internal validity, external validity, reliability, and objectivity (Guba, 1981). Therefore, it is important for pragmatic researchers to balance the usefulness and rigor of the research. The consequence of imbalance is that scientific findings are accepted as adequate and relevance without explaining why it works.

The multiphase mixed methods used in this thesis, has the advantage of directing the research to answer the RQs with both qualitative and quantitative data collected (Eisenhardt, 1989). Research design relying solely on qualitative or quantitative approach would have conflicted with the author's pragmatic worldview and led towards either subjective or objective view. Therefore, the research approach taken in this thesis included design, data collection, implementation, and data analysis (Flynn et al., 1990). Any changes in this process could have altered the outcome of the thesis. However, to keep the balance between the usefulness and rigor of the research, validity and reliability were also taken into the considerations when designing and conducting the research. The methods used were validated according to construct, internal, external and contextual validity (Yin, 2009). For examples, multiple cases with different companies and participants were used in the empirical studies, which increased the external validity; both qualitative and quantitative data were collected to validate the result, so the internal validity is ensured. The data was captured and stored in a structured way, which increased the reliability of the empirical data (Williamson, 2002, Yin, 2009).

6.3 ACADEMIC AND INDUSTRIAL CONTRIBUTION

This thesis contributes to both the academic and industrial communities. For the academic community, the results in relation to RQ1 summarized the benefits and limitations of using VR technology in production systems. It also categorized the previous studies in terms of the types of VR technologies and the application areas in production. An overall picture of current status for the industrial adaptation of VR technology is given. Additionally, by analyzing the study trend, it proved that the direction of integrating VR technology into production is worth further research effort. At the same time, the deviation of research effort spent on different application areas in production provided hints for future research direction. Regarding the results for RQ2, it contribute to the academia with a new approach of supporting FLP tasks. The systematic guidance developed and validated in this research provided a novel approach of redesigning factory layout. It takes the advantage of 3D laser scanning for rapid and realistic modelling as well as the intuitive character of VR technology to visualize and interact with the virtual model, so that stakeholders from different background can be involved and actively contribute to the complex process of redesigning factory layout.

The industrial contribution include the clarification of the VR technology, where in production system domain, the VR technology can be used, what benefit and obstacles are expected as well as detailed guidance on how to use VR technology to improve the current practice of redesigning factory layout. For the industrial audience, the characteristics of VR technology used in production can act as direct input for decisions such as whether or not to start integrating VR and which area suited the most to integrate. The systematic guidance of using VR for FLP provide a step-by-step instructions which can assist industrial organizations to implement and benefit from the latest advancement of VR technology.

6.4 FUTURE RESEARCH

The results of this research have provided directions of future research; the potential ideas are presented in this section.

Firstly, it would be necessary to further validate and improve the systematic guidance of using VR technology for FLP with more cases and larger user base. Validation and further improvement will enable the achievement of effective VR support for planning factory layout.

Another direction is to further explore the computer-mediated reality (or so called XReality technology) related applications in different application area of production. The next generation computing platforms represented by the augmented, mixed and virtual reality (AR/MR/VR) technologies have already started to play an increasing role in our daily lives. It will also bring drastical changes to future manufacturing. More research effort in this field are needed to be better prepared for the coming transformation.

Last but not least is the interaction designs studies for developing AR/MR/VR applications used in production. The result from this research has already shown that VR system has a relatively high learning curve for novel users. Unlike the interaction mediums that people are already familiar with, such as mouse, keyboard and touch screen, the AR/MR/VR technologies have brought completely new ways for human computer interaction, which can be 3D trackable controller, gesture, voice command, etc. Theories and methods that enables effective user interactions are pivotal for the ongoing 4th industry revolution. Therefore, further research in this area is also of great importance to the future manufacturing industry.

7

CONCLUSION

This chapter conclude the thesis by providing the answer to the two research questions.

VR technology with its unique strength is considered a good supporting tool for companies to adapt to the changing requirements. With the aim of this thesis being to improve current factory layout planning (FLP) practice through the development of a systematic guidance that incorporates VR technology into the process, a set of studies have been conducted to investigate ways of smooth VR technology adoption into this production context.

In conclusion, answers to the two research questions are provided as follows:

RQ1: How has virtual reality (VR) technology been used in production system development?

VR technology is gaining increasing attention in production research as the technology itself matures over time. There have been various attempts of employing VR into almost all application areas of production. However, there is an imbalance of effort in different areas, especially, areas such as VR training and FLP need more research effort.

RQ2: How can virtual reality (VR) technology be systematically used to support decision-making during factory layout planning (FLP)?

Base on the results of RQ1, the study moved forward with three iterative empirical studies explained in previous chapters. Incremental knowledge building was achieved through the implementations and evaluations in each study, which at the end resulted with a guidance for integrating VR into FLP. It proposed a working procedures that incorporates point cloud data obtained through 3D laser scanners into the modelling process of virtual factories. The studies have shown the proposed guidance has certain advantages in supporting FLP decision-making in terms of virtual factory modelling time reduction, increased involvement of various affected stakeholders in the planning process, as well as potential design errors reduction and higher operator acceptance.

REFERENCES

Aurich, J.C., D. Ostermayer, and C.H Wagenknecht. 2009. “Improvement of Manufacturing Processes with Virtual Reality-Based CIP Workshops.” *International Journal of Production Research* 47 (19): 5297–5309. https://doi.org/10.1080/00207540701816569.

Aurich, Jan. C., Dirk Ostermayer, and C. H. Wagenknecht. 2006. “Improvement of Manufacturing Processes with Virtual Reality-Technology.” In *Proceedings 5th CIRP ICME*, 239–44. 5th CIRP ICME.

Beraldin, J.-A., F. Blais, S. El-Hakim, L. Cournoyer, and M. Picard. 2007. “Traceable 3D Imaging Metrology: Evaluation of 3D Digitizing Techniques in a Dedicated Metrology Laboratory.” *Proc. of the 8th Conference on Optical 3-D Measurement Techniques: Terrestrial Laser Scanning I*, 310–18.

Berglund, Jonatan, Erik Lindskog, Bjorn Johansson, and Johan Vallhagen. 2014. “Using 3D Laser Scanning to Support Discrete Event Simulation of Production Systems: Lessons Learned.” In *Proceedings of the Winter Simulation Conference 2014*, 2990–99. IEEE. https://doi.org/10.1109/WSC.2014.7020138.

Bi, Z.M., and Lihui Wang. 2010. “Advances in 3D Data Acquisition and Processing for Industrial Applications.” *Robotics and Computer-Integrated Manufacturing* 26 (5): 403–13. https://doi.org/10.1016/j.rcim.2010.03.003.

Carrillo, Janice E, and Cheryl Gaimon. 2000. “Improving Manufacturing Performance Through Process Change and Knowledge Creation.” *Management Science* 46 (2): 265–88. https://doi.org/10.1287/mnsc.46.2.265.11925.

Choi, Sangsu, HyunJei Lee, Juyeon Lee, and Sang Do Noh. 2010. “A Rule-Based System for the Automated Creation of VR Data for Virtual Plant Review CONCURRENT ENGINEERING : Research and Applications.” *CONCURRENT ENGINEERING: Research and Applications*, no. September. https://doi.org/10.1177/1063293X10379763.

Creswell, John. W., and Vicki. L. Plano. Clark. 2011. *Designing and Conducting Mixed Methods Research*. 2nd ed. SAGE Publications.

Cruz-Neira, Carolina, Daniel J. Sandin, and Thomas A. DeFanti. 1993. “Surround-Screen Projection-Based Virtual Reality.” *Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques - SIGGRAPH ’93*, 135–42. https://doi.org/10.1145/166117.166134.

“Definition of Virtual Reality in English by Oxford Dictionaries.” n.d. Accessed February 27, 2017. https://en.oxforddictionaries.com/definition/virtual_reality.

Deming, William E. 1986. *Out of the Crisis: Quality, Productivity and Competitive Position*. Cambridge University Press.

Duffy, Vincent G., Flora F. Wu, and P. P W Ng. 2003. “Development of an Internet Virtual Layout System for Improving Workplace Safety.” *Computers in Industry* 50 (2): 207–30. https://doi.org/10.1016/S0166-3615(02)00121-5.

Filho, Nelson Duarte, Silvia Costa Botelho, Jonata Tyska Carvalho, Pedro De Botelho Marcos, Renan De Queiroz Maffei, Rodrigo Remor Oliveira, Rodrigo Ruas Oliveira, and Vinicius Alves Hax. 2010. “An Immersive and Collaborative Visualization System for Digital Manufacturing.” *International Journal of Advanced Manufacturing Technology* 50 (9–12): 1253–61. https://doi.org/10.1007/s00170-010-2548-z.

Galambos, Péter, Christian Weidig, Péter Baranyi, Jan C Aurich, Bernd Hamann, and Oliver Kreylos. 2012. “VirCA NET : A Case Study for Collaboration in Shared Virtual Space.” In *3rd IEEE International Conference on Cognitive Infocommunications*, 273–77.

Goodman, Paul S., and Terri L. Griffith. 1991. “A Process Approach to the Implementation of New Technology.” *Journal of Engineering and Technology Management* 8 (3–4): 261–85. https://doi.org/10.1016/0923-4748(91)90014-I.

Greis, Noel P. 1995. “Technology Adoption, Product Design, and Process Change: A Case Study in the Machine Tool Industry.” *IEEE Transactions on Engineering Management* 42 (3): 192–202. https://doi.org/Doi 10.1109/17.403737.

Hayes, Robert H., and Kim B. Clark. 1985. “Exploring the Sources of Productivity Differences at the Factory Level.” In *The Uneasy Alliance: Managing the Productivity-Technology Dilemma*, edited by Kim B. Clark, Robert H. Hayes, and Christopher Lorenz. Harvard Business School Press.

Heilig, Morton. 1962. Sensorama Simulator, issued 1962.

Heragu, Sunderesh S. 2016. *Facility Design*. 4th ed. Boston: CRC Press.

Imai, Masaaki. 1986. *Kaizen: The Key To Japan’s Competitive Success*. McGraw-Hill Education.

Ishikawa, Kaoru. 1985. *What Is Total Quality Control? The Japanese Way*. Prentice-Hall.

Jiang, S., S. K. Ong, and A. Y C Nee. 2014. “An AR-Based Hybrid Approach for Facility Layout Planning and Evaluation for Existing Shop Floors.” *International Journal of Advanced Manufacturing Technology* 72 (1–4): 457–73. https://doi.org/10.1007/s00170-014-5653-6.

Jong, Wen-Ren, Tai-Chih Li, and Rong-Ze Syu. 2012. “Algorithm for Automatic Parting Surface Extension in the Mold Design Navigating Process.” *The International Journal of Advanced Manufacturing Technology* 62 (5): 421–41. https://doi.org/10.1007/s00170-011-3831-3.

Korves, B., and M. Loftus. 2000. “Designing an Immersive Virtual Reality Interface for Layout Planning.” *Journal of Materials Processing Technology* 107 (1–3): 425–30. https://doi.org/10.1016/S0924-0136(00)00717-2.

Korves, B, and M Loftus. 1999. “The Application of Immersive Virtual Reality for Layout Planning of Manufacturing Cells.” *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 213 (1): 87–91.

Kunz, Andreas, Markus Zank, Morten Fjeld, and Thomas Nescher. 2016. “Real Walking in Virtual Environments for Factory Planning and Evaluation.” *6th CIRP Conference on Assembly Technologies and Systems (CATS)* 44: 257–62. https://doi.org/10.1016/j.procir.2016.02.086.

Lee, Jonghwan, Soonhung Han, and Jeongsam Yang. 2011. “Construction of a Computer-Simulated Mixed Reality Environment for Virtual Factory Layout Planning.” *Computers in Industry* 62 (1): 86–98. https://doi.org/10.1016/j.compind.2010.07.001.

Liebert, Mary Ann. 2001. “Research on Presence in Virtual Reality: A Survey.” *CyberPsychology & Behavior* 4 (2): 183–201.

Lindberg, Per. 1992. “Management of Uncertainty in AMT Implementation: The Case of FMS.” *International Journal of Operations & Production Management* 12 (7/8): 57–75. https://doi.org/10.1108/EUM0000000001303.

Lindskog, Erik. 2014. “Towards Realistic Visualisation of Production Systems.”

Loeffler, C E, and T Anderson. 1994. *The Virtual Reality Casebook*. Computer Science. Van Nostrand Reinhold. https://books.google.se/books?id=2dtQAAAAMAAJ.

Lu, S.C-Y., M. Shpitalni, and R. Gadh. 1999. “Virtual and Augmented Reality Technologies for Product Realization.” *CIRP Annals - Manufacturing Technology* 48 (2): 471–95.

Mahdavi, Iraj, Babak Shirazi, and Mohammad Mahdi Paydar. 2008. “A Flow Matrix-Based Heuristic Algorithm for Cell Formation and Layout Design in Cellular Manufacturing System.” *The International Journal of Advanced Manufacturing Technology* 39 (9): 943–

53. https://doi.org/10.1007/s00170-007-1274-7.
Maraghy, Hoda A. El. 2006. “Flexible and Reconfigurable Manufacturing Systems Paradigms.” *Flexible Services and Manufacturing Journal* 17 (4 SPECIAL ISSUE): 261–76. https://doi.org/10.1007/s10696-006-9028-7.
Menck, Nicole, Christian Weidig, and J.C. Aurich. 2013. “Virtual Reality as a Collaboration Tool for Factory Planning Based on Scenario Technique.” *Procedia CIRP* 7: 133–38. https://doi.org/10.1016/j.procir.2013.05.023.
Metallo, Adam, and Vince Rossi. 2011. “The Future of Three-Dimensional Imaging and Museum Applications.” *Curator: The Museum Journal* 54 (1): 63–69. https://doi.org/10.1111/j.2151-6952.2010.00067.x.
Muther, Richard. 1974. *Systematic Layout Planning*. 2nd ed. Boston: Cahners Books, Massachusetts.
Ng, Parry P W, Vincent G Duffy, and Gulcin Yucel. 2012. “Impact of Dynamic Virtual and Real Robots on Perceived Safe Waiting Time and Maximum Reach of Robot Arms.” *International Journal of Production Research* 50 (1): 161–76. https://doi.org/10.1080/00207543.2011.571452.
Okulicz, K. 2004. “Virtual Reality-Based Approach to Manufacturing Process Planning.” *International Journal of Production Research* 42 (17): 3493–3504. https://doi.org/10.1080/00207540410001699426.
Ong, S K, and Andrew Nee. 2004. “A Brief Introduction of VR and AR Applications in Manufacturing.”
Phoon, S.-Y., H.-J. Yap, Z Taha, and Y.-S. Pai. 2017. “Interactive Solution Approach for Loop Layout Problem Using Virtual Reality Technology.” *International Journal of Advanced Manufacturing Technology* 89: 2375–2385. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84982161576&doi=10.1007%2Fs00170-016-9219-7&partnerID=40&md5=24d378a477786126a75b467c9eed5898.
Saha, Gobinda, Henk Bikker, and Kees van Luttervelt. 2000. “Approach in Improvement of Factory Performance Through Reengineering of Manufacturing.” In *Proceedings of the 2000 IEEE Engineering Management Society. EMS - 2000 (Cat. No.00CH37139)*, 105–10. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=872485.
Shahin, Arash. 2011. “Facility Layout Simulation and Optimization : An Integration of Advanced Quality and Decision Making Tools and Techniques.” *Modern Applied Science* 5 (4): 95–111. https://doi.org/10.5539/mas.v5n4p95.
Shellshear, Evan, Rolf Berlin, and Johan S. Carlson. 2015. “Maximizing Smart Factory Systems by Incrementally Updating Point Clouds.” *IEEE Computer Graphics and Applications* 35 (2): 62–69. https://doi.org/10.1109/MCG.2015.38.
Smith, Robert P, and Joseph A Heim. 1999. “Virtual Facility Layout Design: The Value of an Interactive Three-Dimensional Representation.” *International Journal of Production Research* 37 (17): 3941–57.
Sutherland, Ivan E. 1965. “The Ultimate Display.” *Multimedia: From Wagner to Virtual Reality*.
———. 1968. “A Head-Mounted Three Dimensional Display.” In *Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, Part I*, 757–64.
Thalmann, Nadia, and Daniel Thalmann. 1999. “Virtual Reality Software and Technology.”
Tompkins, James A., John A. White, Yavuz A. Bozer, and J. M. A. Tanchoco. 2003. *Facilities Planning*. 3rd ed. Wiley.
Welgama, Palitha S, and Peter R Gibson. 1995. “Computer-Aided Facility Layout --- A Status Report.” *The International Journal of Advanced Manufacturing Technology* 10 (1): 66–

77. https://doi.org/10.1007/BF01184280.

Yaman, Ramazan. 2001. “Establishment and Use of Virtual Layouts for Manufacturing.” *Integrated Manufacturing Systems* 12 (6): 400–408. https://doi.org/https://doi.org/10.1108/EUM0000000006105.

Yang, Taho, and Chunwei Kuo. 2003. “A Hierarchical AHP / DEA Methodology for the Facilities Layout Design Problem.” *European Journal of Operational Research* 147: 128–36.

Zetu, D A N, Prashant Banerjee, Paul Schneider, D A N Zetu, Prashant Banerjee, and Paul Schneider. 1998. “Data Input Model for Virtual Reality-Aided Facility Layout Data Input Model for Virtual Reality-Aided Facility Layout.” *IEE Transactions* 30: 597–620. https://doi.org/10.1080/07408179808966505.

APPENDIX – Table of reviewed articles

Title	Year	VR type	Area
Virtual space decision support system	1993	Immersive	FLP
Overview of current Virtual Reality applications	1994	Desktop	Virtual Human
Virtual reality simulation bridges the gap between manufacturing and design	1995	Desktop	Simulation, Machining
Training with virtual reality	1995	Desktop, Immersive	(Dis)Assembly, Training
World of your own	1995	Semi-immersive	Product Design
VHDL-Based Rapid System Prototyping	1996	Desktop	Product Design
Virtual-reality-based point-and-direct robotic inspection in manufacturing	1996	Desktop	Robotics
Virtual assembly using virtual reality techniques	1997	Immersive	(Dis)Assembly
Virtual reality interfaces for feature-based computer-aided design systems	1997	CAVE, Immersive	Product Design
A virtual prototyping approach to product disassembly reasoning	1997		(Dis)Assembly
In-situ quantification of manual assembly forces and postures during the manufacture of TV deflection coils	1997	Desktop	(Dis)Assembly
PCIS: A piece-based construction information system on the World Wide Web	1997	Desktop	Product Design
Human-Machine Collaboration in Robotics: Integrating Virtual Tools with a Collision Avoidance Concept using Conglomerates of Spheres	1997	Desktop	Robotics
Virtual manufacturing system - A test-bed of engineering activities	1997	Desktop	Manufacturing Process
A variant approach to constructing and managing virtual manufacturing environments	1998	Desktop	Virtual factory modelling
Flexible virtual tools for programming robotic finishing operations	1998	Desktop	Robotics
Geometric shape abstractions for internet-based virtual	1998	Desktop	Product Design

prototyping			
A virtual environment for training overhead crane operators: Real-time implementation	1998	Desktop, Immersive	Training
A virtual testbed for the life-cycle design of automated manufacturing facilities	1998	Desktop	Manufacturing Process
Destructive disassembly to support virtual prototyping	1998	Desktop	(Dis)Assembly
Digital humans in the simulated product life cycle	1998	Desktop	Virtual Human
The application of immersive virtual reality for layout planning of manufacturing cells	1999	Immersive	FLP
Invited review: the synergy between virtual reality and robotics	1999	Desktop	Robotics
The generation and practical use of plans for manual assembly using immersive virtual reality	1999	Immersive	(Dis)Assembly
A new collision detection method for CSG-represented objects in virtual manufacturing	1999	Desktop	Manufacturing Process
Virtual plant modeller (VPMOD) for batch-chemical processes	1999	Desktop	Manufacturing Process
Design and Virtual Prototyping of Rehabilitation Aids	1999	Immersive	Product Design
A comparative study of assembly planning in traditional and virtual environments	1999	Desktop, CAVE	(Dis)Assembly
Interactive modeling and simulation of virtual manufacturing assemblies: An agent-based approach	1999	Desktop	(Dis)Assembly
Virtual models gain favor	2000	CAVE	Product Design
Concurrent engineering and virtual reality for human resource planning	2000	Desktop	Training
An image-based fast three-dimensional modelling method for virtual manufacturing	2000		Virtual factory modelling
Implementation of a virtual factory cell scheduling system	2000	Desktop	Manufacturing Process
A behavioral scene graph for rule enforcement in interactive virtual assembly sequence planning	2000		Virtual factory modelling, (Dis)Assembly
Computer-aided process planning in virtual one-of-a-kind production	2000	Desktop	Manufacturing Process
Internet based STEP data exchange framework for virtual enterprises	2000	Desktop	Virtual factory modelling

Collaborative virtual cutting verification and remote robot machining through the Internet	2000	Desktop	Robotics
Product design enhancement by integration of virtual design and assembly analysis tools	2000	Desktop	Product Design, (Dis)Assembly
A virtual reality system for product configuration and analysis based on web, VRML, and CORBA	2001	Desktop	Virtual factory modelling
Multi-user NC machining simulation over the WWW	2001	Desktop	Manufacturing Process
Creation of freeform solid models in virtual reality	2001	Semi-immersive	Virtual factory modelling
Continuous improvement and participative factory planning by computer systems	2001	Semi-immersive	FLP
Virtual prototyping of mold design: geometric mouldability analysis for near-net-shape manufactured parts by feature recognition and geometric reasoning	2001	Immersive	Product Design
A virtual environment for protective relaying evaluation and testing	2001	Desktop	Training
Haptic interaction with non-rigid materials for assembly and dissassembly in product development	2001	Desktop	(Dis)Assembly
Research of guidance technology for assembly modeling in virtual environment	2001	Desktop	(Dis)Assembly
A virtual factory based approach to on-line simulation and scheduling for an FMS and a case study	2001	Desktop	Manufacturing Process
Shape representation and interoperability for virtual prototyping in a distributed design environment	2001	Desktop	Product Design
Integrated virtual manufacturing systems for process optimisation and monitoring	2002	Desktop	Manufacturing Process
Generation of collision-free 5-axis tool paths using a haptic surface	2002	Desktop	Machining
A Framework for Simulation-Based Design of Ship Structures	2002	Desktop, CAVE	Product Design
VMMC: A test-bed for machining	2002	Desktop	Machining
The ergonomic design of workstations using virtual manufacturing and response surface methodology	2002	Desktop	FLP
A novel virtual experimentation approach to planning and training for manufacturing processes - The virtual machine shop	2002	Desktop	Machining
An interactive approach of assembly planning	2002	Desktop	(Dis)Assembly

An internet-based virtual CNC milling system	2002	Desktop	Machining
Applying digital manufacturing technology to ship production and the maritime environment	2002	Desktop	Manufacturing Process
The Internet-based virtual machining system using CORBA	2002	Desktop	Machining
Design and simulation of component-based manufacturing machine systems	2002	Desktop	Manufacturing Process
Virtual Triangulation Sensor Development, Behavior Simulation and CAR Integration Applied to Robotic Arc-Welding	2002	Desktop	Robotics
Modelling and optimisation of Rapid Prototyping	2002	Desktop	Product Design
An Internet-enabled image- and model-based virtual machining system	2002	Desktop	Machining
Implementing Manufacturing Message Specifications (MMS) within collaborative virtual environments over the Internet	2003	Desktop	Virtual factory modelling
A web-based product modelling tool - A preliminary development	2003	Desktop	Product Design
As-built product modeling and reverse engineering in shipbuilding through combined digital photogrammetry and CAD/CAM technology	2003	Desktop	Maintenance
Development and Pilot Testing for Virtual Manufacturing Tools with Intelligent Attributes	2003	Desktop	Robotics
Virtual prototyping of assembly components using process modeling	2003	Desktop	(Dis)Assembly
Computer-supported conflict resolution for collaborative facility designers	2003	Desktop	FLP
Virtual assembly with biologically inspired intelligence	2003	Desktop	(Dis)Assembly
A web-enabled PDM system in a collaborative design environment	2003	Desktop	Product Design
Virtual factory design--a new tool for a co-operative planning approach	2003	Desktop	FLP
Using Virtual Reality technologies for manufacturing applications	2003	Immersive	Robotics, (Dis)Assembly
Modelling and implementation of internet-based virtual machine tools	2003	Desktop	Machining
A Web-Based Product Modelling Tool – A Preliminary Development	2003	Desktop	Product Design

Discrete event simulation implemented in a virtual environment	2003	Immersive, CAVE	Simulation
An architecture to support the manufacturing system design and planning	2003		(Dis)Assembly, FLP, Product Design
Virtual environments in machinery safety analysis	2003	Immersive	Manufacturing Process
A solution to integrate computer-aided design (CAD) and virtual reality (VR) databases in design and manufacturing processes	2003	Desktop	Virtual factory modelling
Vehicle dynamic analysis using virtual proving ground approach	2003	Desktop	Product Design
Towards Virtual Prototyping of Complex-shaped Multi-layered Apparel	2004	Desktop	Product Design
Human-Centered Robotics and Interactive Haptic Simulation	2004	Desktop	Robotics
A virtual prototyping system for rapid product development	2004	Desktop	Product Design
Automatic Microassembly System Assisted by Vision Servoing and Virtual Reality	2004	Desktop	(Dis)Assembly
Virtual reality as a support tool in the shoe life cycle	2004	Desktop	Product Design
Internet marketing and product visualization (IMPV) system: Development and evaluation in support of product data management	2004	Desktop	Product Design, Marketing
Design of research platform on telerobot system based on virtual reality technology	2004	Desktop	Robotics
Dexel-based force-torque rendering and volume updating for 5-DOF haptic product prototyping and virtual sculpting	2004	Desktop	Product Design
Remote sensing, diagnosis and collaborative maintenance with Web-enabled virtual instruments and mini-servers	2004	Desktop	Maintenance
A matrix approach to an FMS control design: From virtual modeling to a practical implementation	2004	Desktop	Manufacturing Process, Robotics
A Supervisory Data-Traffic Controller in Large-scale Distributed Virtual Reality Environments	2004	CAVE	Training, Simulation
A Decision Support System tor Integrating Real-time Manutacturing Control with a Virtual Environment	2004	Desktop	Manufacturing Process
A Hybrid Approach to the Verification and Analysis of Assembly and Maintenance Processes Using Virtual Reality and Digital Mannequin Technologies	2004	Immersive	Maintenance, (Dis)Assembly

Virtual Assembly/Disassembly System Using Natural Human Interaction and Control	2004	Immersive, CAVE	(Dis)Assembly
Interactive 3-D Video Representation and Coding Technologies	2005	Desktop	Virtual factory modelling
Workpiece representation for virtual turning	2005	Desktop	Product Design
Development of the Integrated Design Environment for K-AGT	2005	Desktop	Product Design
A Visibility Sphere Marching algorithm of constructing polyhedral models for haptic sculpting and product prototyping	2005	Desktop	Product Design
Feature-based design for process planning of machining processes with optimization using genetic algorithms	2005	Desktop	Machining
A Web-based curriculum development on nontraditional manufacturing with interactive features	2005	Desktop	Training
Parallel Kinematic Machines: Design, Analysis and Simulation in an Integrated Virtual Environment	2005	Desktop	Machining
A new hybrid dynamic modelling approach for process planning	2005	Desktop	Manufacturing Process
SUPPORTING CUSTOMER-COMPANY INTERACTION IN PRODUCT CUSTOMIZATION USING A WEB-BASED COLLABORATIVE VR ENVIRONMENT	2005	Desktop	Product Design
A multi-material virtual prototyping system	2005	Desktop	Product Design
Virtual and augmented reality support for discrete manufacturing system simulation	2005	CAVE	Simulation
A virtual machine concept for real-time simulation of machine tool dynamics	2005	Desktop	Machining
Virtual reality applications for the next-generation manufacturing	2005	Desktop	Simulation
Intelligent prediction and simulation of tool wear in CNC turning system	2005	Desktop	Machining
VRPS-I: An internet-based virtual rapid prototyping system	2005	Desktop	Product Design
Middleware-based Integration of Multiple CAD and PDM Systems into Virtual Reality Environment	2006	Immersive	Virtual factory modelling
Supervisory control framework for collaborative virtual manufacturing	2006	Desktop	Virtual factory modelling

A CAVE-based Multi-Material Virtual Prototyping System	2006	CAVE	Product Design
Development of a Simulator Based on Train Performance Simulation	2006	Immersive	Product Design
Development of a prototype customer-oriented virtual factory system	2006	Desktop	Product Design
Customer-driven Collaborative Product Assembler for Internet-based Commerce	2006	Desktop	Product Design, (Dis)Assembly
Renault Integrates Sensics Panoramic HMD into ULTIMATE Driving Simulator	2006	CAVE	Product Design
Application of virtual manufacturing in generation of gears	2006	Desktop	Product Design
The role of non-intrusive operator logging to support the analysis and generation of product engineering data using immersive VR	2006	Immersive	Product Design, (Dis)Assembly
Development of a web-based collaboration platform for manufacturing product and process design evaluation using virtual reality techniques	2006	Desktop	Product Design
Virtual manufacturing of milling operations with multiple tool paths	2006	Desktop	Machining
Development of Web-based CAM system	2006	Desktop	Machining
A novel data decomposition and information translation method from CAD system to virtual assembly application	2006	Desktop	(Dis)Assembly
Production engineering-oriented virtual factory: a planning cell-based approach to manufacturing systems design	2006	Desktop	Simulation, Manufacturing Process, FLP
A multichannel visualization module for virtual manufacturing	2006	CAVE, Immersive	Product Design, Virtual factory modelling
A pragmatic system to support interactive assembly planning and training in an immersive virtual environment (I-VAPTS)	2006	Desktop	(Dis)Assembly
Virtual manufacturing as a way for the factory of the future	2006	Desktop	FLP
Web-based product development and simulation with virtual reality	2006	Desktop	Product Design
A Vision-Based Approach af Bare-Hand Interface Design in Virtual Assembly	2006	Desktop	(Dis)Assembly
Virtual engineering approaches in product and process design	2007	Immersive, Desktop	Product Design
Virtual plastic injection molding based on virtual reality	2007	Immersive	Product Design

technique			
Multi-train operation simulation in an interactive virtual environment	2007	Immersive	Training
State of the art of the virtual reality applied to design and manufacturing processes	2007	Immersive	Product Design
Enhanced integrated manufacturing systems in an immersive virtual environment	2007	Immersive	Manufacturing Process
A virtual prototyping system for simulating construction processes	2007	Desktop	Product Design
A web-based 3D virtual technologies for developing product information framework	2007	Desktop	Product Design
An efficient approach to human motion modeling for the verification of human-centric product design and manufacturing in virtual environments	2007	Desktop	Virtual Human
Web-based virtual CNC machine modeling and operation	2007	Desktop	Machining
Linking product design in CAD with assembly operations in CAM for virtual product assembly	2007	Desktop	(Dis)Assembly
Evaluation of multi-sensory feedback on the usability of a virtual assembly environment	2007	Immersive	(Dis)Assembly
Development of a virtual machining and inspection system for ultra-precision diamond turning	2007	Desktop	Machining
Virtual Shoe Test Bed: A Computer-Aided Engineering Tool for Supporting Shoe Design	2007	Desktop	Product Design
A digital mock-up system for construction of product information model in shipbuilding process	2007	Desktop	Product Design
Virtual Product Simulator (VPS)	2007	Desktop	Product Design
Step-by-step STEP 2: Optimized assembly by virtual control	2008	Desktop	(Dis)Assembly
Virtual design modifications yield line-of-sight improvements for LHD operators	2008	Desktop	Product Design
A versatile virtual prototyping system for rapid product development	2008	CAVE, Semi-immersive	Product Design
An integrated approach to the analysis of automotive assembly activities using digital manufacturing tools	2008		(Dis)Assembly

Virtual prototyping of flexible soldering cells for electronic manufacture	2008	Desktop	Product Design
Integrated Virtual Assembly Environment and its application in ship piping layout	2008	CAVE	(Dis)Assembly
Virtual Simulation and Optimization of Milling Operations—Part I: Process Simulation	2008	Desktop	Simulation
A Study on Virtual Reality-based EDM Learning Framework and Effectiveness Analysis	2008	Desktop	Training
A virtual collaborative maintenance architecture for manufacturing enterprises	2008	Desktop	Maintenance
Improvement of manufacturing processes with virtual reality-based CIP workshops	2009	CAVE	FLP
Enabled dynamic tasks planning in Web-based virtual manufacturing environments	2008	Desktop	(Dis)Assembly
A general analytic approach for Santos™ upper extremity workspace	2008	Desktop	Virtual Human
VR collaborative and interactive design over the web: a MEMS case study	2008	Desktop	Product Design
Virtual-reality-based information requirements analysis tool for CIM system implementation: a case study in die-casting industry	2008	Desktop	Manufacturing Process
Development of a virtual machining and inspection system for ultra-precision diamond turning	2008	CAVE	Product Design
Improving decision making by simulating and visualizing geometrical variation in non-rigid assemblies	2008	Desktop	Product Design
Precise manipulation approach to facilitate interactive modular fixture assembly design in a virtual environment	2008	Desktop	(Dis)Assembly
A CAD system for multi-style thermal functional design of clothing	2008	Desktop	Virtual Human
A PLC programming environment based on a virtual plant	2008	Desktop	Manufacturing Process
A virtual injection molding system based on numerical simulation	2009	Desktop	Product Design
Model for surface-roughness parameters determination in a virtual machine shop environment	2009	Desktop	Machining
Development for a web-based EDM laboratory in manufacturing engineering	2009	Desktop	Training

Innovative virtual prototyping environment for reconfigurable manufacturing system engineering	2009	Desktop	Product Design
Mixed Reality-based Interactive Technology for Aircraft Cabin Assembly	2009	Desktop	(Dis)Assembly
A framework for collaborative product review	2009	Desktop	Product Design
Modelling the effect of AGV operating conditions on operator perception of acceptability and hazard	2009	Desktop	Simulation
Towards the development of a desktop virtual reality-based system for modular fixture configuration design	2009	Desktop	Product Design
Multi-objective optimisation method for posture prediction and analysis with consideration of fatigue effect and its application case	2009	Desktop	Virtual Human
Virtual prototyping of automated manufacturing systems with Geometry-driven Petri nets	2009	Desktop	Product Design
Automated design process modelling and analysis using immersive virtual reality	2009	Immersive	(Dis)Assembly
Virtual factory approach for implementation of holonic control in industrial applications: A case study in die-casting industry	2009	Desktop	FLP
Digital manufacture of large-grade hydro turbine's blades	2009	Desktop	Product Design
Data integration from product design to assembly planning in a collaborative environment	2010	Desktop	(Dis)Assembly
Application of the Virtual Reality Modelling Language to Computer Aided Robot Control system ROANS	2010	Desktop	Robotics
Development of a collaborative virtual maintenance environment with agent technology	2010	Desktop	Maintenance
An innovative design system for personalized design of swimsuit	2010	Desktop	Product Design
A Process for Design, Verification, Validation, and Manufacture of Medical Devices Using Immersive VR Environments	2010	CAVE	Product Design
A web-based training framework in automotive electric education	2010	Desktop	Training
An approach for generating a tasks schedule model in web-based virtual manufacturing system of screw threads	2010	Desktop	Manufacturing Process, Training

Active inspection supporting system based on mixed reality after design and manufacture in an offshore structure	2010	Desktop	Maintenance
Implementation of Cosserat theory into haptic sensing technology for miniaturised systems	2010	Desktop	Product Design, Maintenance
A collaborative Design for Usability approach supported by Virtual Reality and a Multi-Agent System embedded in a PLM environment	2010	Immersive	Product Design
A desktop virtual reality-based interactive modular fixture configuration design system	2010	Desktop	Product Design
Using CBR to develop a VR-based integrated system for machining fixture design	2010	Desktop	Machining
Virtual-reality-based methodology for modelling and verifying shop floor control systems	2010	Desktop	Manufacturing Process
An immersive and collaborative visualization system for digital manufacturing	2010	CAVE	Product Design
Construction of a computer-simulated mixed reality environment for virtual factory layout planning	2011	CAVE	FLP
Concurrent consideration of evacuation safety and productivity in manufacturing facility planning using multi-paradigm simulations	2011	CAVE	FLP
Predicting real-world ergonomic measurements by simulation in a virtual environment	2011	Desktop	Virtual Human
Physics-based virtual reality for task learning and intelligent disassembly planning	2011	Desktop	(Dis)Assembly, Training
Modeling and real-time simulation architectures for virtual prototyping of off-road vehicles	2011	CAVE	Product Design
A self-configurable large-scale virtual manufacturing environment for collaborative designers	2011	Desktop	Manufacturing Process
Applying RBR and CBR to develop a VR based integrated system for machining fixture design	2011	Desktop	Product Design
Affective evaluation of user impressions using virtual product prototyping	2011	CAVE	Product Design
Expanding Virtual Simulation in Product Realization	2011	Desktop	Product Design
A modular virtual reality system for engineering laboratory education	2011	Desktop	Training
Virtual reality supported assembly planning in the shipbuilding	2011	Immersive	(Dis)Assembly

industry			
Application of virtual reality technology in simulation of automated workplaces | Primjena tehnologija virtualne stvarnosti u simulaciji automatiziranih radnih mjesta	2011	Immersive	Manufacturing Process
A generic approach of integrating 3D models into virtual manufacturing	2011	Desktop	(Dis)Assembly
Hybrid Reconfigurable System design and optimization through virtual prototyping and digital manufacturing tools	2012	Desktop	Product Design
A virtual inspection framework for precision manufacturing of aerofoil components	2012	Desktop	Maintenance
Motion generation and virtual simulation in a digital environment	2012	Desktop	Manufacturing Process
Impact of multimodal feedback on simulated ergonomic measurements in a virtual environment: A case study with manufacturing workers	2012	Desktop	Virtual Human
Mixed reality distributed platform for collaborative design review of automotive interiors	2012	Semi-immersive, Immersive	Product Design
Integration of virtual and real environments for engineering service-oriented manufacturing systems	2012	Desktop	Virtual factory modelling
Development of Tool-Type Devices for a Multifingered Haptic Interface Robot	2012	Desktop	Robotics
Conceptual Design of Hemp Fibre Production Lines in Virtual Environments	2012	Desktop	Manufacturing Process
Construction industry offsite production: A virtual reality interactive training environment prototype	2012	CAVE	Training
Coupling of interactive manufacturing operations simulation and immersive virtual reality	2012	CAVE	Simulation
A visualization system for integrating maintainability design and evaluation at product design stage	2012	Desktop	Product Design, Maintenance
Noise investigation in manufacturing systems: An acoustic simulation and virtual reality enhanced method	2012	CAVE	Manufacturing Process
Development of Tool-Type Devices for a Multifingered Haptic Interface Robot	2013	Desktop	Robotics
Augmented and Virtual Reality techniques for footwear	2013	Desktop	Product Design
3D simulation as training tool in container terminals: The TRAINPORTS simulator	2013	CAVE, Desktop	Training

A web-based virtual system for turn-millin	2013	Desktop	Machining
Semantic Virtual Factory supporting interoperable modelling and evaluation of production systems	2013	Desktop	FLP
Dimensional and geometrical errors of three-axis CNC milling machines in a virtual machining system	2013	Desktop	Robotics
Using of the virtual reality application with the scanning device kinect for manufacturing processes planning	2013	Desktop	Product Design
An approach for capturing the Voice of the Customer based on Virtual Prototyping	2013	Semi-immersive	Product Design
An integrated methodology for the functional design of dental prosthesis	2013	Desktop	Product Design
The prediction of process-induced deformation in a thermoplastic composite in support of manufacturing simulation	2013	Desktop	Machining
Assessment of a Virtual Functional Prototyping Process for the Rapid Manufacture of Passive-Dynamic Ankle-Foot Orthoses	2013	Desktop	Product Design
Utilization of advanced simulation methods for solving of assembly processes automation partial tasks	2013	Semi-immersive	(Dis)Assembly
Environment sensing for the creation of work cell models	2013	Desktop	Robotics
VREM: An advanced virtual environment for micro assembly	2014	Desktop	(Dis)Assembly
A computer vision-based assistant system for the assembly of narrow cabin products	2014	Desktop	(Dis)Assembly
Virtual machining considering dimensional, geometrical and tool deflection errors in three-axis CNC milling machines	2014	Desktop	Robotics
Toward a Methodology for Assessing Electric Vehicle Exterior Sounds	2014	CAVE	Product Design
The development of a physics and constraint-based haptic virtual assembly system	2014	Desktop	(Dis)Assembly
Future internet-based collaboration in factory planning	2014	Immersive	FLP
Design of Virtual Machine Assembly Simulation System in Single-Channel Immersion	2014	Immersive	(Dis)Assembly
Simulation and Optimization of Cockpit Based on Three-dimensional Localization Algorithm	2014	Desktop	Virtual Human
A STEP-compliant Industrial Robot Data Model for robot off-line programming systems	2014	Desktop	Robotics

Virtual Commissioning with Process Simulation (Tecnomatix)	2014	Desktop	Simulation
Design, programming and orchestration of heterogeneous manufacturing systems through VR-powered remote collaboration	2015	Immersive	Training, Product Design
Structured design of flexibly automated manufacturing cells through semantic models and petri nets in a virtual reality environment	2015	Desktop	Manufacturing Process
Construction of a virtual reality environment for robotic manufacturing cells	2015	Desktop	FLP, Robotics
Haptics assisted virtual assembly	2015	Desktop	(Dis)Assembly
A lightweight and cross-platform Web3D system for casting process based on virtual reality technology using WebGL	2015	Desktop	Manufacturing Process
A Publishing Method of Lightweight Three-Dimensional Assembly Instruction for Complex Products	2015	Desktop	(Dis)Assembly
Immersive virtual reality to vindicate the application of value stream mapping in an US-based SME	2015	Immersive	FLP
Collaborative robot monitoring and control for enhanced sustainability	2015	Desktop	Robotics
Streamlining virtual manufacturing cell modelling by behaviour modules	2015	Desktop	Robotics
Fashion Design Bases on Computer Three-Dimensional Virtual Reality Environment	2015	Desktop	Virtual Human
vMES: Virtualization aware manufacturing execution system	2015	Desktop	Manufacturing Process
A physically based approach with human–machine cooperation concept to generate assembly sequences	2015	Desktop	(Dis)Assembly
Arezzo-flexible manufacturing system: A generic flexible manufacturing system shop floor emulator approach for high-level control virtual commissioning	2015	Desktop	Simulation
Context-specific design interventions in blending workstation: An ergonomics perspective	2016	Desktop	Virtual Human
Enhancing fidelity of virtual assembly by considering human factors	2016	Desktop	(Dis)Assembly
Design and simuation of a vehicle test bed based on intelligent transport systems	2016	Desktop	Product Design
The development of a clothing fit evaluation system under virtual environment	2016	Desktop	Product Design, Virtual Human

Measurement wear of drill in the manufacturing process and its simulation in virtual reality	2016	Desktop	Manufacturing Process
Tool Deflection Error of Three-Axis Computer Numerical Control Milling Machines, Monitoring and Minimizing by a Virtual Machining System	2016	Desktop	Machining
Virtual environment in control and programming system for reconfigurable machining robot	2016	Desktop	Robotics
Technology enabled learning of metal forming processes for engineering graduates using virtual simulation lab	2016	Desktop	Training
Workstations for people with disabilities: an example of a virtual reality approach	2016	Desktop	Virtual Human
Ergonomics product development of over bed table for bedridden patients	2016	Desktop	Virtual Human, Product Design
Human-machine Collaboration in Virtual Reality for Adaptive Production Engineering	2017	Immersive	Robotics, (Dis)Assembly
VR-based Product Personalization Process for Smart Products	2017	Immersive	Product Design
Head-mounted-display tracking for augmented and virtual reality	2017		
The Benefits of Human-centred Design in Industrial Practices: Re-design of Workstations in Pipe Industry	2017	Semi-immersive	Product Design
Accuracy analysis of tool deflection error modelling in prediction of milled surfaces by a virtual machining system	2017	Desktop	Machining
Introduction and establishment of virtual training in the factory of the future	2017	Desktop	Training
An Industry Case Study: Investigating Early Design Decision Making in Virtual Reality	2017	CAVE	Product Design
Interactive solution approach for loop layout problem using virtual reality technology	2017	Desktop	FLP
Testing Autonomous Vehicle Software in the Virtual Prototyping Environment	2017	Desktop	Product Design
Effectiveness and acceptability of a virtual environment for assessing human–robot collaboration in manufacturing	2017	Immersive	Robotics, Manufacturing Process