THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Developing extended reality systems for the manufacturing industry

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Gothenburg, Sweden 2020

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ISBN: 978-91-7905-410-6

Doctoral thesis at Chalmers University of Technology
New series number: 4877
ISSN: 0346-718X

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Printed by
Chalmers Reproservice
Gothenburg, Sweden 2021

ABSTRACT

In the digital transformation of the manufacturing industry, computer-mediated reality, also known as extended technology reality (XR) technology is believed to be the foundation for realising the Industry 4.0 vision. XR technology, with its three representative forms, augmented reality (AR), mixed reality (MR) and virtual reality (VR) have created new ways for users and computer systems to interact. Although previous studies and pilot industrial projects have highlighted potential applications of XR technologies in manufacturing activities, it remains largely unadopted in current manufacturing.

The goals of this thesis are to contribute to knowledge about integrating XR technology into manufacturing and helping the manufacturing industry benefit from the latest advancements in XR technologies. Thus, this thesis aims to bridge the knowledge gap and facilitate the process of integrating the latest XR technologies into manufacturing.

In addressing the above purpose and aims, this research effort adopted a pragmatic approach to eleven empirical studies (based on real-world manufacturing problems within five companies) and two testbeds. Eleven XR systems, ranging from AR to VR, were developed and tested for applications covering all four phases of production: design, learning, operational and disruptive. Accordingly, this thesis has identified critical factors and reported the effects of integrating XR technologies into a manufacturing context. Furthermore, the framework dealing with the necessary steps to integrate XR technology into manufacturing activities was developed, explained and validated through internal as well as external cases. This has proved effective in guiding the process of integrating XR into manufacturing and assuring the quality of that integration.

Keywords: virtual reality, mixed reality, augmented reality, extended reality, manufacturing

ACKNOWLEDGEMENTS

The road towards a PhD was full of joys and challenges. It has been a journey filled with lessons and memories. I would not have finished this thesis without the help and support of my supervisors, colleagues, friends and family. I would like to take this opportunity to express my sincere thanks to each one of them.

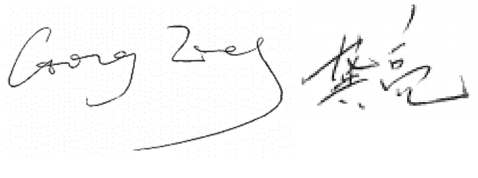
First and foremost, I would like to thank my supervisors, Professor Björn Johansson and Professor Åsa Fast-Berglund for your constant support and belief in me. Your feedback along the way was invaluable to me and I will always be thankful for it. I would also like to thank my examiner, Professor Johan Stahre. This thesis would not have been possible without your efforts and input.

It has been a great privilege to have the lovely, inspiring, working atmosphere at the Department of Industrial and Materials Science. I would like to thank all my colleagues for the great times we had and for our discussions during coffee breaks. Your input and encouragements helped me through the tough times.

I would also like to thank all the industrial partners that collaborated in the research projects, as well as the Swedish and European Union funding agencies. This research would not have been possible without your work and their contribution.

During this year, 2020, the whole world has been fighting Covid-19. I would like to express my sincere gratitude to all the medical staff and others working on the front line. Together, we will get through it.

Last but not least, I want to thank my family and friends for their love and support.
To my parents, thank you for always being supportive.
To my wife Zhang Canwei (张粲葳), I am so lucky to have you in my life and would not have come this far without your love. I love you!



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Gothenburg

November 2020

APPENDED PUBLICATIONS

Paper I **Gong, L.**, Li, D., Mattsson, S., Åkerman, M., & Fasth-Berglund, Å. (2017). The comparison study of different operator support tools for assembly task in the era of global production. Procedia Manufacturing, 11, 1271–1278. https://doi.org/https://doi.org/10.1016/j.promfg.2017.07.254

Contribution Gong Liang initiated this paper and contributed by implementing and testing the VR case, plus data analysis and writing the paper. Dan Li, Sandra Mattsson, Magnus Åkerman conducted the non-VR parts of the test and collected the corresponding data. Åsa helped design the study and provided valuable comments and advice.

Paper II **Gong, L**., Berglund, J., Fast-Berglund, Å., Johansson, B., Wang, Z., & Börjesson, T. (2019). Development of virtual reality support to factory layout planning. International Journal on Interactive Design and Manufacturing, 13(3), 935–945. https://doi.org/10.1007/s12008-019-00538-x

Contribution Gong Liang contributed by implementing cases and writing the paper. Jonatan Berglund assisted with data collection. Åsa Fash-Berglund helped with data analysis and provided comments and advice on writing, alongside Björn Johansson. Zhiping Wang and Tobias Börjesson facilitated access to the industrial partners.

Paper III **Gong, L.**, Fast-Berglund, Å., and Johansson, B. (2021). "A Framework for Extended Reality System Development in Manufacturing," in IEEE Access, vol. 9, pp. 24796-24813. https://doi.org/10.1109/ACCESS.2021.3056752.

Contribution Gong Liang designed the study and wrote the paper. Åsa Fast-Berglund and Björn Johansson provided valuable comments and suggestions on the design of the study and the writing.

Paper IV **Gong, L**., Söderlund, H., Bogojevic, L., Fast-Berglund, Å., Johansson, B. (2020). Interaction design for multi-user virtual reality systems: An automotive case study. Procedia CIRP, 93, 1259-1264. https://doi.org/10.1016/j.procir.2020.04.036

Contribution Gong Liang designed the study and implemented the solution, based on early development by Henrik Söderlund and Leonard Bogojevic. He also contributed by conducting the tests and writing the paper. Åsa Fast-Berglund and Björn Johansson provided valuable comments and suggestions for designing the study and writing the paper.

ADDITIONAL PUBLICATIONS

Berglund, J., Gong, L., Sundström, H., & Johansson, B. (2017). Adaptation of High-Variant Automotive Production System Using a Collaborative Approach. In Dynamics of Long-Life Assets (pp. 255–276). https://doi.org/10.1007/978-3-319-45438-2_14

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 Dynamics of Long-Life Assets (pp. 115–132). https://doi.org/10.1007/978-3-319-45438-2_7

Fasth Berglund, Å., Gong, L., & Li, D. (2018). Testing and validating extended reality (XR) technologies in manufacturing. Procedia Manufacturing, 25, 31–38. https://doi.org/10.1016/j.promfg.2018.06.054

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. https://doi.org/10.1016/j.procir.2017.03.089

Gong, L., Berglund, J., Wang, Z., Larborn, J., Skoogh, A., & Johansson, B. (2016). Improving manufacturing process change by 3D visualization support: A pilot study on truck production. Procedia CIRP, 57(C), 298–302. https://doi.org/10.1016/j.procir.2016.11.052

Mattsson, S., Li, D., Fasth Berglund, Å., & Gong, L. (2017). Measuring Operator Emotion Objectively at a Complex Final Assembly Station. Advances in Neuroergonomics and Cognitive Engineering, 488, 223–232. https://doi.org/10.1007/978-3-319-41691-5_19

Nåfors, D., Berglund, J., Gong, L., Johansson, B., Sandberg, T., & Birberg, J. (2020). Application of a hybrid digital twin concept for factory layout planning. Smart and Sustainable Manufacturing Systems, 4(2). https://doi.org/10.1520/SSMS20190033

Nåfors, D., Lindskog, E., Berglund, J., Gong, L., Johansson, B., & Vallhagen, J. (2018). Realistic virtual models for factory layout planning. Proceedings of the 2017 Winter Simulation Conference, 3976–3987. https://doi.org/10.1109/WSC.2017.8248107

Stylidis, K., Dagman, A., Almius, H., Gong, L., & Söderberg, R. (2019). Perceived Quality Evaluation with the Use of Extended Reality. Proceedings of the International Conference on Engineering Design, ICED, 1(1), 1993–2002. https://doi.org/10.1017/dsi.2019.205

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LIST OF ABBREVIATIONS

3D	Three-dimensional
AR	Augmented reality
BHI	Bare-hand interaction
CAD	Computer-aided design
CAVE	Cave automatic virtual environment
CBI	Controller-based interaction
CIP	Continuous improvement process
CNC	Computer numerical control
DoF	Degrees of freedom
FLP	Factory layout planning
FOV	Field of view
FPS	Frames per second
HCI	Human-computer interaction
HMD	Head-mounted display
IT	Information technology
LIDAR	Light detection and ranging
MR	Mixed reality
PC	Personal computer
PLC	Programmable logic controller
RBI	Reality-based interaction
RTI	Reality trade-offs interaction
SAM	Self-assessment manikin
SLP	Systematic layout planning
SUS	System usability scale
UX	User experience
VirCA	Virtual collaboration arena platform
VLP	Virtual layout planning
VR	Virtual reality
XR	Extended reality
WIMP	Window, icon, menu and pointer

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1

INTRODUCTION

This chapter describes the background of the research and structure of the thesis.

1.1 BACKGROUND

The manufacturing industry is constantly under pressure to achieve greater productivity, quality and safety while reducing costs and time. Adopting the latest technologies to the manufacturing process has been a key building block in reaching these goals. During the First Industrial Revolution (the Industry 1.0 era in the late 18th Century), the introduction of steam power to manufacturing is recognised as the trigger which enabled mechanisation and greatly improved productivity. Starting in the early 20th Century, the use of electricity brought about the Second Industrial Revolution, in which electric conveyor belts made mass production into a reality. Thereafter, computers came on the scene and enabled robotic control with programmable logic controllers (PLC) and computer numerical control (CNC) machining. This resulted in the Third Industrial Revolution.

Today we are witnessing another revolution in the manufacturing industry, as the trend in this ever globalised world shifts from mass production to mass customisation (El Maraghy, 2006). Initiatives such as Industry 4.0, coined by the German government (Wahlster, 2012) and Smart Manufacturing, coined by the USA (Kang et al., 2016) were proposed to guide the development. Although given different names, the essential direction is the same; the digitalisation of manufacturing activities. In other words, integration of the latest digital technologies to use more useful and effective tools in support of different manufacturing activities. Among the various technologies being studied and introduced to improve current manufacturing practices, computer-mediated reality (also known as extended technology reality, or XR) has shown great potential in improving activities across different manufacturing processes. This is considered an essential foundation of the Fourth Industrial Revolution (Nee and Ong, 2013).

XR technology includes three representative forms: 1) augmented reality (AR), 2) mixed reality (MR) and 3) virtual reality (VR). XR systems project computer-generated digital content to users at different levels of immersion. However, the digital content appears to actually exist in the physical world. Thus, human minds are provided with seemingly limitless direct access to digital information. The richness and flexibility of XR systems have been reported as beneficial in product design, factory layout planning, assembly and training (Choi et al., 2015). According to Fortune Business Insight, the global virtual reality in the manufacturing industry was USD 924.7 million in 2018 and is projected to reach USD 14,887.0 million by 2026 (Insights 2018). XR technologies are garnering increasing attention both in academia and industry. The outcome of such a technology movement is going to shape the manufacturing industry in the industry 4.0 era.

1.2 PROBLEM STATEMENT

Academic studies and pilot industrial projects have shown the potential of applying XR technologies to manufacturing activities. However, they are still not widely adopted in today's manufacturing and there are many different potential causative factors in this.

The first possible cause is whether there is a need to introduce XR technology into an existing system. As briefly mentioned at the beginning of this thesis, the manufacturing industry is undergoing a digital transformation, to better cope with the mass customisation trend and realise the Industry 4.0 vision. Manufacturing companies' investment in research and development of new technologies confirms their willingness to make changes which may improve production. At the same time, previous studies also prove that XR technologies would benefit the activities of different manufacturing areas. It is, therefore, safe to exclude a lack of need or willingness by industry as a cause of slow XR integration.

Concerns about affordability and capability represent another important factor in the introduction of new technology (Tuttle et al., 2012). When they were first introduced, hardware and software limitations meant that XR systems were usually expensive and fixed to a certain purpose. However, thanks to the rapid pace of development, XR systems are maturing, in terms of both cost and flexibility. XR has become as affordable as normal computer hardware, especially in the past five years. Thus, cost is less likely to be a hindrance. The author therefore believes the problem lies with knowledge and expertise in efficient XR integration into manufacturing systems and making XR easy to use for end-users. There are currently no clear guidelines available to address these issues.

The complex nature of the manufacturing context and rapidly evolving XR technologies make it difficult to select a solution for manufacturing activity. On the one hand, manufacturing activities cover a wide range of areas; everything from product design and production to after-sales service or maintenance. Each area has its unique requirements and constraints when it comes to integrating an XR system to bring about improvement. On the other hand, XR technologies vary in their degree of virtuality. Different virtuality levels come with advantages and disadvantages for certain tasks. A simple example is that VR systems have the flexibility to immerse users in a computer-generated environment but require more precise modelling, while AR systems may easily augment a user's view with important information but often perform poorly in tracking and object registration. Even within the same virtuality level, there are numerous pieces of hardware and software with diverse specifications. Wireless VR solutions are easy to move around but often entail less computing power and shorter active times. Finding a good match between manufacturing activities and XR solutions requires expertise in both fields. Identifying a good match is the important initial step in a successful integration.

System compatibility is recognised as another great challenge to manufacturing companies wanting to successfully adopt XR technology (Okulicz, 2004). XR systems need to be populated with product and production data so that they may be tailored to specific manufacturing activities. In reality, this process is not as smooth as it should be due to the different standards and formats used. Even when data is compatible between systems, data created for one purpose often needs modification for another system. For example, a product model created in the product design phase often comprises such details as materials and inner structure. However, when visualising the product in VR systems the inner structure becomes redundant as it would require extra computing power or even affect general user experience.

The user-experience-related issues of XR systems are also reported as being pivotal to XR integration into manufacturing (Andreas et al., 2007; Lin et al., 2017; Ho et al., 2018). While advancements in XR technologies bring promising features, they also entail a new medium for users to interact with computer systems. In XR systems, digital content is presented to users through head-mounted displays (HMD). 3D-trackable controllers and motion sensors replace the conventional mouse and keyboard interfaces. The ergonomic and usability aspects associated with these new mediums may make for a steep learning curve, or even hinder the wide use of such systems.

In short, this challenge requires multidisciplinary expertise to join forces and pave the way for successful integration of XR technologies into a manufacturing context. There are currently no clear guidelines or path available for industry to resolve these issues.

1.3 PURPOSE, AIM AND RESEARCH QUESTIONS

The purpose of this thesis is to contribute to the knowledge of XR technology integration into manufacturing and help manufacturing industry benefit from the latest advancements in XR technologies. The vision for digitalisation and Industry 4.0 makes the importance of, and potential for, integrating XR systems into manufacturing obvious to decision-makers. However, existing knowledge offers no clarity on how to ensure successful integration between already complex manufacturing activities and newly matured XR technologies. This thesis therefore aims to bridge this gap through multiple empirical studies. The following three research questions (RQ) are thus drawn:

RQ1: *What are the critical factors when integrating extended reality (XR) systems into the manufacturing industry?*

The first RQ addresses the obstacles which may prevent industrial adoption of XR technologies. It highlights those areas in which extra effort is needed when considering implementing such systems into the manufacturing context.

RQ2: *What are the effects of extended reality (XR) systems on manufacturing activities?*

The second RQ focuses on the implications of introducing XR systems into the manufacturing context. It highlights the possible consequences, in terms of the advantages gained through XR systems and new problems arising from them.

RQ3: *How might extended reality (XR) systems be implemented so that they fit different manufacturing activities?*

The third RQ is about the development of a general framework to guide the process of XR integration into manufacturing and ensure its success by addressing the identified critical factors and potential outcomes.

1.4 DELIMITATION

The scope of this thesis is limited to integrating XR technologies into the manufacturing context. Hence, it focuses on those manufacturing areas which would potentially benefit from XR technology and on ensuring a smooth process of applying XR technologies within the intended areas. It therefore has the following delimitations:

- the research is not about developing new XR technologies but about applying existing ones within suitable areas of manufacturing;
- the studies of manufacturing activities in this research are limited to operator support for assembly and maintenance, training, product design and factory layout planning;
- the industrial partners involved in this research are all Swedish-based multinational manufacturing companies with factory plants in more than one country.

1.5 THESIS STRUCTURE

This thesis comprises six chapters. The content of each chapter is 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 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. Results and synthesis	This chapter synthesises the results of the appended papers and provides answers to the research questions.
5. 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.
6. Conclusion	This chapter concludes the thesis by describing the answers to the three research questions.

2

FRAME OF REFERENCE

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

2.1 EXTENDED REALITY SYSTEMS

2.1.1 Overview (virtuality continuum)

The concept of enhancing human perception through computer-mediated reality dates back to the 1960s (Sutherland, 1968). Over the years, this evolved into different subsets, resulting in different terminologies which may be confusing for many. In this paper, XR is used as an umbrella term, representing all computer-mediated reality technologies which merge the physical and virtual worlds to provide an enhanced experience.

It is important to distinguish the different types of XR systems so that the right decisions may be made for any specific manufacturing applications (Fast-Berglund et al., 2018). A widely adopted approach is the reality-virtuality continuum, whereas real-world environment and virtual environment are at either end (Milgram et al., 1995). As shown in Figure. 1, the level of virtuality increases from left to right, with augmented reality (AR), mixed reality (MR) and then virtual reality (VR).

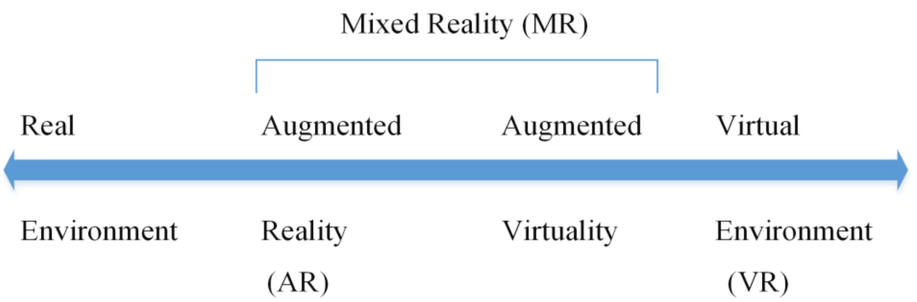

Figure 1. Relationship between the extended technologies and the environment.

Definition

The most widely accepted definition of AR was proposed by Azuma in his 1997 survey paper. According to Azuma, AR must have the following three characteristics:

- combining real and virtual;
- interactive in real time;
- registered in 3D.

In AR systems, digital content such as information and objects are overlaid onto the real world. This means users may still see and interact with the surrounding environment while receiving an enhanced experience with digital details such as text descriptions, images and animated illustrations. Users are provided with an enhanced experience through either wearable devices like smart glasses or handheld ones like smartphones. The IKEA Place app is a typical example of an AR application; it allows customers to visualise their chosen product overlaid onto their living space through a smartphone.

2.1.2 Mixed reality systems

Definition

Mixed reality may be defined as applications in which "real world and virtual world objects are presented together within a single display, that is, anywhere between the extrema of the virtuality continuum" (Milgram and Kishino, 1994).

MR systems go one step beyond AR because virtual objects are not only overlaid onto the real world but users may also interact with them as though they were real objects. Achieving an MR experience requires a headset equipped with an integrated computer, translucent glass, and sensor. The real-world environment is usually mapped in real time by the integrated sensors, so that virtual objects may interact with the actual environment and be manipulated by users. In a sense, MR is a more immersive and interactive type of AR. A famous example of MR headset is the Microsoft HoloLens found in many MR applications.

2.1.3 Virtual reality systems

Definition

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). Previous studies have drawn various definitions of VR which are essentially identical, even though the descriptions vary. Some key components of VR may be identified: computer-generated 3D environment, multi-sensory, real-time interactive and viewer-centred. These features ensure the system may 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 which 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.

The VR system sits at the right-hand end of a reality-virtuality continuum consisting of entirely computer-generated content. Users are fully immersed in the virtual environment and cannot see or interact with the real-world environment. The full immersion and high level of presence in VR systems give great flexibility when playing what-if scenarios. There are three typical setups for VR systems: 1) a standalone headset which provides the virtual experience through a combination of a smartphone with either a cardboard or integrated solution; 2)

CAVE (Cave Automatic Virtual Environment), another setup with multiple large projection screens as the walls and floor of a room, with users fully immersed; and 3) a head-mounted display (HMD) connected to a standalone computer. This setup has become dominant in recent years as it is increasingly affordable and offers a great VR experience.

2.1.4 Contemporary hardware and software

Hardware

Over the years, numerous XR devices have been developed. These are becoming ever more powerful yet smaller and easier to use. Figure 2 shows a selection of widely-used models, according to the types of XR to which they belong.

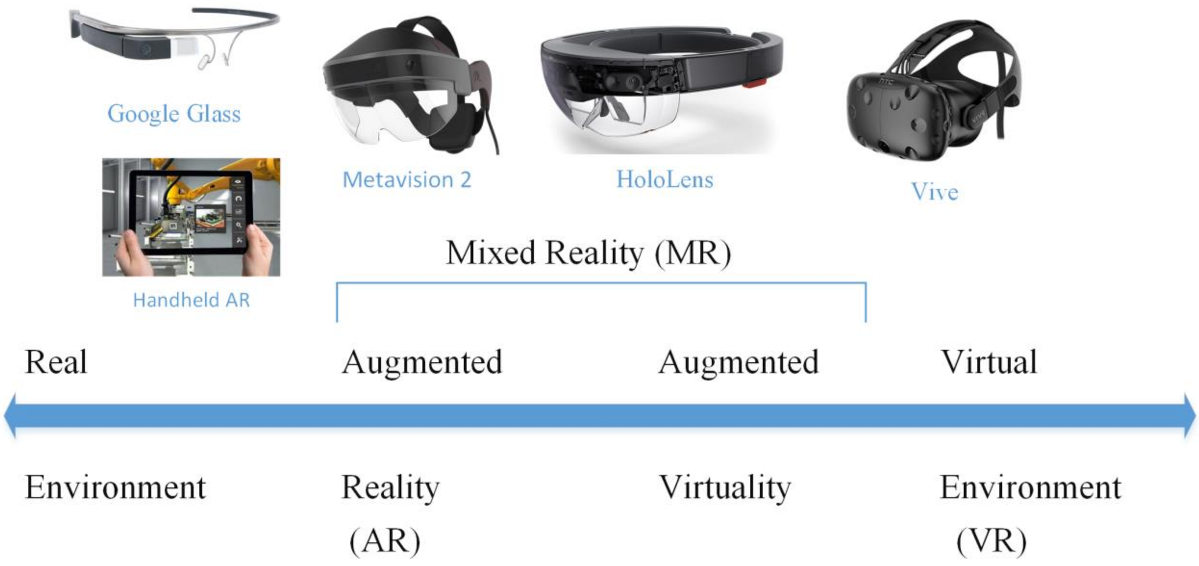

Figure 2. A selection of typical XR devices relative to the reality-virtuality continuum.

The XR devices vary not only in appearance but also according to the technological characteristics associated with them. Some important parameters include weight, operating mode, field of view (FOV) and frames per second (FPS).

These parameters interact with each other and affect the overall user experience. The weight of a device is a major factor affecting ergonomic issues.

The operating mode relates to whether the device is a standalone system or needs connecting to an external computer. Connection to computers varies depending on whether the connection is wired or wireless. The different combination of these parameters determines the appropriateness of an XR device for a given manufacturing problem.

The FOV parameter of a screen defines the extent of the visible area at any given moment. It directly affects the amount of virtual information which may be rendered. Human eyes have a binocular FOV of around 114 degrees horizontally (Howard and Rogers, 1996). Ideally, screens used in XR systems will have a similar FOV so that users may have a seamless experience with all important information properly displayed. However, the currently available screens have varying FOVs. Normally, AR and VR devices will have much smaller FOVs (30-60 degrees), meaning that limited virtual content may be presented at any given time. This has proved problematic when rendering large virtual objects. However, as the real-world environment is not excluded from the AR or MR systems, the limited screen view would not affect a user's perception provided the virtual content is adapted to the proper size.

Today's VR headsets have a wider FOV (90-110 degrees) and some advanced models even claim 200 degrees, which is greater than a human's natural FOV. Since users are fully immersed in digital content, the FOV becomes more important in terms of user experience. Headsets with smaller FOVs proved distracting to users, with their noticeable "tunnel vision effect".

FPS is the frequency at which consecutive frames of a moving image appear on a screen (Howard and Rogers, 1996). A higher FPS means smoother motion for the content. Like FOV, this parameter is more important in VR systems than AR or MR ones. While 30-60 FPS would be enough for AR or MR systems, the ideal for VR systems is 90 FPS. Because users are immersed in content that is completely computer-generated, lower FPS might result in motion jitter, causing motion sickness in users. However, it is worth noting that FPS is determined not only by the hardware but also the software. Thus, it is important to fine-tune virtual scenes during development and achieve the desired FPS.

Software

The XR systems used in manufacturing are developed using various pieces of software. These may be categorised into two major approaches: 1) open development platform and 2) extensions of established commercial software. An open development platform has the advantage of a fully controlled development process which can be tailored to individual needs. However, it requires software engineering expertise. Established commercial software used in current manufacturing also expands support for XR features. Thus, existing users can create a seamless XR experience without much effort. However, such software offers only limited freedom to explore new XR features, as it depends on updates from the software providers.

Of the different open platforms which support XR development, Unity3D[1] and Unreal Engine[2] are the two dominant ones. Both started in the gaming industry but, in recent years, have expanded into use by other industries. The large and vibrant community on these platforms has provided rapidly evolving plugins which the manufacturing industry can quickly adopt into its customised XR development. While Unity3D has established itself in the manufacturing field by collaborating with leading manufacturers around the world, Unreal Engine is renowned for the relative ease with which it generates photorealistic visualisations. A keyword search in Scopus[3] shows that the number of publications using Unity3D to develop XR applications surged from only two in 2008 to 611 in 2019. Open platforms are playing an increasingly significant role in XR development.

On the established commercial side, as XR technology becomes ever more mature, garnering increased attention, more and more commercial software already in use within manufacturing is expanding its support into various XR features. Plant Simulation from Siemens, with its extended VR support for visualising and interacting with simulation models, has been reported as facilitating analysis of assembly line design (Sujová et al., 2018) and steam turbine maintenance training (Zhou et al., 2020). Thanks to its realistic visualisation of product design in VR (Stylidis et al., 2019), VRED from Autodesk is used to boost the perceived quality of product design. The VR feature rolled out in the latest version of Robot

[1] https://unity.com/
[2] https://www.unrealengine.com/
[3] https://shorturl.at/txFNU

Studio from ABB helped create better workplace stations with robotic systems (Holubek et al., 2014). Vuforia Studio enabled the rapid development of AR applications for operator support and training (Luo et al., 2018; Kascak et al., 2019). These are a few examples of XR applications reportedly developed using established commercial software. While this route lacks the freedom for greater tailoring and customisation, it saves on the time and cost of (re-)creating common functions, whilst facilitating XR integration within the manufacturing industry.

2.2 HISTORY AND TRENDS OF EXTENDED REALITY IN MANUFACTURING

In 1968, Ivan Sutherland demonstrated the first VR system with its head-mounted display (HMD) giving the user a stereoscopic 3D view. This was slaved to a sensing device which tracked the user's head movements (Sutherland, 1968). Ever since that time, many studies have followed the same path of exploring potential use cases for such computer-mediated reality technologies. Due to the hardware and software constraints at the time, Sutherland's invention did not result in many promising applications. Then, in the late 1990s, powerful computers and software became widely affordable.

The following paragraphs will go through key studies on XR applications in manufacturing, reported post-1999. By summarising these previous studies, the intention is to position this thesis and provide context for the research activities conducted within it.

Factory layout planning (FLP) is one reported application area which may be greatly improved by the introduction of XR technologies. In 1999, an immersive VR approach to planning and implementing manufacturing cells was proposed. The aim was to reduce the required skill level with the visual and interaction capabilities of VR (Korves and Loftus, 1999). Turbulence within manufacturing requires planned changes and VR was reported to have been used in factories' participative planning of continuous improvement processes (CPI) (Westkämper and Briel, 2001). Duffy et al. (2003) designed an internet-based VR system to test the influence of modifications to the virtual environment (lighting, sound and so on) on hazard perception during an FLP process. In a similar study, Ng et al. (2012) demonstrated the potential applications of VR in improving FLP in terms of hazard and risk perception, safe waiting time and maximum reach of robot arms. Okulicz (2004) developed a VR-based manufacturing and layout planning system which focused on evaluating the ergonomics and accumulated loads for operators. Aurich et al. (2009) further developed their CIP workshop for FLP by integrating VR technology and proposing a VR-based CIP workshop. They demonstrated that 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 in a 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 involving dynamic components, plus collaborative VR visualisation between geographically distributed users. An AR-based hybrid approach was developed to facilitate onsite factory layout planning and evaluation in real time (Jiang, Ong and Nee, 2014). Thus, users are fed an augmented visualisation of the factory with candidate equipment to be laid out and corresponding decision-making support, based on the geometric data, defining the criteria and constraints. VR has also been reported as being used as an interactive solution for loop layout problems. This solution reduced the gap between traditional numerical and analytical simulation results and the real situation by using an enhanced human-machine interface (Phoon et al., 2017).

Many studies have been devoted to the use of XR for improving assembly. Back in the late 1990s, a VR system was developed to help experienced assembly operators generate downstream assembly plans (Ritchie et al., 1999). This reportedly shortened the product innovation cycle and captured the assembly experience early in the design process. This VR-based interactive approach to assembly planning was later reported to have the edge over traditional approaches to improving overall performance in assembly planning, concerning such aspects as handling difficulty, excessive reorientation and dissimilarity of assembly operations (Ye et al., 1999; Yuan, 2002). Similar interactive VR assembly systems with different emphases were subsequently reported. Ji et al. (2002) presented a virtual design and assembly system (VDAS) which allowed engineers to design, modify and assemble mechanical products. Yao et al. (2006) proposed the immersive virtual assembly planning and training system (I-VAPTS) for complex pump assembly processes. Peng et al. (2008) further improved on this via a hybrid method using rule-based reasoning and fuzzy comprehensive judgment to capture the user's operational intent and recognise geometric constraint, so that precise manipulation of objects by VR might be achieved. In 2009, an MR-based system combining the advantages of interactivity in VR and the strong realism of AR was reported as being used into support aircraft cabin assembly (Li et al., 2009). Haptic devices were then introduced so that VR assembly systems provided not only visual, auditory and tactile feedback but force as well (Lim, Ritchie, and Garbaya, 2014; Abidi et al., 2015). Cecil and Jones (2014) extended its use to micro-assembly and therefore proposed an Internet of Things (IoT)-based collaborative framework for electronics assembly, with the VR assembly environment playing a key role in supporting multiple collaborating users using haptic VR devices (Krishnamurthy and Cecil, 2018; Cecil et al., 2019). At the same time, studies were reported on assessing the performance of VR assembly training, showing it to be risk-free when used in potentially dangerous assembly tasks (Ho et al., 2018), as well as effective, efficient and with fewer errors (Abidi et al., 2019).

In the area of product development, various studies were reported as incorporating XR technologies intended to offer improvement. The initial emphasis was on easing product designers' tasks through VR-enabled rapid prototyping. Several virtual prototyping systems were developed in the early 2000s, allowing a product design concept to be visualised and evaluated with relative ease (Choi and Samavedam, 2002). Choi and Chan (2004) further improved this system with two new simulation methodologies; the dexel-based and layer-based fabrication approaches. These allowed detailed analysis of product designs, through the provision of numerical simulation results and realistic product visualisation. A CAVE-based virtual prototyping system was developed, to enhance the realistic visualisation, and the fully immersive environment was reported as enabling advanced product design and aiding substantial reductions in product development time and cost (Choi and Cheung, 2006). Thereafter, the XR applications for product design did not stop at serving product designers; a clear trend shift could be observed, with an increasing emphasis on benefitting other product development stakeholders. Design for maintainability, for example. It has been reported that a VR system which incorporates maintainability of design and evaluation early on in the product development stage, may facilitate communication, coordination, control as well as integrating product maintainability validation and improvement activities (Peng et al., 2012). Another evident change is the involvement of the end-user in product development via XR technologies. Carulli et al. (2013) proposed an approach to capture end-user opinion through a virtual prototyping system. Lin et al. (2017) demonstrated the use of VR to involve end customers in the personalisation process of smart products. Kato (2019) shown the advantage of VR systems in verifying customer perceptions of car design. Production operators also benefitted from XR integration, cf. Azizi et al. (2019), who showed that an iterative virtual design system with an ergonomic framework could be used to optimise production and reduce operator fatigue.

Studies of XR applications in manufacturing may also be found in other areas, such as telerobotics (Chen et al., 2005; Pérez et al., 2019), training (Liang, 2008; Hashemipour, Manesh and Bal, 2008; Dado et al., 2018) and simulation (Mujber et al., 2004; Dangelmaier et al., 2005; Jönsson et al., 2005; Jun et al., 2006; Zhou et al., 2011; Al-ahmari et al., 2016; Turner et al., 2016; Havard et al., 2019). These studies covered almost every area relating to manufacturing. The advantages of such applications are clear and would benefit manufacturing companies on the road to the realising the Industry 4.0 vision.

3

RESEARCH APPROACH

This chapter describes the structure of the research by explaining its 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 for conducting research. It is based on three interconnected components, as illustrated in Figure 3: philosophy, research design and research methods (Creswell, 2013). When planning research, it is therefore important to think through: a) the philosophical worldview behind any studies, b) the research design relevant to that worldview and c) the specific methods which translate into a practical approach.

The following sections explain the planning of this research, relative to these three components.

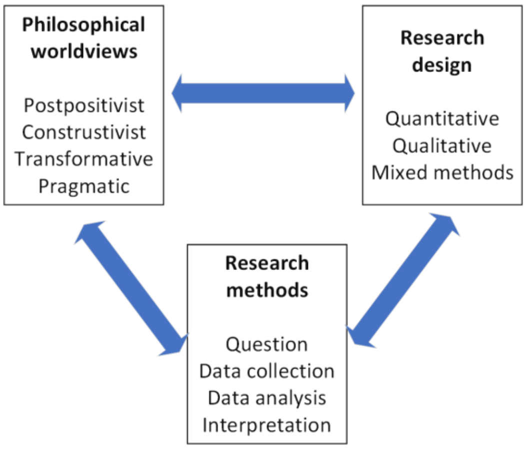

Figure 3. Interconnection of worldview, design and research methods (Creswell, 2013).

3.1 PHILOSOPHICAL WORLDVIEW

The philosophical element embodies the researcher's worldview, understood as "a basic set of beliefs that guide action" (Creswell, 2013). It provides a general philosophical orientation for research work. According to Creswell and Clark (2011), there are essentially four possible worldviews which may 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) (Guba and Lincoln, 2000; Creswell, 2009). Different research problems call for different worldviews.

This thesis deals with problems arising in a manufacturing context. Manufacturing systems are known for their complex environments, in which various interconnected entities such as humans, machines, materials and systems interact with each other. The focus of this thesis is on facilitating the integration of XR technology into manufacturing. After considering the applied science nature of the research problem and the various worldviews' characteristics, pragmatism was found most suitable and was applied throughout this research.

Pragmatism is a set of ideas articulated by many scholars, such as Cherryholmes (1992). 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 data collection methods to inform the problems being examined in the study. Thus, pragmatism is pluralistic and orientated 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 RESEARCH DESIGN

Bryman and Bell (2011) define a research design as something which "represents the structure that guides the execution of a research method and the analysis of subsequent data". In general, quantitative research design involves collecting and analysing numbers. Its broad aim is to achieve breadth. Qualitative research design, by contrast, emphasises the collection and analysis of words, with the broad aim of achieving depth (Onwuegbuzie and Johnson, 2006). These terms represent different ends of a continuum (Newman and Benz, 1998), in the middle of which lies the mixed-methods design. This kind of design uses a combination of quantitative and qualitative methods to gain deeper understanding of a phenomenon (Östlund et al., 2011; Zohrabi, 2013).

Thus, eleven empirical case studies using mixed-methods research design were conducted in this research. The studies were carried out in sequence and comprise the basis of the four appended papers. Each case, with their differing focuses, helped answer the three research questions. Each empirical study represents one iteration of the systematic empirical research approach inspired by Flynn et al. (1990), as shown in Figure 4. The incremental results obtained through each case further refined the next iteration and ultimately provide guidelines for answering the RQs.

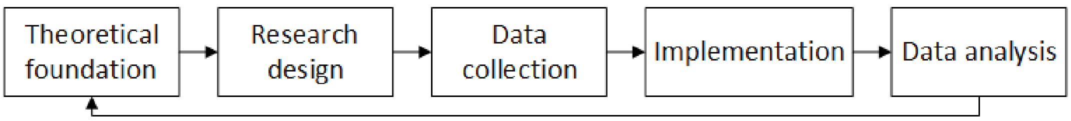

Figure 4. Iterations of systematic approach of empirical research, inspired by (Flynn et al., 1990).

A summary of the eleven empirical cases appears in Table 2. It shows the industries covered, the application areas, the XR technology types and the connections to the appended papers.

Table 2. Summary of the eleven cases.

	Industry	*XR technology*	*Application area*	
Case 1	Testbed facility	VR	Assembly	Paper I
Case 2	Aerospace	VR	Factory layout planning	
Case 3	Truck production	VR	Factory layout planning	Paper II
Case 4	Snus production	VR	Factory layout planning	
Case 5	Snus production	AR	Maintenance support	
Case 6	Drone factory testbed	AR&MR	Assembly support	
Case 7	Ventilation production	MR	Logistics/order-picking	Paper III
Case 8	Drone factory testbed	VR	Assembly training	
Case 9	Truck production	VR	Design for maintainability	
Case 10	Car production	VR	Virtual manufacturing	
Case 11	Car production	VR	Product design review	Paper IV

The research started with a case relating to VR-based training for assembly operations at a testbed facility. It compared the VR-based training with five conventional approaches. Objective measurements (such as completion time) and subjective measurements (of participants' experiences) were recorded, mainly to address RQ1 and RQ2. This is reported in Paper I.

Thereafter, three cases (Cases 2-4) were conducted, focusing on using VR in FLP activities. In Case 2, the idea of hybrid modelling a VR environment incorporating point cloud data and existing CAD data for FLP was implemented using a demo application which the stakeholders then tested. Qualitative feedback was collected using semi-structured interviews. In Case 3, the knowledge and theory were then refined and further developed based on the results of Case 2. A second demo application was developed and evaluated. Quantitative and qualitative measures were taken into account, using a scale rating and open-ended questionnaires. Supplemented by Case 3, which further explored immersive VR for FLP using the hybrid modelling approach, a general guideline for the effective and systematic use of VR technology in FLP was extracted and reported in Paper II. This mainly contributed to answering RQ3 but also touched upon the first two RQs.

Subsequently, six cases (Cases 5-10) covering a wide range of application areas in different manufacturing industries were studied by implementing the different XR technologies. The same mixed methods were applied and quantitative and qualitative data were collected and analysed, thus providing answers to RQ1 and RQ2. More importantly, the results were synthesised and became the foundation of the proposed frameworks for XR development in manufacturing. These frameworks were validated through external sources from seven previously published papers, plus one internal evaluation in Case 11. These are reported in Paper III.

Case 11 relates to the internal evaluation of the proposed XR development framework, in which a multi-user VR system for product design review was developed by following the steps described in the framework. The system's outcome was evaluated in a demonstration workshop at the case company and feedback on the developed VR system was obtained through questionnaires and semi-structured interviews. This study is reported in Paper IV.

3.3 RESEARCH METHODS

Research methods are all the methods or techniques used to conduct research (Kothari, 2004). The mixed-methods research approach, chosen for this thesis, involves combining data collection methods and selecting the most appropriate in each case. A pragmatic worldview enables the results to be strengthened by combining and converging data from the various data collection methods. The following sections discuss a variety of data collection and data analysis methods, with descriptions of how these methods were applied in this research.

3.3.1 Data collection methods

Literature review

Previous studies about developing and evaluating XR systems in the manufacturing context were researched and form the basis of this thesis. Initially, a five-stage, systematic literature review was conducted for XR technology usage in the production field (Rutter and Francis, 2010). This included defining, searching, selecting, analysing and presenting. Journal publications and conference proceedings from the late 1990s to 2020 were selected and included. The articles were analysed and categorised according to the types of XR technologies and application areas in production. As Creswell and Clark (2011) pointed out, a literature review may accomplish several purposes. The results allowed this author to identify initial research gaps and barriers. This narrowed down the research scope to three feasible research questions. The literature reviews were used as benchmarks for comparing the results with the findings of other researchers.

Interviews and questionnaire

Interviews may be designed in various forms, depending on their purpose. They may also be divided into three distinct types: structured, semi-structured and unstructured (Bryman and Bell, 2011). Structured interviews follow a fixed sequence, using the same questions in each interview session (Williamson, 2002). Semi-structured interviews have a predefined list of questions, but allow the interviewer to ask follow-up questions. Unstructured interviews do not follow any predefined structure or questions (Williamson, 2002; DiCicco‐Bloom and Crabtree, 2006), with the questions generated from the previous answer. Questionnaires are useful 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 closed-ended questions to allow quantification and ensure questions are intelligible (Bryman and Bell, 2011). Among the different approaches of questionnaire surveys, the system usability scale (SUS) developed by Brooke (1996) is a widely-used, standardised questionnaire for assessing perceived usability. The self-assessment manikin (SAM) questionnaire introduced by Bakker et al. (2014) focuses on measuring the subjective emotions of users.

In this thesis, semi-structured interviews and closed-ended, scale-rating questionnaires (based on SUS and SAM questionnaire principles) were used in each empirical study. Once the participants had tested the proposed XR systems, there followed a semi-structured interview and scale-rating to get feedback and triangulate the results. The developed XR applications served as a stimulus to help focus on the specific product or ideas of interest to the research (Dagman et al., 2010). The conversational nature of this approach made respondents feel more comfortable. The research gained richer information due to this format.

Observations

Participant observation is a data collection method used in qualitative research. The method is used when a researcher means to collect objective data on events or situations (Kawulich, 2005; Mack et al., 2005). It allows the researcher to gain insight into context, relationships and behaviours (Mack et al., 2005) and allows them to add dimensions to, and increase understanding of, the context or phenomenon being studied. More specifically, observations may be invaluable aids in understanding the actual use of technology (Yin, 2013).

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

3.3.2 Data analysis methods

Statistical analysis

There are many statistical analysis methods which may be used in quantitative studies. These include statistical significance testing or inferential statistical tests and aspects such as the confidence interval and effect size may 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, statistical significance testing and inferential tests were also conducted for the collected scale-rating results. This allowed comparison with qualitative data, further enhancing the validity of this research.

Content analysis

This concerns analysing the content of written or oral material (often transcribed from interviews) and is regarded as the major qualitative method for studying an overall message (Kothari, 2004). The methods used in collecting qualitative data usually result in copious amounts of raw data which must be analysed (Bryman and Bell, 2011). Qualitative data analysis is about making sense of raw data; taking it apart as well as putting it back together again (Creswell, 2013). The assembled data should then be analysed to draw valid inferences for use in further research (Blessing and Chakrabarti, 2009).

To analyse the qualitative data collected in this research, semi-structured interviews were transcribed alongside observational notes. The data was analysed to generate recurring themes and categories. The converging of qualitative and quantitative results contributed to the validity and conclusions of this thesis.

3.4 RESEARCH QUALITY

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

Validity relates to the concept of result validation and is the quality of the relationship between reality and research outcome (Maxwell, 2005). It answers the question, "did the research do the right things?” It is commonly categorised as the construct of internal, external and contextual validity (Ihantola and Kihn, 2011). To ensure validity in this research, multiple cases from different companies were used in the empirical studies, to increase the external validity. At the same time, qualitative and quantitative data was collected to validate the results, thus ensuring internal validity.

Reliability is the concept of research verification and is often measured as the capability to repeat the methods used and achieve the same results in a repeat study (Flynn et al., 1990). It answers the question, “did the research do things right?” Qualitative studies have practical issues, in terms of 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 (2013). Creswell (2013) proposes strategies such as checking transcripts and crosschecking codes, to ensure reliability within mixed-methods research. The reliability of this research is assured by the detailed and structured documentation of the procedures for each study and the data collected (Yin, 2013; Williamson, 2002).

4

RESULTS AND SYNTHESIS

This chapter highlights the findings of the whole study, with the emphasis on providing answers to the research questions. More detailed results may be found in the appended papers.

4.1 SUMMARY OF APPENDED PAPERS

A total of eleven empirical case studies were conducted during this research. Each empirical case addressed a particular manufacturing activity with the potential to be improved by integrating a certain type of XR technology. In all cases, a single functioning XR system was developed and tested, to synthesise the results of the research questions. Table 3 illustrates the contribution of the appended papers and their relationship to the research questions.

Table 3. Appended papers and cases, related to the research questions.

	PAPER I	PAPER II	PAPER III	PAPER IV
RQ1	X	x	x	X
RQ2	X	x		X
RQ3	x	X	X	x
	Case 1	Case 2-4	Case 5-10	Case 11

4.1.1 Paper I

In this paper, assembly training outcomes through a VR system were compared with four other approaches (in-person teaching, text-and-picture instruction, video instruction and remote guidance), as shown in Figure 5. The aim was to improve operator support through better training results and enable training to be conducted in a more flexible setup than conventional approaches (which require trainer and trainee to be in the same place at the same time).

Face-to-face	Text picture	Remote guidance	Movie-based	VR-based
15 participants	15 participants	8 participants	8 participants	11 participants

Figure 5. The five assembly training approaches tested in this study.

For assembly training, a 21-component LEGO gearbox was developed and used as the product. Eleven participants joined the test for the VR-based training group. They undertook two rounds of training in the VR environment and assembled the real LEGO gearbox three times. The completion time and rate were recorded, plus self-reported emotions based on the SAM questionnaire.

The completion time for each assembly was measured in seconds, from the first move to placement of the last gearbox component.

Figure 6 illustrates the average times for the five assemblies in all five groups. It is clear that the first assembly in all five scenarios took the longest. However, the time shortened in later attempts. The movie-based group took the longest on their first assembly (414.9s) but gradually reduced their time until it was 83.5s on their last attempt. All groups managed to complete the fifth assembly in around 80s. The VR-based group took 130.7s and 140.9s on their first virtual and real assemblies. The switch from VR environment to real-world was not smooth, with the completion time increasing from 87.2s to 140.9s during the transition. However, after one round of real-world assembly, the completion times were shortened to levels resembling the other groups.

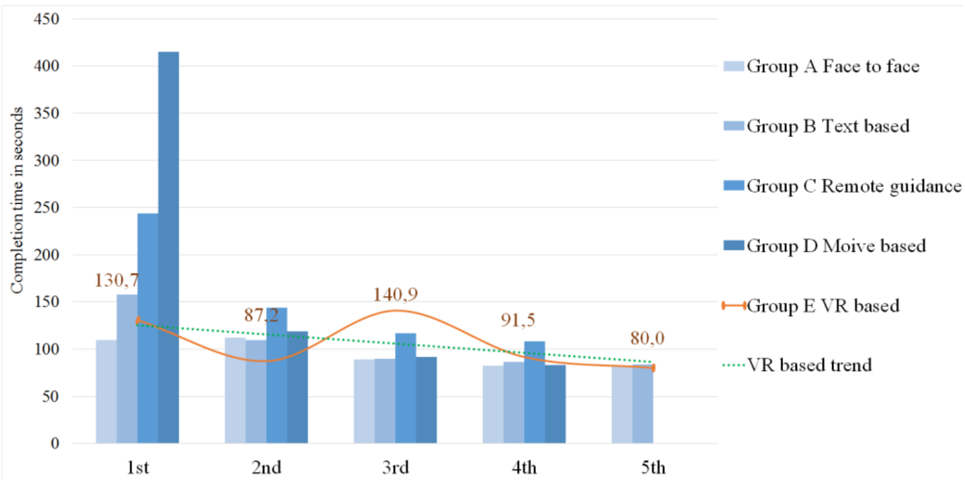

Figure 6. Average completion time for the five groups.

Regarding the quality of assembly, the test subjects were evaluated to see whether they had correctly assembled each LEGO component in its designated position, to form the complete gearbox. This is represented by the average completion rate which is the percentage of correctly placed components. The results from the five groups are compared and shown in Figure 7. The remote guidance and movie-based groups achieved the highest assembly quality, with a 100% completion rate. The text-based group showed the lowest assembly quality in the first two rounds but improved to the same level as other groups in the later rounds. For the VR-based group, the assembly quality was better than the average for the other groups. It is also interesting to note that the assembly quality dipped to 81.8% in the transition from virtual to real environment but climbed to 100% again right after the first physical assembly.

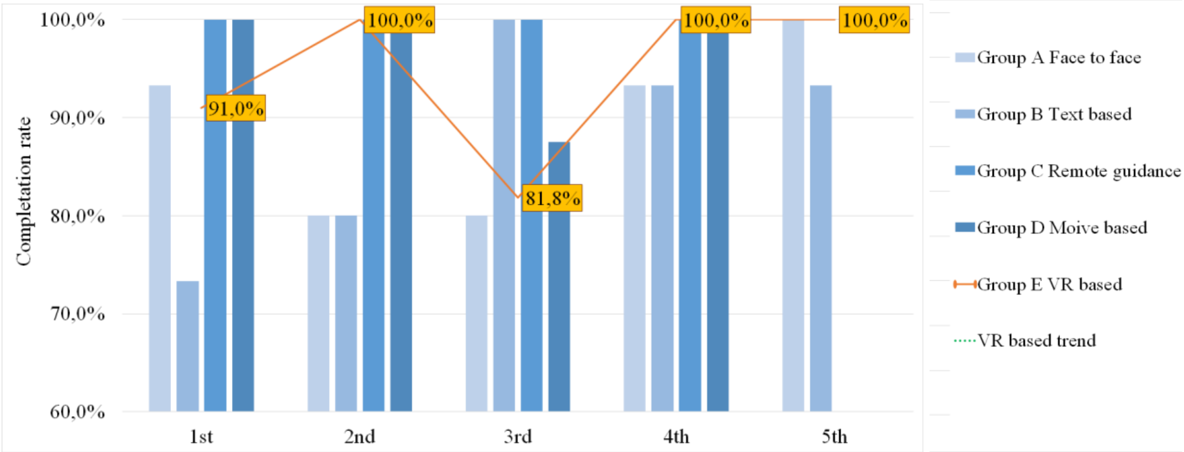

Figure 7. Average completion rate for the five groups within the five test rounds.

The result of the SAM questionnaire is shown in Table 4, with the average change in absolute values for the valence, arousal and dominance of all participants before and after each assembly round. The value change represents the fact emotional changes had occurred while the absolute values show the extent to which they changed. The face-to-face training had the greatest influence on participants' valence and dominance, while arousal changed the most in the movie-based group. The VR-based training had medium impact on the self-assessed emotions, as compared with the other groups.

Table 4. Average change in absolute values for the groups, from the SAM questionnaire.

Groups	*Valence*	*Arousal*	*Dominance*
Face-to-face	0.86	1.46	1.26
Text-based	0.33	1.13	0.60
Remote guidance	0.50	1.13	1.38
Movie-based	0.63	2.00	0.88
VR-based	0.64	1.36	1.00

4.1.2 Paper II

This paper focused on the factory layout planning (FLP) process; when changes are about to be made due to the introduction of new products, machines or production processes. A conceptual framework of virtual factory modelling was presented, based on three industrial case studies. These adopted a hybrid approach to developing a VR environment for FLP, combining point cloud data generated from a 3D laser scanner with existing CAD. It aimed to provide a realistic and intuitive virtual environment for all stakeholders. It allowed them to actively engage and contribute to the decision-making for the new layout. It also allowed design errors to be detected early in the process, thus increasing user acceptance of the new layout. The VR systems developed for the three industrial cases are illustrated in Figure 8.

Figure 8. VR environment developed for the three cases.

The developed VR systems were tested and evaluated at the case companies by the stakeholders. The evaluation consisted of a closed-ended scale rating questionnaire with statements relating to the usefulness of the VR systems in the FLP process, plus follow-up interviews with open-ended questions.

A total of 49 participants answered using a four-level Likert scale (strongly disagree, disagree, agree and strongly agree) and the results are summarised in Table 5. There were 32 valid answers for the correlation statistics. The reliability statistics (Cronbach alpha) were 0.875 (N = 4) for this study. The mean values for all four statements were high, indicating that the VR system for FLP is seen as a mature and easy-to-use technology. The majority of participants were positive about the potential benefits of this VR approach and wanted to share the system or recommend it for wider usage. Because the tested VR systems were in the prototype phase, user experience-related ratings were not as good as the potential benefits.

Table 5. Descriptive statistics of the scale-rating result.

Statements	*Means*	*Standard deviation*	*N*
Easy to use	3.45	0.597	40
Clear benefit	3.55	0.552	40
Useful to my job	3.16	0.628	32
Recommend to others	3.58	0.502	33

The correlations between the different statements were analysed and are illustrated in Table 6. This shows the same pattern as for the mean values. The strongest and most significant correlation is between easy to use and recommend to others (0.939) (meaning that the participants thought the VR environment for FLP was easy to use) but also that they would recommend the tools to others. The participants could also see a clear benefit with the tools and the ease of using them (0.863). There were moderate or weak correlations between “useful to my job” and the other statements. This may be due to the fact there were few examples of successful XR integration in manufacturing at the time.

The open-ended questionnaire feedback pointed to some recurring themes, such as the VR environment being easy to navigate and it being easy to visualise the planned layout. It also effectively created the basis for stakeholders to engage in constructive discussion on the planned layout. The immersive visualisation and interaction in the virtual model allowed stakeholders from different backgrounds to gain a coherent understanding of the planned changes.

Table 6. Correlation analysis of the four statements.

		Easy to use	Clear benefit	Useful to my job	Recommend
Easy to use	Pearson correlation	1	0.863[a]	0.509[a]	0.939[a]
	Sig. (2-tailed)	–	0.000	0.003	0.000
Clear benefit	Pearson correlation	0.863[a]	1	0.496[a]	0.768[a]
	Sig. (2-tailed)	0.000	–	0.004	0.000
Useful to my job	Pearson correlation	0.509[a]	0.496[a]	1	0.518[a]
	Sig. (2-tailed)	0.003	0.004	–	0.002
Recommend	Pearson correlation	0.939[a]	0.768[a]	0.518[a]	1
	Sig. (2-tailed)	0.000	0.004	0.002	–

[a]Correlation is significant at the 0.01 level (2-tailed)

4.1.3 Paper III

This paper covers the development of a user-centred, extended reality system development framework. It is based on six real-world cases in which different types of XR technologies were applied, in support of a particular manufacturing-related activity. The six cases involved four companies and one testbed facility and the XR technologies used in them covered AR, MR and VR. The manufacturing applications spanned from product design, logistics and order-picking to aftermarket product maintainability. Figure 9 illustrates the XR systems developed for the six cases and the defining characteristics of each case.

Figure 9. The six XR systems with regard to application area and types of XR.

In the moist smokeless tobacco (snus) production case, the AR-supported maintenance was studied via two iterations of development and testing.

In the first iteration, a simple toolbox maintenance task was created and tested at a nationwide maintenance fair in which 17 participants tried out the AR solution. Observations and questionnaire data showed that most participants spent an unexpectedly long period getting started with the AR device. It was also evident that switching focus from the physical world to augmented reality instructions was problematic. The AR text instructions were largely neglected because participants were overwhelmed by other appealing visuals, such as 3D objects and animations.

The second iteration of the AR system development was improved, based on the findings from the first round. The upgraded system was tested by 16 participants from the case company and the questionnaire results showed that more than 80% believed the AR system might improve current maintenance practice. They were also willing to have similar supporting systems in their future maintenance work. However, they also expressed a need for improvements to the wearable AR glass, in terms of ergonomics and tangle-free connection.

To support drone assembly using AR and MR systems, instructions based on structural and action diagrams were developed for AR tablets and wearable MR devices. Twelve participants took part in the test. They were randomly assigned to either the tablet or wearable groups and undertook their assembly tasks with appropriate support. The action diagram-based instructions were shown to result in faster assembly and greater accuracy than the structural diagram-based approach, despite the action diagram instructions taking longer to play due to the inclusion of animation. The follow-up questionnaire also showed that participants preferred animated instructions, as demonstrated for the action diagram-based approach. On average, the tablet group performed better than the wearable glass one. This correlates well with users' previous experience with these devices, as touchscreen interaction is already widely used and accepted. Users were also observably quite nervous when conducting the assembly whilst wearing AR glasses. However, if users are to have both hands free for assembly work the tablet needs mounting to a fixture on the workstation. This relatively fixed position limits the flexibility of adjustment to individual users' and may create ergonomic problems.

In a ventilation production company, an MR system based on the pick-by-vison principle was developed for warehouse order-picking tasks. Two orders consisting of 12 and 14 items were first benchmarked using existing support. Thereafter, 20 order-picks were conducted by five participants from the case company using the MR system. Each participant did the two orders twice using the MR glasses. The average completion time with MR support for order one was 38% longer than the benchmarked time. For order two, meanwhile, a much smaller difference can be found; the MR support group took 364s, as compared to 354s in the benchmark. The questionnaire results showed that participants agreed on the potential of wearing glasses to improve order-picking operations. However, they also pointed out that the usability of the MR system needed further improvement.

The fourth case in this paper was aimed at better understanding the effects of assembly training in VR which follows reality-based interaction (RBI) and approaches inspired by reality trade-offs (RTI). A VR training environment was developed for a drone assembly task, with the instruction developed using both RBI and RTI approaches. In total, 22 participants were randomly assigned to the two scenarios and conducted the training test. On average, the RBI scenario took 42% longer to complete the VR assembly training than the RTI scenario. However, after both training approaches, no significant difference was detected during the real-world assembly task which followed after the VR training. In terms of how realistically the VR training represented actual assembly, the survey results showed that the RBI scenario received a slightly higher average rating of 4.64, while RTI received 4.45. Both these values are high, given the scale of 1-5 scale, in which 1 indicated "completely different" and 5 indicated "completely the same". Another interesting finding was that prior experience with assembly work showed no obvious effect on the training outcome. Yet prior experience with VR systems has a noticeable correlation with better performance.

The VR-supported design for product maintainability was studied within a truck manufacturing company. A VR system with natural hand interaction was developed based on the requirement to provide four maintainability analysis scenarios. Nine participants from the case company carried out the product maintainability analysis and provided feedback about their experience through semi-structured interviews and a scale-rating questionnaire. All percipients believed that the VR system allowed better communication of the product concepts across different function groups, so that potential product maintenance problems could be detected early in the development process. The nature hand tracking made accessibility evaluation as easy as with a physical product. However, geometrical analysis in this VR system is difficult. It would be more efficient to simply use the conventional desktop computer system. Table 7 shows the scale-rating result of the questionnaire with regard to the subjects' experience in carrying out the maintainability analysis using the VR system, desktop software and physical product. This confirms the interview findings.

Table 7. Scale-rating result comparing maintainability analysis in VR, desktop and physical product.

	VR system	*Desktop*	*Physical product*
Realism of situation (surrounding awareness)	4	2.8	5
Understanding of product properties (size, function in context etc.)	3.9	2.6	4.7
Ability to *understand variants*' *effects on information creation*	3.8	2.9	3.8
Conduct *ergonomic analyses*	3.3	2.3	4.9
Conduct *requirement analysis*	3.7	2.6	4.9
Reliability *of* analysis *findings*	3.6	2.9	4.7
Communicate information between roles and departments	4.1	3.3	4.2
*Test and verif*ication *solutions*	3.2	2.3	4.8
Ability to identify errors	3.8	2.9	4.7

The last case in this paper concerns product design reviewing at a carmaker. The bare-hand interaction (BHI) and controller-based interaction (CBI) approaches were applied to the development of a VR system to support design review tasks. Thus, the system was tested and evaluated by 22 engineers in the case company. The data was collected, as shown in Table 8, in regard to immersion, interaction and autonomy. It therefore serves as a comparison between the different effects of these two approaches on user experience. The inclusion of hand tracking and synchronised visualisation of hand models was greatly preferred by the users. This is because it provides more realistic sensation in the VR sessions and may thus positively affect the level of immersion. However, the different details and quality of hand models being rendered seem to have no significant impact on user perception. Overall, hand interaction with virtual objects (such as basic pick-and-place actions) was found to be more complicated than using controllers. There was apparently extra difficulty using hand tracking to move large objects as the tracking sensor used in this study was mounted on the HMD, which is not as stable as the stationary sensors. The palm-coupled virtual buttons for navigation proved cumbersome for all users. This is because smooth movement requires both head (where the sensor is positioned) and hand (which points the direction of movement) need to be stable.

Table 8. Effects of bare-hand interaction and controller-based interaction on user experience.

		Bare-hand interaction	*Controller-based interaction*
Immersion		+	/
Interaction	Large objects	-	+
	Small objects	/	+
	Menu buttons	/	+
Autonomy	Navigation/teleportation	-	+
	Activity: spot-welding training		
	Activity: product design review for service tool accessibility		

4.1.4 Paper IV

This paper reported on a study which followed the framework proposed in Paper III, to integrate a VR system to support the product design review process in a globally distributed automotive manufacturer. A VR system that allows multiple users to join the same virtual product design review session from different parts of the world was developed and evaluated by the industrial partner. This system is illustrated in Figure 10.

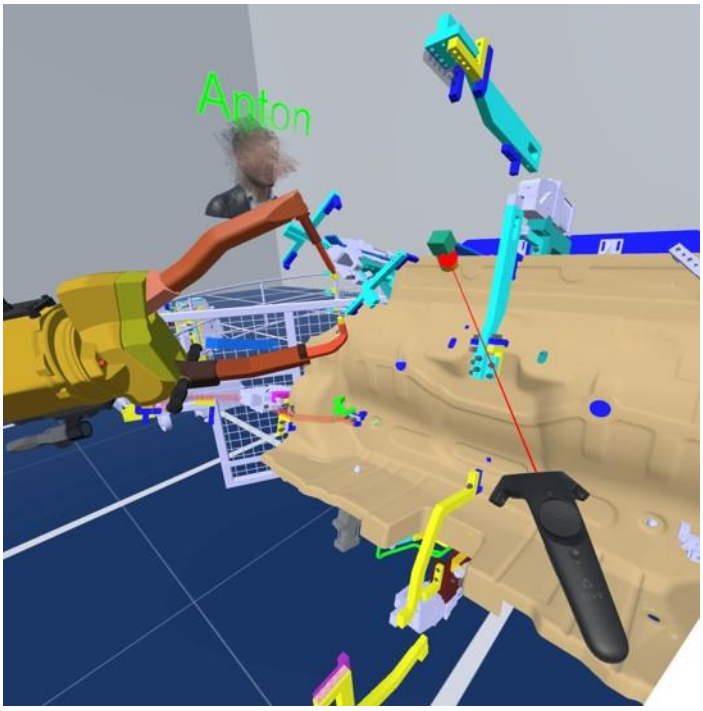

Figure 10. Multi-user VR interface for product design review.

The scale-rating questionnaire with a series of statements was rated by 22 participants based on their experience with the proposed VR system. A selection of the questionnaire's result appears in Figure 11. This shows all participants believe this type of multi-user VR system would be of great benefit to their daily work. The customised user avatars allow users to easily identify their colleagues in VR, thus increasing their feeling of being present in the virtual environment. Most participants still prefer controller interaction over the 2D GUI. However, when there is an admin role supervising the VR on-screen review session, it would be preferable to have the 2D GUI so that the admin might control the review process. When it comes to the question of whether all users should have the same functions, there are diverging views. While 10 out of 16 believe the point cloud data makes the virtual model more realistic, some questioned the need for it, especially in design review tasks which are independent of the factory environment.

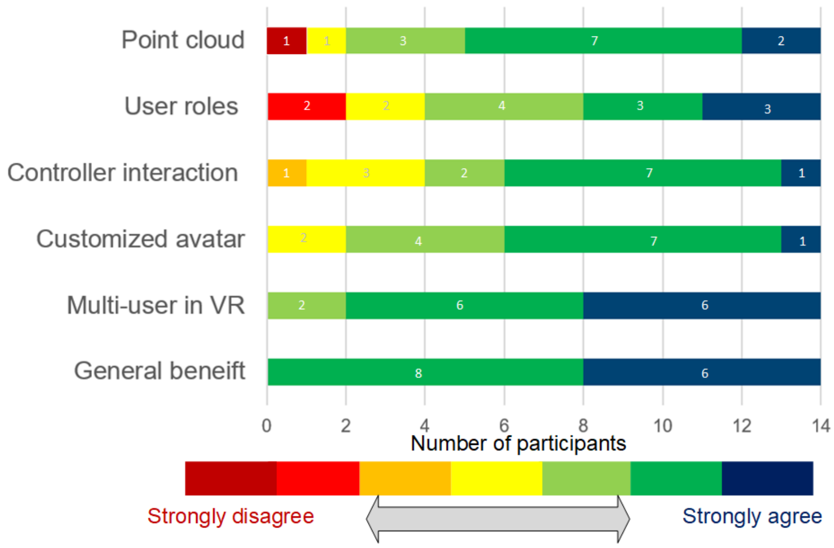

Figure 11. Questionnaire results in relation to the statements.

4.2 RESULTS IN RELATION TO RESEARCH QUESTIONS

4.2.1 Research question one

***RQ1**: What are the critical factors when integrating extended reality (XR) systems into the manufacturing industry?*

Based on the data collected in the empirical cases, the following recurring themes have been identified as critical factors which would heavily affect the outcome of XR integration into manufacturing:

- suitability of XR technology for the intended manufacturing activity
- data compatibility
- usability/user experience (UX) of the XR systems.

"Suitability" refers to whether the particular XR technology is a good match for the intended manufacturing activity. Throughout the studies, it is common for industrial partners to mix different types of XR technologies, with their associated merits and drawbacks. This is understandable when taking into account the various terminologies that have been created to introduce the different XR technologies. Especially when the XR field is developing rapidly in this decade. However, it does make selecting the right technology a challenge. It is evident from Paper III that some of the cases were not as successful as anticipated, due to poor choice of XR technologies. In Paper I, handheld controllers were used so that operators could grab and place product components. This may be further improved with bare-hand interaction, allowing it to match the actual work more precisely. Understanding the differences between the available XR technologies is the primary factor affecting the outcome of an XR integration.

The study shows data compatibility to be the next factor greatly influencing the efficiency and quality of XR integration. When integrating XR into manufacturing, various data sources need to be populated so that the XR system may fulfil its intended task. Ideally, data from existing systems should be compatible or easily reused in the XR systems. However, this is not as straightforward as one might expect. There is currently no central strategy for streamlining data across different systems. Thus, adapting a data pipeline to convert existing data to fit the intended XR system becomes an unavoidable developmental step. The time, cost and quality of the XR development depend on the effectiveness and efficiency of the chosen data pipeline.

The usability (or UX) of XR systems is another notable factor which may affect user acceptance of new technology and ultimately influence XR integration into manufacturing. This factor may be divided into two parts: 1) ergonomics and 2) user interaction design in 3D. Among all the test participants, some reported that it a relatively long session caused neck pain. Motion sickness was present in participants in the early cases, as these systems were not optimised to deliver smoothly rendered 3D visualisation. This issue is less evident in systems developed later on, as more effort was devoted to balancing system performance so it could maintain the 90 Hertz (Hz) framerate and low latency. However, the interaction design for the 3D environment of XR systems is another big challenge. There is no commonly recognised practice, as there is for desktop PC programs. Developers and users alike are new to the interaction opportunities brought by XR technologies. Therefore, a thorough tutorial on interacting with the system was given for each test, in all cases. Even so, difficulty or failure to conduct the intended tasks was still noted among the test participants.

The comprehensiveness of functions provided in the proposed XR systems was found to influence general user experience and user acceptance. Due to the duration of the research projects and the limited software development resources, all the XR systems developed in this thesis resolved only the basic requirements in their corresponding cases. Thus, they have limited functions with which to cover all the features which might be needed. For this reason, much of the negative feedback related to the fact that the proposed systems cannot fully replace the software or tools currently in use. For example, in Paper I, the VR training outcome was universally average perhaps because the ceiling effect and proposed VR system only supports fixed assembly sequences. In reality, assembly operators may have preferred sequences which differ from those presented but which complete the task well.

4.2.2 Research question two

***RQ2**: What are the effects of extended reality (XR) systems on manufacturing activities?*

The four appended papers reported the positive and negative effects of the tested XR applications. Paper I highlights the flexibility of having VR training for assembly tasks; these maintain good training quality but are unrestricted by a need to have trainer and trainee physically present together. Paper II shows how introducing a VR system into factory layout planning means users have less need for computer knowledge to grasp differences in proposed layout designs. It enables stakeholders from different backgrounds to participate in the decision-making process early in the design phase. It may, therefore, reduce the number of potential errors and help communicate the design concept across different teams, saving money and increasing user acceptance of the change. The six cases reported in Paper III cover use cases of different XR technologies applicable to maintenance, operator support in order-picking and assembly, assembly training and product design. This paper shows that intended manufacturing activities may be improved by implementing suitable XR technologies. Paper IV demonstrated the advantages of a multi-user VR system for product design review, breaking down geolocation boundaries and reducing the amount of travelling and number of physical prototypes.

The negative effects noted in these papers concern potential ergonomic issues, connected to the hardware and software of the XR system. On the hardware side, the HMD can be heavy to wear for long periods. The software side concerns the smoothness and responsiveness of the virtual content which may cause dry eyes and motion sickness. It is worth noting that individual experiences relating to ergonomics vary greatly, with one small group of test participants which was more sensitive to deviations.

4.2.3 Research question three

RQ3*: How might extended reality (XR) systems be implemented so that they fit different manufacturing activities?*

The thesis aimed to develop general guidelines which might be adopted when implementing XR solutions for a specific manufacturing activity. The empirical cases served as the basis for Papers II and III, which propose such guidelines.

In Paper II, reported a conceptual framework, as shown in Figure 12. This was specifically concerned with integrating VR into factory layout planning. Its major contribution is the hybrid approach; this processes 3D laser scans of point cloud data from the existing environment and produces CAD models, for more realistic virtual modelling of a factory layout.

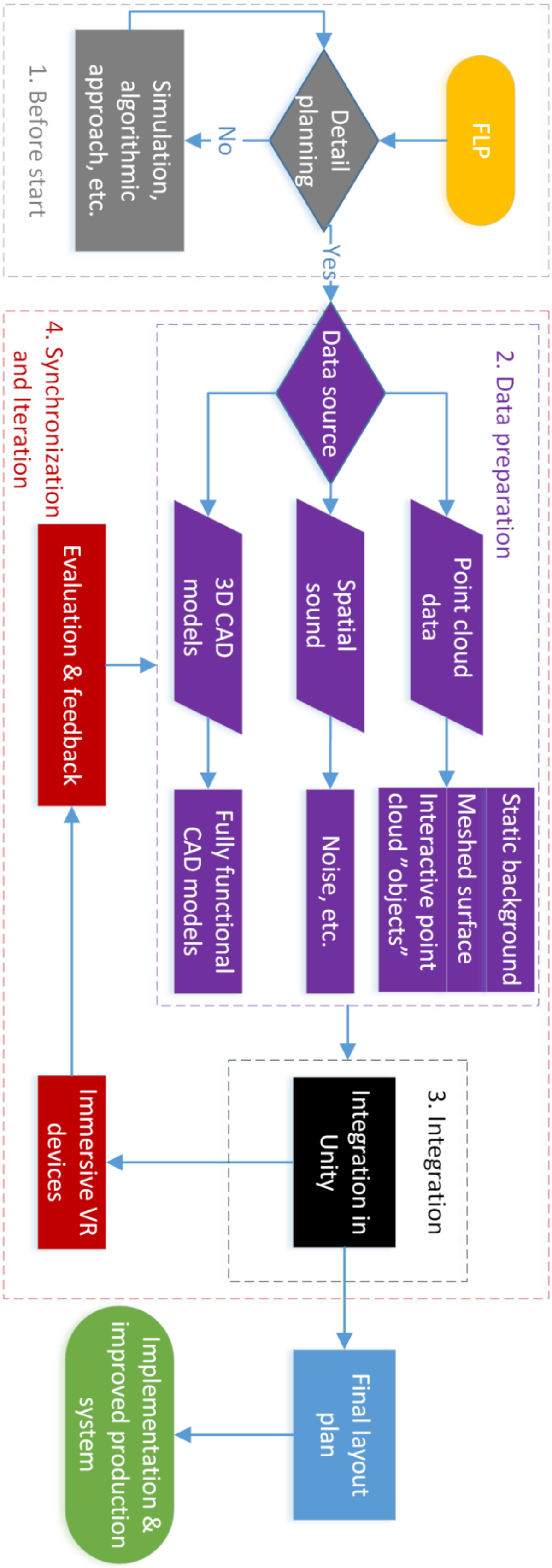

Figure 12. Conceptual framework of the guidance for hybrid virtual factory modelling.

Paper III reported on a more general framework (shown in Figure 13) for user-centred extended reality system development for the manufacturing context. It highlighted the user perspective and development iterations to produce a good match between the XR technology and manufacturing activity.

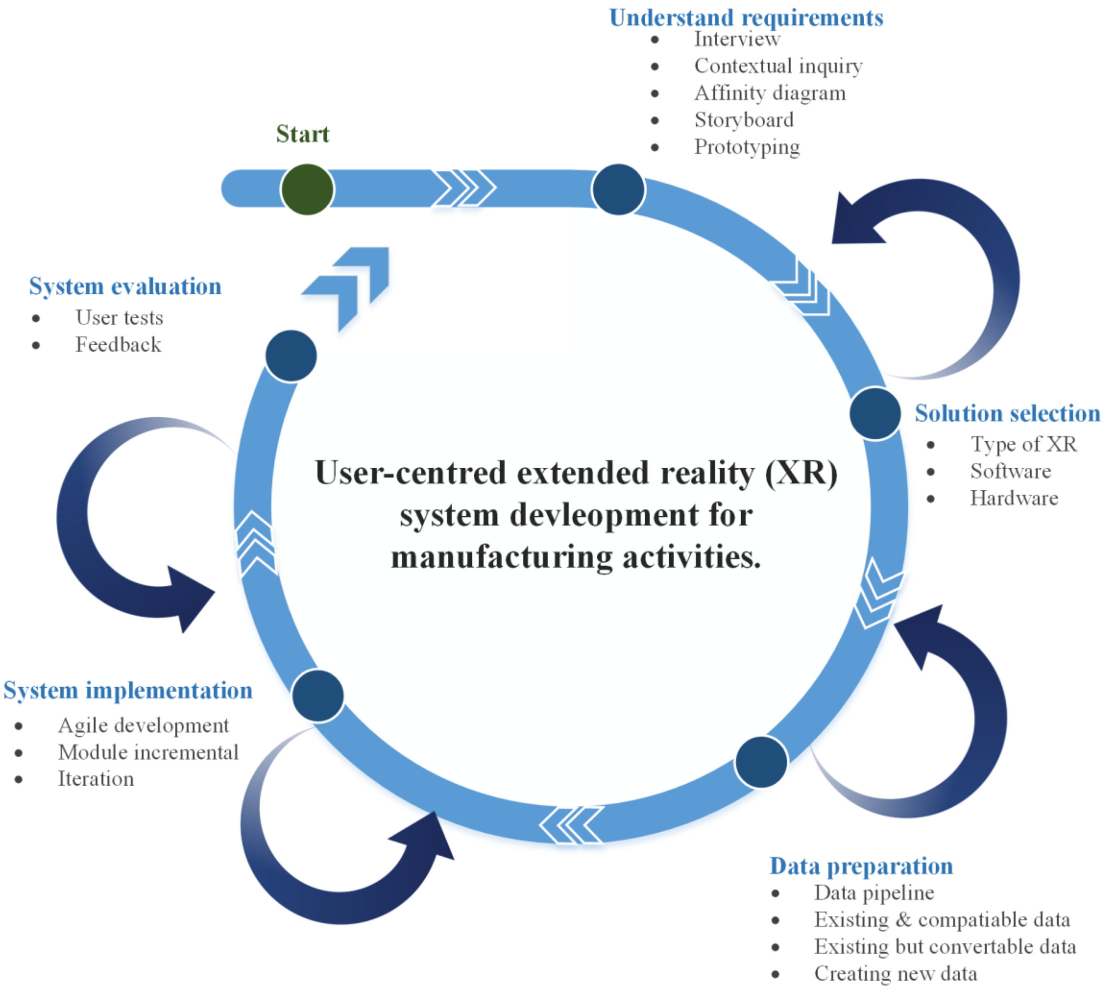

Figure 13. Framework for user-centred extended reality system development for manufacturing activities.

5

DISCUSSION

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

5.1 DISCUSSION OF THE RESULTS

***RQ1**: What are the critical factors when integrating extended reality (XR) systems into the manufacturing industry?*

This thesis has outlined four main factors which would affect the outcome of XR system integration into a manufacturing context. These are 1) the suitability of XR technology for the intended manufacturing activity, 2) data compatibility, 3) comprehensiveness of the XR systems and 4) usability/user experience (UX) of the XR systems. Crucially, this author is not claiming the identified factors are the only ones which would affect the results of XR adoption in a manufacturing context. These four factors are highlighted based on the empirical cases the author has conducted in his research.

It may seem obvious that, in any system implementation, a good match is desirable between an identified problem and its proposed solution. This is especially difficult in this case, as XR technologies are developing rapidly. As described in Section 2.1, there are various types of XR systems and, within each type, different choices of hardware and software. The features and capabilities of those solutions are evolving fast. A certain XR system which is a poor fit for a manufacturing activity, may become a perfect match the next month, or even next day, with the introduction of new hardware or software. The combined forces of multidisciplinary expertise are needed to make a good match.

The data compatibility problem (as mentioned in Section 4.2.1) plays an important role in XR system development. The goal here is to reuse existing data in XR development. However, the data was created without the XR requirements in place. For this reason, a variety of formats are used by computer-aided design software. Some need to be modified for the XR system; still others need to be re-created from scratch. In all the cases covered by this thesis, the development of proposed XR systems underwent a certain degree of data conversion. This process is time-consuming and undermines the quality of the system. It is of great importance for companies to have a central strategy for their future modelling process which takes XR requirements into account and allows unnecessary conversion processes to be avoided. In the transition process for existing but incompatible data, an effective automated data pipeline would be ideal, rather than manual conversion for each piece of data. This would reduce the time spent in preparing data and quality-assuring models.

Due to the time constraints and explorative nature of the research, the XR systems developed and tested in this thesis offer limited coverage of the functionalities. While the significant advantages of XR technologies were demonstrated in each case, they remain far from ready to replace conventional practice. The research helps highlight a possible path, highlighting the potential benefits of XR technologies. However, it provides no off-the-shelf XR systems which might be used immediately. The ideal would be rigorous XR system development based on the findings of this research. This would move things one step further from concept demonstration and towards a practical solution for use in day-to-day practice.

The usability of an XR system is another major factor which would influence the wide use of XR in industry. This thesis has emphasised the fact that a user-centred approach becomes especially important due to the new devices being introduced to developers and end-users. Compare to the conventional desktop system development, or the so-called window, icon, menu and pointer (WIMP) interface, the post-WIMP interfaces with their wearable displays and motion sensors pose an extra challenge as there is no universally accepted practice available to WIMP applications. Thus, the user-centred approach (which takes the end-user closer to the development loop) would help ensure satisfactory user experience of newly introduced XR systems.

RQ2: *What are the effects of extended reality (XR) systems on manufacturing activities?*

The eleven case studies conducted in this research explored a variety of XR applications in manufacturing. These cover the design phase, learning phase, operation phase and disruptive phase, as shown in Figure 14. The results have shown XR technology to have the advantage of improving current practice in manufacturing. At the same time, the potential impact and new challenges associated with XR adoption were reported.

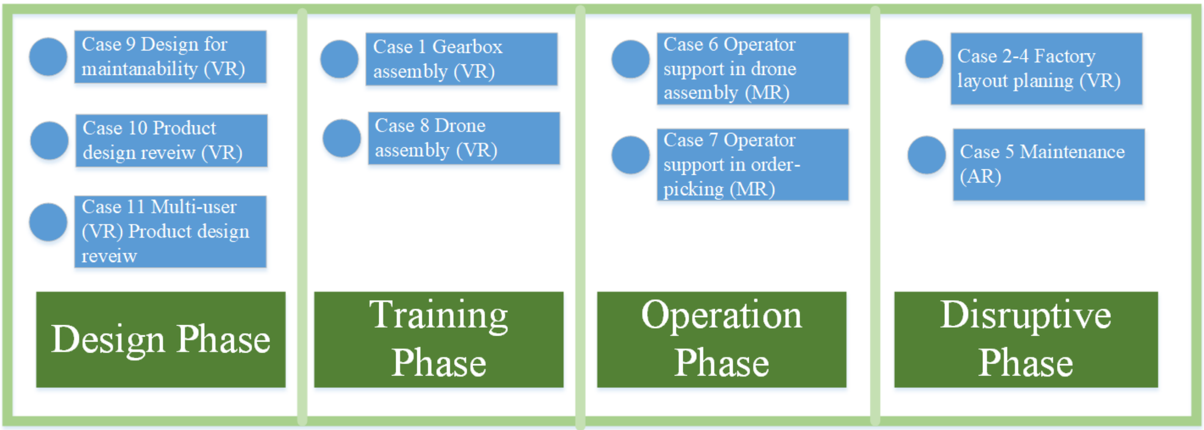

Figure 14. The eleven cases in relation to the different manufacturing phases.

In the design phase, products are created with the aid of CAD software. A major issue in this phase is the difficulty of communicating product concepts across different functional teams. In Case 9 of Paper III, the focus is on design for better maintainability of trucks due to the shift in business focus, from selling products to selling services. In current practice, the maintainability of the product is evaluated using CAD drawing on a desktop monitor, through physical prototypes or even through making the product. Obviously, these approaches are limited to achieving better maintainability. A maintenance engineer does not usually have the expertise to understand design solutions in CAD and thereby detect potential maintenance problems. Physical prototypes are problematic in that they involve longer development times, higher costs and more waste. The realistic visualisation and intuitive interaction in VR systems have shown great potential for improving current practice by facilitating communication between different stakeholders and reducing the number of physical prototypes. However, VR systems are not advanced enough to fully replace current practice. They should be regarded as a supplementary tool to help detect potential errors in the early design phase. Case 10 (Paper III) and Case 11 (Paper IV) are also about product design review but their focus is on cooperation in the globally distributed context, in which research and development are located in different countries. The multi-user VR environment provides a rich context, allowing team members across the globe to join in virtual factory-floor meetings and review product design concepts. Besides the benefits of strengthened communication and fewer physical prototypes, they would also reduce the amount of international travel needed.

With automation playing an increasing role in manufacturing, the amount of manual assembly work may decrease. However, the remaining assembly work usually requires skilled operators due to the complexity of tasks (Katz, 2008). In particular, given the shifting trend from mass production to mass customisation in recent years (El Maraghy, 2006), having vast numbers of product variants poses the extra challenge of equipping assembly operators with the necessary support. Thus, the training phase becomes an important step affecting assembly performance. Typical training methods include face-to-face teaching, written or video instructions and remote advice. These vary in the degree of flexibility and interactability which influences the outcome of training. Face-to-face teaching may have good interactions but requires trainer and trainee to be at the same place at the same time. Written or video instructions are flexible but lack the element of interaction. It is difficult to achieve optimal training results with such approaches. Cases 1 and 8, VR studied training; the results show that it has the advantages of being flexible and interactive while keeping the same level of training outcome. However, given the time and effort needed to develop such VR training systems, the drawbacks might outweigh the benefits. It is reasonable to limit such VR training to assembly tasks of serious complexity or with major safety requirements.

Cases 6 and 7 (Paper III) addressed the challenges in the operation phase. The focus here was on real-time support for ongoing operations in production. It was reported that experienced assembly operators cause most of the quality issues in assembly work (Joundi et al., 2019). The main reason is that assembly instructions are ignored because experienced operators tend to think they know what to do or find it burdensome to go around checking instructions. The wearable MR glasses introduced in Cases 6 and 7 (Paper III) tried to mitigate such effect by providing operators with the right visual information at the right time. The MR system in Case 6 provides 3D animated instructions in real-time for the assembly task. This has shown great potential for quality-assuring assembly work. Similar improvement was anticipated in the order-picking operation in Case 7 (Paper III). Instead of a list of part numbers which operators need to interpret (what to pick and where), spatial hints are visualised in the glass to guide the operators. However, while the two studies showed promising results for such solutions, ergonomic issues and hardware constraints were also reported. The weight of MR glasses can be problematic in long-term use and their tracking precision is not ideal, especially in large warehouse settings.

In the disruptive phase, the factory layout may need to be changed in order to adopt new products or production processes. Also, machines may need to undergo maintenance. Cases 2-4 (Paper II) and Case 5 (Paper III) resolved factory layout planning and maintenance activities respectively. Factory environments are complex in nature, as various operations are carried out. Even a minor change in the layout might affect multiple actors. When introducing changes such as replacing machines, the new layout plan needs to be thoroughly reviewed. This requires the involvement of all stakeholders, from management to operators. In practice, it is difficult to communicate efficiently across such diverse groups and not uncommon for design errors to be found only after implementation, resulting in difficult and costly fixes. The VR solution which exploits the hybrid modelling approach (using both point cloud representations from 3D laser scans and existing CAD models) was developed in Cases 2-4 (Paper II). It provides a virtual environment closely representing the real factory and has the flexibility to easily test what-if scenarios for different layout options. It also lowered the computer skill requirements so that all stakeholders affected by the change may be actively involved and contribute to the new layout design. Case 5 (Paper III) studied maintenance support through an AR system. This is, in essence, similar to the operator support for assembly work. Besides the advantages reported in the assembly cases, a lesson-learned from this study was the importance of having a good match between manufacturing problems and XR solutions. The corded AR glasses used in this case limited the potential gains from adopting such an AR system to improve the quality of maintenance work.

***RQ3**: How might extended reality (XR) systems be implemented so that they fit different manufacturing activities?*

The frameworks presented in this thesis provides guidance to manufacturing companies in their XR integrations. They were developed based on the results of the different empirical cases which address identified critical factors and mitigate potential negative impact, so that the promised benefits of XR technologies may be reaped in practice. Due to the multi-disciplinary nature of the problem, the frameworks cover the extent of the necessary steps but lack in-depth guidance for each step. They therefore serve more as general guidance providing an overall picture of the XR system development for manufacturing. Accordingly, they should be applied in combination with other established methods during the actual implementation of each step. For example, in the understanding requirements step, methods and techniques such as contextual inquiry (from the user-centred design approach (Bullinger et al., 2010)) might be adopted. The evaluation method for AR glasses developed by Syberfeldt (2017) may be a good aid to finding a decent match during the solution selection step. In the system implementation step, methodologies from the software engineering such as agile development (Highsmith and Cockburn, 2001) field may be adopted to ensure efficient development.

5.2 DISCUSSION OF METHODOLOGY

The author’s pragmatic worldview has led to the use of multiple case studies, as described in Chapter 3. It also helped him not to view the manufacturing systems an absolute reality. It enables the author to use different research methods to answer the research questions. The impact of the pragmatic worldview on the outcome and quality of this thesis is discussed below.

Creswell and Cark (2007) pointed out that pragmatic researchers hold truth as being what works at the time, with some even arguing that metaphysical concepts such as truth should be abandoned. This viewpoint focuses mostly on the usefulness of the research rather than its rigour, 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 rigour of their research. The consequence of imbalance is that scientific findings become accepted as adequate and relevant with no explanation as to why they work.

The multiple cases used in this thesis offer the advantage of directing the research to answer the RQs by collecting both qualitative and quantitative data (Eisenhardt, 1989). Research design relying solely on a qualitative or quantitative approach would have conflicted with the author's pragmatic worldview and led towards either a subjective or an 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 rigour of the research, validity and reliability were also taken into consideration when designing and conducting it. The methods used were validated according to construct and internal, external and contextual validity (Yin, 2009). For example, multiple cases with different companies and participants were used in the empirical studies, which increased the external validity. Both qualitative and quantitative data was collected to validate the results, so that internal validity was ensured. The data was captured and stored in a structured way, which increased the reliability of the empirical data (Williamson, 2002, Yin, 2013).

5.3 ACADEMIC AND INDUSTRIAL CONTRIBUTION

This thesis contributes to both the scientific and industrial communities. To the scientific community, the answer to RQ1 highlights four critical factors which would influence the success of XR technology integration in a manufacturing context. The positive and negative impact which XR might bring were also discussed with regard to RQ2. The frameworks developed in relation to RQ3 provided a holistic viewpoint from which to examine the issue and emphasised the need for further joint research into this multi-disciplinary field.

The industrial contribution includes the clarification of the XR technology. The multiple cases also exemplified the potential use cases. For the industrial audience, the developed frameworks provide step-by-step instructions which may assist in the process of XR adoption in industry. Therefore, this thesis contributes by helping manufacturing companies realise the promised benefits of XR technology advancement and, ultimately, to achieving the Industry 4.0 vision.

5.4 FUTURE RESEARCH

The continuation of this research should focus on two main directions. First, further studies are needed, into ensuring a satisfactory user experience (UX) for the XR systems in manufacturing. The progress of XR technology integration into manufacturing would depend heavily on the general UX and user acceptance of the technology. The XR development can learn from the conventional user-centred design approach shown to work so well for software engineering. However, efforts are also needed to establish common standards and practices unique to the XR field. Another direction concerns the verification and validation of XR solutions in manufacturing. The potential benefits were largely evaluated using subjective data. It may be difficult to follow up and quantify the actual benefits if an XR system were to be introduced into manufacturing. However, it would be worth expending the resources to develop methods and quantitative measures which may help quantify the benefits.

6

CONCLUSIONS

This chapter presents the conclusions drawn from this research.

This thesis aims to facilitate the process of integrating the latest XR technology in manufacturing and thus contribute to a realisation of the Industry 4.0 vision. In pursuit of answers to the three research questions arising from the aims of this thesis, the pragmatic approach was applied to eleven empirical studies based on real-world manufacturing problems from five companies and two testbeds. Therefore, eleven XR systems ranging from AR to VR were developed and tested for applications covering all four phases of production: design, learning, operational and disruptive.

The thesis identified three critical factors which influence the success of XR integration in manufacturing. Firstly, there was the compatibility between XR technology and the intended manufacturing activity. Secondly, a central strategy for improving data compatibility across systems may shorten the time needed for XR system development and ensure system quality. Thirdly, usability-related problems of XR systems, including 3D user interface design, ergonomics and system function comprehensiveness are major obstacles to the wide usage of XR in manufacturing. A user-centred approach, with an iterative process involving users in the development process, has proved effective in improving the general user experience and user acceptance.

This thesis also highlighted the advantages of XR solutions compared with conventional approaches in terms of the flexibility, realistic visualisation and nature interaction. This may save time, help with design cost issues and facilitate involvement and communication across all stakeholders. Moreover, this thesis proposed the general framework of user-centred extended reality system development. This provides clear guidelines on the steps and methods needed for integrating XR systems into manufacturing. The framework was validated via internal and external cases and was shown to be effective in guiding the XR integration process in manufacturing and in ensuring the quality of integration.

Manufacturing companies which plan to adopt XR technologies as part of their Industry 4.0 vision may benefit from the knowledge generated in this thesis. Such knowledge might help kick-start the integration of XR whilst avoiding common mistakes. This thesis also proposes future academic research directions into XR technology integration within the manufacturing industry.

REFERENCES

Abidi, M.H., Ahmad A., S Darmoul, and A Al-Ahmari. 2015. “Haptics Assisted Haptics Assisted Virtual Assembly Haptics Haptics Assisted Assisted Virtual.” In *IFAC-Papers OnLine*, 48:100–105. Elsevier Ltd. https://doi.org/10.1016/j.ifacol.2015.06.065.

Abidi, M.H., Abdulrahman Al-Ahmari, A Ahmad, Wadea Ameen, and Hisham Alkhalefah. 2019. “Assessment of Virtual Reality-Based Manufacturing Assembly Training System.” *International Journal of Advanced Manufacturing Technology* 105: 3743–59.

Al-ahmari, Abdulrahman M, Mustufa H Abidi, and Ali Ahmad. 2016. “Development of a Virtual Manufacturing Assembly Simulation System.” *Advances in Mechanical Engineering* 8 (3): 1–13. https://doi.org/10.1177/1687814016639824.

Andreas, D, Raphaël Grasset, Hartmut Seichter, and Mark Billinghurst. 2007. “Applying HCI Principles to AR Systems Design.” In *International Workshop on Mixed Reality User Interfaces: Specification, Authoring, Adaptation (MRUI ’07)*.

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.

Azizi, Aydin, Poorya Ghafoorpoor Yazdi, and Majid Hashemipour. 2019. “Interactive Design of Storage Unit Utilizing Virtual Reality and Ergonomic Framework for Production Optimization in Manufacturing Industry.” *International Journal on Interactive Design and Manufacturing* 13 (1): 373–81. https://doi.org/10.1007/s12008-018-0501-9.

Bakker, Iris, Theo van der Voordt, Peter Vink, and Jan de Boon. 2014. “Pleasure, Arousal, Dominance: Mehrabian and Russell Revisited.” *Current Psychology* 33 (3): 405–21. https://doi.org/10.1007/s12144-014-9219-4.

Blessing, Lucienne, and Amaresh Chakrabarti. 2009. *DRM, a Design Research Methodology*. *DRM, a Design Research Methodology*. https://doi.org/10.1007/978-1-84882-587-1.

Brooke, John. 1996. “SUS: A ‘Quick and Dirty’ Usability Scale.” In *Usability Evaluation In Industry*, edited by Patrick W. Jordan, B. Thomas, Ian Lyall McClelland, and Bernard Weerdmeester, 189–94. London: Taylor & Francis.

Bryman, A., and E. Bell. 2011. *Business Research Methods*. Oxford University Press.

Bullinger, Hans‐Jörg, Wilhelm Bauer, Günter Wenzel, and Roland Blach. 2010. “Towards User Centred Design (UCD) in Architecture Based on Immersive Virtual Environments.” *Computers in Industry* 61 (4): 372–79. https://doi.org/10.1016/j.compind.2009.12.003.

Carulli, M., M. Bordegoni, and U. Cugini. 2013. “An Approach for Capturing the Voice of the Customer Based on Virtual Prototyping.” *Journal of Intelligent Manufacturing* 24 (5): 887–903. https://doi.org/10.1007/s10845-012-0662-5.

Cecil, J., and James Jones. 2014. “VREM: An Advanced Virtual Environment for Micro Assembly.” *International Journal of Advanced Manufacturing Technology* 72 (1–4): 47–56. https://doi.org/10.1007/s00170-014-5618-9.

Cecil, J, Sadiq Albuhamood, Aaron Cecil-xavier, and P Ramanathan. 2019. “An Advanced Cyber Physical Framework for Micro Devices Assembly.” *IEEE Transactions on Systems, Man, and Cybernetics: Systems* 49 (1): 92–106. https://doi.org/10.1109/TSMC.2017.2733542.

Chen, Junjie, Weiyi Huang, and Aiguo Song. 2005. “Design of New Research Platform of Telepresence Telerobot System.” *2005 IEEE International Conference on Information*

Acquisition, 5 pp. https://doi.org/10.1109/ICIA.2005.1635064.
Cherryholmes, C.H. 1992. “Notes on Pragmatism and Scientific Realism.” *Educational Researcher* 21: 13–17.
Choi, S. H., and H. H. Cheung. 2006. “A CAVE-Based Multi-Material Virtual Prototyping System.” *Computer-Aided Design and Applications* 3 (5): 557–66. https://doi.org/10.1080/16864360.2006.10738409.
Choi, S.H., and S. Samavedam. 2002. “Modelling and Optimisation of Rapid Prototyping.” *Computers in Industry* 47 (1): 39–53. https://doi.org/10.1016/S0166-3615(01)00140-3.
Choi, S H, and A M M Chan. 2004. “A Virtual Prototyping System for Rapid Product Development.” *CAD Computer Aided Design*.
Choi, Sangsu, Kiwook Jung, and Sang Do Noh. 2015. “Virtual Reality Applications in Manufacturing Industries : Past Research, Present Findings, and Future Directions.” *CONCURRENT ENGINEERING: Research and Applicationsand Applications* 23 (1): 40–63. https://doi.org/10.1177/1063293X14568814.
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. 2009. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. Los Angeles, USA: SAGE Publications.
———. 2013. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. Thousand Oaks, CA: SAGE Publications.
Creswell, John. W., and Vicki. L. Plano. Clark. 2011. *Designing and Conducting Mixed Methods Research*. 2nd ed. SAGE Publications.
Dado, Miroslav, Luboš Kotek, Richard Hnilica, and Zdeněk Tůma. 2018. “The Application of Virtual Reality for Hazard Identification Training in the Context of Ma- Chinery Safety : A Preliminary Study” 18 (5): 732–36.
Dagman, J, M Karlsson, and L Wikström. 2010. “Investigating the Haptic Aspects of Verbalised Product Experiences.” *International Journal of Design* 4 (3): 15–27. https://www.scopus.com/inward/record.uri?eid=2-s2.0-79952889571&partnerID=40&md5=921fac78bdb8510269751504440e993e.
Dangelmaier, Wilhelm, Matthias Fischer, Jurgen Gausemeier, Michael Grafe, Carsten Matysczok, and Bengt Mueck. 2005. “Virtual and Augmented Reality Support for Discrete Manufacturing System Simulation.” *Computers in Industry* 56 (4): 371–83. https://doi.org/10.1016/j.compind.2005.01.007.
“Definition of Virtual Reality in English by Oxford Dictionaries.” n.d. Accessed February 27, 2017. https://en.oxforddictionaries.com/definition/virtual_reality.
DiCicco‐Bloom, Barbara., Crabtree, Benjamin F. 2006. “The Qualitative Research Interview.” *Medical Education* 40 (4).
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.
Fast-Berglund, Åsa, Liang Gong, and Dan Li. 2018. “Testing and Validating Extended Reality (XR) Technologies in Manufacturing.” *Procedia Manufacturing* 25: 31–38.
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.

Flynn, B.B., S. Sakakibara, R.G. Schroeder, K.A. Bates, and E.J. Flynn. 1990. "Empirical Research Methods in Operations Management." *Journal of Operations Management* 9 (2): 250–84.

Guba, Egon, and Yvonna Lincoln. 2000. "Paradigmatic Controversies, Contradictions, and Emerging Confluences." *The SAGE Handbook of Qualitative Research* 8 (January).

Hashemipour, Majid, Hamed Farahani Manesh, and Mert Bal. 2008. "A Modular Virtual Reality System for Engineering Laboratory Education," 305–14. https://doi.org/10.1002/cae.20312.

Havard, Vincent, Benoit Jeanne, Marc Lacomblez, David Baudry, Vincent Havard, Benoit Jeanne, Marc Lacomblez, et al. 2019. "Digital Twin and Virtual Reality : A Co-Simulation Environment for Design and Assessment of Industrial Workstations for Design and Assessment of Industrial Workstations." *Production & Manufacturing Research* 7 (1): 472–89. https://doi.org/10.1080/21693277.2019.1660283.

Highsmith, J, and A Cockburn. 2001. "Agile Software Development: The Business of Innovation." *Computer* 34 (9): 120–22. https://doi.org/10.1109/2.947100.

Ho, Nicholas, Pooi-mun Wong, Matthew Chua, and Chee-kong Chui. 2018. "Virtual Reality Training for Assembly of Hybrid Medical Devices." *Multimed Tools Appl* 77: 30651–82.

Holubek, R, D R Delgado Sobrino, P Košťál, and R Ružarovský. 2014. "Offline Programming of an ABB Robot Using Imported CAD Models in the RobotStudio Software Environment." *Applied Mechanics and Materials* 693: 62–67. https://doi.org/10.4028/www.scientific.net/AMM.693.62.

Howard, Ian P., and Brian J. Rogers. 1996. *Binocular Vision and Stereopsis*. New York, NY, USA: Oxford University Press.

Ihantola, Eeva-Mari, and Lili-Anne Kihn. 2011. "Threats to Validity and Reliability in Mixed Methods Accounting Research." *Qualitative Research in Accounting & Management* 8 (April): 39–58. https://doi.org/10.1108/11766091111124694.

Insights, Fortune Business. 2018. "Virtual Reality in Manufacturing Industry Share, Trends & Industry Analysis." https://www.fortunebusinessinsights.com/industry-reports/virtual-reality-vr-in-manufacturing-industry-101714.

Ji, Ping, Albert C.K. Choi, and Lizhong Tu. 2002. "VDAS : A Virtual Design and Assembly System in a Virtual Reality Environment." *Assembly Automation* 22 (4): 337–42. https://doi.org/10.1108/01445150210446201.

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.

Jönsson, Anders, Johan Wall, and Göran Broman. 2005. "A Virtual Machine Concept for Real-Time Simulation of Machine Tool Dynamics." *International Journal of Machine Tools & Manufacture* 45: 795–801. https://doi.org/10.1016/j.ijmachtools.2004.11.012.

Joundi, Jamil, Peter Conradie, Jan van Den Bergh, and Jelle Saldien. 2019. "Understanding and Exploring Operator Needs in Mixed Model Assembly." *CEUR Workshop Proceedings* 2503: 130–38.

Jun, H.-K., D.-H. Lee, and D.-C. Yang. 2006. "Development of a Simulator Based on Train Performance Simulation." *Computer-Aided Design and Applications* 3 (1–4): 465–73. https://doi.org/10.1080/16864360.2006.10738485.

Kang, Hyoung Seok, Ju Yeon Lee, SangSu Choi, Hyun Kim, Jun Hee Park, Ji Yeon Son, Bo Hyun Kim, and Sang Do Noh. 2016. "Smart Manufacturing: Past Research, Present Findings, and Future Directions." *International Journal of Precision Engineering and Manufacturing-Green Technology* 3 (1): 111–28. https://doi.org/10.1007/s40684-016-

0015-5.
Kascak, J, M Teliskova, J Torok, P Baron, J Zajac, and J Husar. 2019. “Implementation of Augmented Reality into the Training and Educational Process in Order to Support Spatial Perception in Technical Documentation.” In *2019 IEEE 6th International Conference on Industrial Engineering and Applications, ICIEA 2019*, 583–87. https://doi.org/10.1109/IEA.2019.8715120.
Kato, Takumi. 2019. “Verification of Perception Difference between Actual Space and VR Space in Car Design.” *International Journal on Interactive Design and Manufacturing* 13 (3): 1233–44. https://doi.org/10.1007/s12008-019-00568-5.
Katz, Jonathan. 2008. “Engineering Jobs Top U.S. Skills Shortage List.” *IndustryWeek*, 2008.
Kawulich, Barbara B. 2005. “Participant Observation as a Data Collection Method.” *Forum Qualitative Sozialforschung / Forum: Qualitative Social Research; Vol 6, No 2 (2005): Qualitative Inquiry: Research, Archiving, and ReuseDO - 10.17169/Fqs-6.2.466*, May. http://www.qualitative-research.net/index.php/fqs/article/view/466/996.
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: 87–91.
Kothari, C.R. 2004. *Research Methodology: Methods and Techniques*. 2nd editio. New Delhi: New Age International Publishers.
Krishnamurthy, Rajesh, and J Cecil. 2018. “A Next-Generation IoT-Based Collaborative Framework for Electronics Assembly.” *The International Journal of Advanced Manufacturing Technology*, 39–52.
Li, Shiqi, Tao Peng, Junfeng Wang, and Chi Xu. 2009. “Mixed Reality-Based Interactive Technology for Aircraft Cabin Assembly.” *CHINESE JOURNAL OF MECHANICAL ENGINEERING-ENGLISH EDITION* 22 (3): 403–9.
Liang, J.S. 2008. “A Study on Virtual Reality-Based EDM Learning Framework and Effectiveness Analysis.” *Computer-Aided Design and Applications* 5 (1–4): 391–400. https://doi.org/10.3722/cadaps.2008.391-400.
Lim, Theodore, James Ritchie, and Samir Garbaya. 2014. “The Development of a Physics and Constraint-Based Haptic Virtual Assembly System.” *Assembly Automation* 34 (1): 41–55. https://doi.org/10.1108/AA-03-2013-023.
Lin, Y., S. Yu, P. Zheng, L. Qiu, Y. Wang, and X. Xu. 2017. “VR-Based Product Personalization Process for Smart Products.” *Procedia Manufacturing* 11: 1568–76. https://doi.org/10.1016/j.promfg.2017.07.297.
Luo, X, and C D Mojica Cabico. 2018. “Development and Evaluation of an Augmented Reality Learning Tool for Construction Engineering Education.” In *Construction Research Congress 2018: Sustainable Design and Construction and Education - Selected Papers from the Construction Research Congress 2018*, 2018-April:149–59. https://doi.org/10.1061/9780784481301.015.
Mack, N, Cynthia Woodsong, Kathleen Macqueen, Greg Guest, and Emily Namey. 2005. *Qualitative Research Methods: A Data Collector’s Field Guide*. *Fam Health Int*.
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.
Maxwell, J.A. 2005. *Qualitative Research Design an Interactive Approach*. 2nd ed. SAGE Publications.
Milgram, Paul, and Fumio Kishino. 1994. “Taxonomy of Mixed Reality Visual Displays.” *IEICE Transactions on Information and Systems* E77-D (12): 1321–29. https://doi.org/10.1.1.102.4646.

Milgram, Paul, Haruo Takemura, Akira Utsumi, and Fumio Kishino. 1995. “Augmented Reality: A Class of Displays on the Reality-Virtuality Continuum.” In *Proceedings of SPIE - The International Society for Optical Engineering*, 2351:282–92. https://www.scopus.com/inward/record.uri?eid=2-s2.0-0029211386&partnerID=40&md5=5b462c4a3302c15337dc75ecf522b105.

Mujber, T. S., T. Szecsi, and M. S J Hashmi. 2004. “Virtual Reality Applications in Manufacturing Process Simulation.” *Journal of Materials Processing Technology* 155–156 (1–3): 1834–38. https://doi.org/10.1016/j.jmatprotec.2004.04.401.

Nee, A Y C, and S K Ong. 2013. “Virtual and Augmented Reality Applications in Manufacturing.” In *7th IFAC Conference on Manufacturing Modelling, Management, and Control, MIM 2013*, 15–26. Mechanical Engineering Department, National University of Singapore, Singapore, Singapore. https://doi.org/10.3182/20130619-3-RU-3018.00637.

Newman, Isadore, and Carolyn R. Benz. 1998. *Qualitative-Quantitative Research Methodology: Exploring the Interactive Continuum*. SIU Press.

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.

Onwuegbuzie, A.J., and R.B. Johnson. 2006. “The Validity Issue in Mixed Research.” *RESEARCH IN THE SCHOOLS* 113 (1): 48–63.

Östlund, U., L. Kidd, Y. Wengström, and N. Rowa-Dewar. 2011. “Combining Qualitative and Quantitative Research within Mixed Method Research Designs: A Methodological Review.” *International Journal of Nursing Studies* 48 (3): 369–83.

Peng, Gaoliang, Xu He, Haiquan Yu, Xin Hou, and Alipour Khalil. 2008. “Precise Manipulation Approach to Facilitate Interactive Modular Fixture Assembly Design in a Virtual Environment.” *Assembly Automation* 28 (3): 216–24. https://doi.org/10.1108/01445150810889475.

Peng, Gaoliang, X. Hou, J. Gao, and D. Cheng. 2012. “A Visualization System for Integrating Maintainability Design and Evaluation at Product Design Stage.” *International Journal of Advanced Manufacturing Technology* 61 (1–4): 269–84. https://doi.org/10.1007/s00170-011-3702-y.

Pérez, Luis, Eduardo Diez, Rubén Usamentiaga, and Daniel F García. 2019. “Computers in Industry Industrial Robot Control and Operator Training Using Virtual Reality Interfaces.” *Computers in Industry* 109: 114–20. https://doi.org/10.1016/j.compind.2019.05.001.

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.

Ritchie, James M., Richard G. Dewar, and John E. L. Simmons. 1999. “The Generation and Practical Use of Plans for Manual Assembly Using Immersive Virtual Reality.” *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 213 (5): 461–74. https://doi.org/10.1243/0954405991516930.

Rutter, Deborah, and Jennifer Francis. 2010. *SCIE Systematic Research Reviews: Guidelines*. London: Social Care Institute for Excellence. https://doi.org/10.1021/i650600a738.

Stylidis, Kostas, Andreas Dagman, Håkan Almius, Liang Gong, and Rikard Söderberg. 2019. "Perceived Quality Evaluation with the Use of Extended Reality." In *Proceedings of the Design Society: International Conference on Engineering Design*, 1:1993–2002.

Sujová, E, E Střihavková, and H Čierna. 2018. "An Analysis of the Assembly Line Modernization by Using Simulation Software." *Manufacturing Technology* 18 (5): 839–45. https://doi.org/10.21062/ujep/180.2018/a/1213-2489/MT/18/5/839.

Sutherland, Ivan E. 1968. "A Head-Mounted Three Dimensional Display." In *Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, Part I*, 757–64.

Syberfeldt, Anna, Oscar Danielsson, and Patrik Gustavsson. 2017. "Augmented Reality Smart Glasses in the Smart Factory: Product Evaluation Guidelines and Review of Available Products." *IEEE Access* 5: 9118–30. https://doi.org/10.1109/ACCESS.2017.2703952.

Turner, Christopher J, Windo Hutabarat, and John Oyekan. 2016. "Discrete Event Simulation and Virtual Reality Use in Industry : New Opportunities and Future Trends." *IEEE TRANSACTIONS ON HUMAN-MACHINE SYSTEMS*, 1–13.

Tuttle, Paul, Joseph Bobinis, and Lockheed Martin Corporation. 2012. "Affordability Specification," no. Ad M: 1–13.

Wahlster, W. 2012. "From Industry 1.0 to Industry 4.0: Towards the 4th Industrial Revolution." In *3rd European Summit on Future Internet towards Future Internet International Collaborations*.

Westkämper, E., and R.von Briel. 2001. "Continuous Improvement and Participative Factory Planning by Computer Systems." *CIRP Annals - Manufacturing Technology*. https://doi.org/10.1016/S0007-8506(07)62137-4.

Williamson, K. 2002. *Research Methods for Students, Academics and Professionals - Information Management and Systems*. Centre for Information Studies.

Yao, Y. X., P. J. Xia, J. S. Liu, and J. G. Li. 2006. "A Pragmatic System to Support Interactive Assembly Planning and Training in an Immersive Virtual Environment (I-VAPTS)." *International Journal of Advanced Manufacturing Technology* 30 (9–10): 959–67. https://doi.org/10.1007/s00170-005-0069-y.

Ye, Nong, Prashant Banerjee, Amarnath Banerjee, and Fred Dech. 1999. "A Comparative Study of Assembly Planning in Traditional and Virtual Environments" 29 (4): 546–55.

Yin, R.K. 2013. *Case Study Research: Design and Methods*. 5th ed. Thousand Oaks, CA: SAGE Publications.

Yuan, Xiaobu. 2002. "An Interactive Approach of Assembly Planning." *IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS—PART A: SYSTEMS AND HUMANS* 32 (4): 522–26.

Zhou, Y, Y Zhou, and W Liu. 2020. "Design of Virtual Overhaul System for Condensing Steam Turbine Based on Unity3D." In *Proceedings - 2020 12th International Conference on Measuring Technology and Mechatronics Automation, ICMTMA 2020*, 204–7. https://doi.org/10.1109/ICMTMA50254.2020.00053.

Zhou, Zewei, Yiping Feng, Gang Rong, and Yucheng Wu. 2011. "Virtual Reality Based Process Integrated Simulation Platform in Refinery : Virtual Refinery and Its Application." *China Petroleum Processing and Petrochemical Technology* 13 (3): 74–84.

Zohrabi, M. 2013. "Mixed Method Research: Instruments, Validity, Reliability and Reporting Findings." *Theory and Practice in Language Studies* 3 (2): 254–62.